

Climate Change Vulnerability and Adaptation in the Northern Rocky Mountains

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Abstract

The Northern Adaptation Partnership (NRAP) identified climate change issues relevant to resource management in the Northern Rockies (USA) region, and developed solutions that minimize negative effects of climate change and facilitate transition of diverse ecosystems to a warmer climate. The NRAP region covers 183 million acres, spanning northern Idaho, Montana, northwest Wyoming, North Dakota, and northern South Dakota, and includes 15 national forests and 3 national parks across the U.S. Forest Service Northern Region and adjacent Greater Yellowstone Area. U.S. Forest Service scientists, resource managers, and stakeholders worked together over a two-year period to conduct a state-of-science climate change vulnerability assessment and develop adaptation options for national forests and national parks in the Northern Rockies region. The vulnerability assessment emphasized key resource areas—water, fisheries, wildlife, forest and rangeland vegetation and disturbance, recreation, cultural heritage, and ecosystem services—regarded as the most important for local ecosystems and communities. Resource managers used the assessment to develop a detailed list of ways to address climate change vulnerabilities through management actions. The large number of adaptation strategies and tactics, many of which are a component of current management practice, provide a pathway for slowing the rate of deleterious change in resource conditions.

Keywords: adaptation, climate change, ecological disturbance, climate-smart resource management, Northern Rocky Mountains, vulnerability assessment

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Summary

The Northern Rockies Adaptation Partnership (NRAP) is a science-management partnership consisting of 15 national forests in the Northern Region of the U.S. Forest Service, three national parks, the U.S. Forest Service Pacific Northwest and Rocky Mountain Research Stations, the University of Washington, and numerous other organizations and stakeholders. These organizations worked together over a period of two years to identify climate change issues relevant to resource management in the Northern Rocky Mountains (USA) and to find solutions that can minimize negative effects of climate change and facilitate transition of diverse ecosystems to a warmer climate. The NRAP provided education, conducted a climate change vulnerability assessment, and developed adaptation options for national forests and national parks that manage more than 28 million acres in northern Idaho, Montana, northwestern Wyoming, North Dakota, and northern South Dakota.

Global climate models project that the Earth's current warming trend will continue throughout the 21st century in the Northern Rockies. Compared to observed historical temperature, average warming across the five NRAP subregions is projected to be about 4 to 5 °F by 2050, depending on greenhouse gas emissions. Precipitation may increase slightly in the winter, although the magnitude is uncertain.

Climatic extremes are difficult to project, but they will probably be more common, driving biophysical changes in terrestrial and aquatic ecosystems. Droughts of increasing frequency and magnitude are expected in the future, promoting an increase in wildfire, insect outbreaks, and non-native species. These periodic disturbances, will rapidly alter productivity and structure of vegetation, potentially altering the distribution and abundance of dominant plant species and animal habitat.

Highlights of the vulnerability assessment and adaptation options for the Northern Rockies include the following:

Water resources and infrastructure

- Effects: Decreasing snowpack and declining summer flows will alter timing and availability of water supply, affecting agricultural, municipal, and public uses in and downstream from national forests, and affecting other forest uses including livestock, wildlife, recreation, firefighting, road maintenance, and instream fishery flows. Declining summer low flows will affect water availability during late summer, the period of peak demand (e.g., for irrigation and power supply). Increased magnitude of peak streamflows will damage roads near perennial streams, ranging from minor erosion to extensive damage, thus affecting public safety, access for resource management, water quality, and aquatic habitat. Bridges, campgrounds, and national forest facilities near streams and floodplains will be especially vulnerable, reducing access by the public.
- Adaptation options: Primary adaptation strategies to address changing hydrology in the Northern Rockies include restoring the function of watersheds, connecting floodplains, reducing drainage efficiency, maximizing valley storage, and reducing hazardous fuels. Tactics include adding wood to streams, restoring beaver populations, modifying livestock management, and reducing surface fuels and forest stand densities. Primary strategies for infrastructure include increasing the resilience of stream crossings, culverts, and bridges to higher peak flows and facilitating response to higher peak flows by reducing the road system and disconnecting roads from streams. Tactics include completing geospatial databases of infrastructure (and drainage) components, installing higher capacity culverts, and decommissioning roads or converting them to alternative uses. It will be important to map aquifers and alluvial deposits, improve monitoring to provide feedback on water dynamics, and understand the physical and legal availability of water for aquifer recharge. Erosion potential to protect water quality can be addressed by reducing hazardous fuels in dry forests, reducing non-fire disturbances, and using road management practices that prevent erosion.

Fisheries

- Effects: Decreased snowpack will shift the timing of peak flows, decrease summer low flows, and in combination with higher air temperature, increase stream temperatures, all of which will reduce the vigor of cold-water fish species. Abundance and distribution of cutthroat trout and especially bull trout will be greatly reduced, although effects will differ by location as a function of both stream temperature and competition from non-native fish species. Increased wildfire will add sediment to streams, increase peak flows and channel scouring, and raise stream temperature by removing vegetation.
- Adaptation options: Primary strategies to address climate change threats to cold-water fish species include maintaining or restoring functionality of channels and floodplains to retain (cool) water and buffer against future changes, decreasing fragmentation of stream networks so aquatic organisms can access similar habitats, and developing wildfire use plans that address sediment inputs and road failures. Adaptation tactics include using watershed analysis to develop integrated actions for vegetation and hydrology, protecting groundwater and springs, restoring riparian areas and beaver populations to maintain summer baseflows, reconnecting and increasing off-channel habitat and refugia, identifying and improving stream crossings that impede fish movement, decreasing road connectivity, and revegetating burned areas to store sediment and maintain channel geomorphology. Removing non-native fish species and reducing their access to cold-water habitat reduces competition with native fish species.

Forest vegetation

- Effects: Increasing air temperature, through its influence on soil moisture, is expected to cause gradual changes in the abundance and distribution of tree, shrub, and grass species throughout the Northern Rockies, with more drought tolerant species becoming more competitive. The earliest changes will be at ecotones between lifeforms (e.g., upper and lower treelines). Ecological disturbance, including wildfire and insect outbreaks, will be the primary facilitator of vegetation change, and future forest landscapes may be dominated by younger age classes and smaller trees.

High-elevation forests will be especially vulnerable if disturbance frequency increases significantly. Increased abundance and distribution of non-native plant species, as well as the legacy of past land uses, create additional stress for regeneration of native forest species.

- Adaptation options: Most strategies for conserving native tree, shrub, and grassland systems focus on increasing resilience to chronic low soil moisture (especially extreme drought and low snowpack), and to more frequent and extensive ecological disturbance (wildfire, insects, non-native species). These strategies generally include managing landscapes to reduce the severity and patch size of disturbances, encouraging fire to play a more natural role, and protecting refugia where fire-sensitive species can persist. Increasing species, genetic, and landscape diversity (spatial pattern, structure) is an important “hedge your bets” strategy that will reduce the risk of major forest loss. Adaptation tactics include using silvicultural prescriptions (especially stand density management) and fuel treatments to reduce fuel continuity, reducing populations of non-native species, potentially using multiple genotypes in reforestation, and revising grazing policies and practices. Rare and disjunct species and communities (e.g., whitebark pine, quaking aspen) require adaptation strategies and tactics focused on encouraging regeneration, preventing damage from disturbance, and establishing refugia.

Rangeland vegetation

- Effects: A longer growing season is expected to increase net primary productivity of many rangeland types, especially those dominated by grasses, although responses will depend on local climate and soil conditions. Elevated atmospheric carbon dioxide may increase water use efficiency and productivity of some species. In many cases, increasing wildfire frequency and extent will be particularly damaging for big sagebrush and other shrub species that are readily killed by fire. The widespread occurrence of cheatgrass and other non-natives facilitates frequent fire through annual fuel accumulation. In montane grasslands, wildfire may kill Douglas-fir and other species that have recently established in rangelands through fire exclusion. Shrub species

that sprout following fire may be quite resilient to increased disturbance, but may be outcompeted by more drought tolerant species over time.

- Adaptation options: Adaptation strategies for rangeland vegetation focus on increasing resilience of rangeland ecosystems, primarily through non-native species control and prevention. Using ecologically based non-native plant management focuses on strategies to repair damaged ecological processes that facilitate invasion, and seeding of desired natives can be done where seed availability and dispersal of natives are low. Proactive management to prevent establishment of non-native species is also critical (early detection-rapid response), including tactics such as weed-free policies, education of employees and the public, and collaboration among multiple agencies to control weeds. Livestock grazing can also be managed through the development of site-specific indicators that inform livestock movement guides and allow for maintenance and enhancement of plant health.

Wildlife

- Effects: Few data exist on the direct effects of climatic variability and change on most animal species. Therefore, projected climate change effects must be inferred from what is known about habitat characteristics and the autecology of each species. Habitat for mammals that depend on high-elevation, snowy environments for both predators (Canada lynx, fisher, wolverine) and prey (snowshoe hare) is expected to deteriorate relatively soon if snowpack continues to decrease. Species that are highly dependent on a narrow range of habitat (pygmy rabbit, Brewer's sparrow, greater sage-grouse,) will be especially vulnerable if that habitat decreases from increased disturbance (e.g., sagebrush mortality from wildfire). Species that are mobile or respond well to increased disturbance and habitat patchiness (deer, elk) will probably be resilient to a warmer climate in most locations. Some amphibian species (Columbia spotted frog, western toad) may be affected by pathogens (e.g., amphibian chytrid fungus) that are favored by a warmer climate.

- Adaptation options: Adaptation for wildlife is focused on maintaining adequate habitat and healthy wildlife populations, and increasing knowledge of species' needs and climate sensitivities. Connectivity is an important conservation strategy for most species in the Northern Rockies. Maintaining healthy American beaver populations will provide riparian habitat structure and foraging opportunities for multiple species. Quaking aspen habitat, which is also important for several species, can be enhanced by allowing wildfire, protecting aspen from grazing, and reducing conifer encroachment. Restoration of more open stands of ponderosa pine and mixed conifer forest through reduction of stand densities will benefit species such as fisher and flammulated owl. Excluding fire and reducing non-native species will maintain sagebrush habitats that are required by several bird and mammal species.

Recreation

- Effects: Recreation has a significant economic impact throughout the Northern Rockies. A warmer climate will generally improve opportunities for warm-weather activities (hiking, camping, sightseeing) because it will create a longer time during which these activities are possible, especially in the spring and autumn "shoulder seasons." However, it will reduce opportunities for snow-based, winter activities (downhill skiing, cross-country skiing, snowmobiling) because snowpack is expected to decline significantly in the future. Recreationists will probably seek more water-based activities in lakes and rivers in order to seek refuge from hotter summer weather. Higher temperatures may have both positive and negative effects on wildlife-based activities (hunting, fishing, birding) and gathering of forest products (e.g., berries, mushrooms), depending on how target habitats and species are affected.
- Adaptation options: Recreationists are expected to be highly adaptable to a warmer climate by shifting to different activities and different locations, behavior that is already observed from year to year. For example, downhill skiers may switch to ski areas that have more reliable snow, cross-country skiers will travel to higher elevations, and larger ski areas on federal lands may expand to

multi-season operation. Water-based recreationists may adapt to climate change by choosing different sites that are less susceptible to changes in water levels. Hunters may need to adapt by altering the timing and location of hunts. Federal management of recreation is currently not very flexible with respect to altered temporal and spatial patterns of recreation. This can be at least partially resolved by assessing expected use patterns in a warmer climate, modifying opening times of facilities, and deploying seasonal employees responsible for recreational facilities earlier in the year.

Ecosystem services

Ecosystem services are increasingly valued on federal lands, beyond just their economic value. Climate change effects will vary greatly within different subregions of the Northern Rockies, with some ecosystem services being affected in the short term and others in the long term. Of the many ecosystem services provided in the Northern Rockies, eight are considered here, most of which are relevant to other resource categories included in the assessment.

- While annual *water yield* is not expected to change significantly, timing of water availability will likely shift, and summer flows may decline. These changes may result in some communities experiencing summer water shortages, although reservoir storage can provide some capacity. Rural agricultural communities will be disproportionately affected by climate change if water does become limiting.
- *Water quality* will decrease in some locations if wildfires and floods increase, adding sediment to rivers and reservoirs. Agriculture is currently the major source of impairment, affecting riparian systems, aquatic habitat, water temperatures, and fecal coliform. Climate change is expected to amplify these effects. Hazardous fuel treatments, riparian restoration, and upgrading of hydrologic infrastructure can build resilience to disturbances that damage water quality.
- *Wood products* are a relatively small component of the Northern Rockies economy, and effects from economic forces will probably have the biggest impacts in the future. As wildfires and

insect outbreaks become more common, wood supply could become less reliable, but overall effects will generally be small except in small towns that depend on steady timber supply.

- *Minerals* and mineral extraction are important economic drivers in eastern Montana and western North Dakota. The biggest effects on this industry will be economic factors, as well as how it connects to other ecosystem services, particularly water quality. Wildfires and floods can put mineral extraction infrastructure at risk in some watersheds.
- *Forage for livestock* is expected to increase in productive grasslands as a result of a longer growing season and in some cases elevated carbon dioxide. Therefore, ranching and grazing may benefit from climate change. Primary effects on grazing include loss of rural population, spread of non-native grasses, and fragmentation of rangelands.
- *Viewsheds and air quality* will be negatively affected by increasing wildfires and longer pollen seasons. A growing percentage of the Northern Rockies population will be in demographic groups at risk for respiratory and other medical problems on days with poor air quality. Hazardous fuel treatments can help build resilience to disturbances that degrade air quality.
- *Regulation of soil erosion* will be decreased by agricultural expansion, spread of non-native plants, and increased frequency of wildfire and floods. Increased capital investments may be needed for water treatment plants if water quality degrades significantly. Climate-smart practices in agriculture and road construction can reduce some negative effects.
- *Carbon sequestration* will be increasingly difficult if wildfires, insect outbreaks, and perhaps plant disease increase as expected, especially in the western part of the Northern Rockies. At the same time, managing forests for carbon sequestration is likely to become more important in response to national policies on carbon emissions. Hazardous fuel treatments can help build resilience to disturbances that rapidly oxidize carbon and emit it to the atmosphere.

Cultural resources

261 Disturbances such as wildfires, floods, and soil erosion place cultural and heritage values at risk.
262 Damage to cultural and historic sites are irreversible, making protection a key management focus.
263 Climate-induced changes in terrestrial and aquatic habitats affect abundance of culturally-valued plants
264 and animals (especially fish), affecting the ability of Native American tribes to exercise their treaty rights.
265 Effects on cultural resources are amplified by external social forces that include a growing regional
266 population, vandalism, and loss of traditional practices in a globalizing culture.

267

268 The NRAP facilitated the largest climate change adaptation effort on public lands to date, including
269 participants from federal agencies and stakeholder organizations interested in a broad range of resource
270 issues. It achieved specific goals of national climate change strategies for the U.S. Forest Service and
271 National Park Service, providing a scientific foundation for resource management and planning in the
272 Northern Rockies. The large number of adaptation strategies and tactics, many of which are a component
273 of current management practice, provide a pathway for slowing the rate of deleterious change in resource
274 conditions. Rapid implementation of adaptation—in land management plans, National Environmental
275 Policy Act documents, project plans, and restoration—will help maintain functionality of terrestrial and
276 aquatic ecosystems in the Northern Rockies, as well as build the organizational capacity of federal
277 agencies to incorporate climate change in their mission of sustainable resource management. Long-term
278 monitoring will help detect potential climate change effects on natural resources, and evaluate the
279 effectiveness of adaptation options that have been implemented.

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DRAFT

Chapter 1: Introduction

S. Karen Dante-Wood

The Northern Rockies Adaptation Partnership (NRAP) is a science-management partnership among the Forest Service, U.S. Department of Agriculture regional offices and national forests (mostly in the Northern Region, and small portions of the Intermountain and Rocky Mountain Regions); U.S. Forest Service Pacific Northwest and Rocky Mountain Research Stations; Glacier, Yellowstone and Grand Teton National Parks; Great Northern and Plains and Prairie Potholes Landscape Conservation Cooperatives; Department of Interior North Central Climate Science Center; Greater Yellowstone Coordinating Committee; Oregon State University; and EcoAdapt.

Initiated in 2013, the NRAP is a collaborative project with the goals of increasing climate change awareness, assessing vulnerability, and developing science-based adaptation strategies to reduce adverse effects of climate change and ease the transition to new climate states and conditions (see <http://adaptationpartners.org/nrap>). Developed in response to proactive climate change strategies of the Forest Service (USDA FS 2008, 2010a,c), and building on previous efforts in national forests (Halofsky et al. 2011; Littell et al. 2012; Raymond et al. 2013, 2014; Rice et al. 2012; Swanston and Janowiak 2012; Swanston et al. 2011), the partnership brings together resource managers and research scientists to plan for climate change in the Northern Rockies.

CLIMATE CHANGE RESPONSE IN THE FOREST SERVICE AND NATIONAL PARK SERVICE

Climate change is an agency-wide priority for the U.S. Forest Service (USFS), which has issued direction to administrative units for responding to climate change (USDA FS 2008) (table 1.1). In 2010, the USFS provided specific direction to the National Forest System in the form of the National Roadmap for Responding to Climate Change (USDA FS 2010a) and the Performance Scorecard for Implementing the Forest Service Climate Change Strategy (USDA FS 2010a). The goal of the USFS climate change

strategy is to “ensure our national forests and private working lands are conserved, restored, and made more resilient to climate change, while enhancing our water resources” (USDA FS 2010a). To achieve this goal, starting in 2011, each national forest and grassland began using a 10-point scorecard system to report accomplishments on ten elements in four dimensions: (1) increasing organizational capacity; (2) partnerships, engagement, and education; (3) adaptation; and (4) mitigation and sustainable consumption. Progress towards accomplishing elements of the scorecard must be reported annually by each national forest and national grassland; all units are expected to accomplish 7 of 10 criteria by 2015, with at least one “yes” in each dimension.

Similarly, the National Park Service (NPS) Climate Change Response Strategy provides direction for addressing the impacts of climate change on the National Park System lands (NPS 2010) (table 1.2). The strategy has four components to guide NPS actions: science, adaptation, mitigation and communication. The science component involves conducting and synthesizing research at various scales, monitoring trends and conditions, and delivering information to resource managers and partners. It also provides the scientific basis for adaptation, mitigation, and communication. Adaptation involves developing capacity within the agency to assess climate change scenarios and risks and implementing actions to better manage natural and cultural resources and infrastructure for a changing climate. Mitigation efforts focus on reducing the agency carbon footprint and enhancing carbon sequestration. Finally, the strategy requires the NPS to take advantage of agency capacity for education and interpretation to communicate the effects of climate change to NPS employees and to the public. Park rangers and other employees are encouraged to engage visitors about climate change, because national parks are visible examples of how climate change can affect natural and cultural resources. The similarity of USFS and NPS climate response strategies facilitated coordination between the two agencies.

The NRAP built on existing efforts in ecosystem-based management and ecological restoration to address climate change and put these efforts in a broader regional context in the Northern Rockies. Restoration is a priority in most national forests in this region, particularly related to hazardous fuel reduction in dry forests (stand density reduction plus surface fuel removal, often with prescribed burning),

and restoration of riparian areas to improve hydrologic and biological function. The NRAP works in conjunction with these management priorities to access the best available science on climate change effects and implement climate change adaptation plans.

In 2010, a climate change report was developed for the Kootenai and Idaho Panhandle National Forests planning effort (USDA FS 2010b). At the time, this was the most comprehensive climate change vulnerability assessment and adaption document compiled for the Northern Region. Although this report addressed many issues, it did not include non-forested vegetation, cultural resources, recreation resources, or ecosystem services. The Northern Region also partially funded the University of Washington Climate Impacts Group to provide datasets of historical (1916-2006) and future (2040s, 2080s) downscaled climate and hydrologic data for the Upper Missouri River and Columbia River basins (Littell et al. 2011).

Building on these downscaled data, the Northern Region developed climate change “primers” to help assess and evaluate regionally specific climate-related trends. Primers for wildland fire, watershed ecology, forest regeneration, and forest landscapes were in progress when the NRAP was initiated and have been incorporated into this publication. In addition to these primers, the Northern Region is currently developing a watershed-based climate change vulnerability assessment, downscaling regional water and stream temperature data for the Lolo National Forest, focused on bull trout (*Salvelinus confluentus*) and a preliminary discussion of the western pearlshell mussel (*Margaritifera falcata*), water supply, and forest infrastructure (USDA FS 2015).

The NRAP also incorporates existing USFS Northern Region efforts to consider and address climate change effects in management operations. In 2011, the Northern Region developed an Integrated Restoration & Protection Strategy that provided a framework for climate change adaptation (Bollenbacher et al. 2014, USDA FS 2011). In addition, periodic Northern Region restoration and resiliency reports provide baseline information on vegetative characteristics to better understand the effects of adaptive management (USDA FS 2014).

Most previous efforts to consider climate change effects and adaption strategies in the Northern Rockies have focused on vegetation and aquatic resources. The NRAP broadens these efforts to develop a

synthesis for a more comprehensive list of resource values, and to develop adaptation strategies for resources that have not been emphasized in management operations.

SCIENCE-MANAGEMENT PARTNERSHIPS

Previous efforts in the Pacific Northwest and beyond have demonstrated the success of science-management partnerships for increasing climate change awareness among resource managers and adaptation planning on federal lands. Olympic National Forest and Tahoe National Forest initiated the first science-management partnerships for developing adaptation options for individual national forests (Littell et al. 2012). The Olympic climate change study assessed resource vulnerabilities and developed adaptation options for Olympic National Forest and Olympic National Park on the Olympic Peninsula in Washington (Halofsky et al. 2011). Similar to efforts in the Olympics, the North Cascadia Adaptation Partnership assessed vulnerabilities and formulated adaptation options for two national forests and two national parks in Washington (Raymond et al. 2014).

In collaboration with three management units in California—Tahoe National Forest, Inyo National Forest, and Devils Postpile National Monument—the USFS Pacific Southwest Research Station held climate change education workshops and developed the Climate Project Screening Tool in order to incorporate adaptation into project planning (Morelli et al. 2012). In response to requests from the Shoshone National Forest in northern Wyoming, the Forest Service Rocky Mountain Research Station synthesized information on past climate, future climate projections, and potential effects of climate change on the multiple ecosystems within the forest (Rice et al. 2012).

In the largest effort to date in the eastern United States, the USFS Northern Research Station, in collaboration with the Chequamegon-Nicolet National Forest in northern Wisconsin and numerous other partners, conducted a vulnerability assessment for natural resources (Swanston et al. 2011) and developed adaptation options (Swanston and Janowiak 2012). Another joint national forest and Forest Service research vulnerability assessment effort focused on the vulnerability of watersheds to climate change (Furniss et al. 2013). Watershed vulnerability assessments, conducted on 11 national forests throughout the United States, were locally focused (at a national forest scale) and included water resource values,

hydrologic reaction to climate change, watershed condition and landscape sensitivity. The assessments were intended to help national forest managers identify where limited resources could be best invested to increase watershed resilience to climate change.

The processes, products, and techniques used for several studies and other climate change efforts on national forests have been compiled in a guidebook for developing adaptation options for national forests (Peterson et al. 2011). The guidebook outlines four key steps to facilitate adaption in national forests: (1) become aware of basic climate change science and integrate that understanding with knowledge of local conditions and issues (review), (2) evaluate sensitivity of natural resources to climate change (rank), (3) develop and implement options for adapting resources to climate change (resolve), and (4) monitor the effectiveness of on-the-ground management (observe) and adjust as needed. The NRAP is focused on implementation of the principles and practices in the guidebook.

THE NORTHERN ROCKIES ADAPTATION PARTNERSHIP PROCESS

The NRAP includes 15 national forests, 7.8 million acres of wilderness, and 3 national parks across the U.S. Forest Service Northern Region and the adjacent Greater Yellowstone Area. The NRAP region covers 183 million acres (fig.1.1), spanning northern Idaho, Montana, northwest Wyoming, North Dakota, and northern South Dakota. In order to facilitate analyses and interpretations, the NRAP assessment is divided into the following 5 subregions:

- **Western Rockies:** Idaho Panhandle National Forest, Kootenai National Forest, Nez Perce-Clearwater National Forest, Glacier National Park
- **Eastern Rockies:** Beaverhead-Deerlodge National Forest (eastern portion), Custer National Forest (eastern portion), Gallatin National Forest (northern portion), Helena National Forest, Lewis and Clark National Forest
- **Central Montana:** Bitterroot National Forest, Flathead National Forest, Lolo National Forest
- **Grassland:** Custer National Forest (part), Dakota Prairie National Grassland
- **Greater Yellowstone Area:** Bridger-Teton National Forest, Caribou-Targhee National Forest, Shoshone National Forest, Gallatin National Forest (southern portion), Custer National Forest

(western portion), Beaverhead-Deerlodge National Forest (western portion), Grand Teton National Park, Yellowstone National Park

The NRAP process includes: (1) a vulnerability assessment of the effects of climate change on hydrology and roads, fisheries, wildlife, forested and non-forested vegetation and disturbance, recreation, and cultural, ecosystem services, (2) development of adaptation options that will help reduce negative effects of climate change and assist the transition of biological systems and management to a warmer and a changing climate, and (3) development of an enduring science-management partnership to facilitate ongoing dialogue and activities related to climate change in the Northern Rockies region. These resource sectors were selected based on their importance in the region and current management concerns and challenges.

Vulnerability assessments typically involve exposure, sensitivity, and adaptive capacity (Parry et al. 2007), where exposure is the degree to which the system is exposed to changes in climate, sensitivity is an inherent quality of the system that indicates the degree to which it could be affected by climate change, and adaptive capacity is the ability of a system to respond and adjust to the exogenous influence of climate. Vulnerability assessments can be both qualitative and quantitative and focus on whole systems or individual species or resources (Glick et al. 2011). Several tools and databases are available for systematically assessing sensitivity (e.g., Lawler and Case 2010, Luce et al. 2014) and vulnerability of species (e.g., Potter and Crane 2010).

For the NRAP, we used scientific literature and expert knowledge to assess exposure, sensitivity and adaptive capacity to identify key vulnerabilities for the identified resource areas. The assessment process took place over 16 months, and involved monthly phone meetings for each of the resource-specific assessment teams (see appendix 1A for assessment team members). Each assessment team refined key questions that the assessment needed to address, selected values to assess, and determined which climate change impact models best informed the assessment. In some cases, assessment teams conducted spatial analyses and/or ran and interpreted models, selected criteria in which to evaluate model outputs, and developed maps of model output and resource sensitivities. To the greatest extent possible, teams focused

on effects and projections specific to the NRAP region and used the finest scale projections that are scientifically valid (Littell et al. 2011).

By working collaboratively with scientists and resource managers and focusing on a specific region, the goal of NRAP was to provide the scientific foundation for operationalizing climate change in planning, ecological restoration, and project management (Peterson et al. 2011; Raymond et al. 2013, 2014; Swanston and Janowiak 2012). After identifying key vulnerabilities for each resource sector, five workshops were convened in October and November 2014 in Bismarck (North Dakota), Bozeman (Montana), Coeur d'Alene (Idaho), Helena (Montana), and Missoula (Montana) to present and discuss the vulnerability assessment, and to elicit adaptation options from resource managers (see appendix 1A for workshop participants).

During these workshops, scientists and resource specialists presented information on climate change effects and current management practices for each of the resources. Facilitated dialogue was used to identify key sensitivities and adaption options. Participants identified strategies (general approaches) and tactics (on-the-ground actions) for adapting resources and management practices to climate change, as well as opportunities and barriers for implementing these adaptation actions into projects, management plans, partnerships and policies. Participants generally focused on adaptation options that can be implemented given our current scientific understanding of climate change effects, but they also identified research and monitoring that would benefit future efforts to assess vulnerability and guide management practices. Information from the region-wide assessment was also downscaled to identify the most significant vulnerabilities to climate change for priority resources in each subregion. Facilitators captured information generated during the workshops with a set of spreadsheets adapted from Swanston and Janowiak (2012). Initial results from the workshops were augmented with continued dialogue with federal agency resource specialists.

This publication contains a chapter on expected climatological changes in the Northern Rockies, and one chapter for each of the resource sectors covered in the vulnerability assessment (water resources, fisheries, forested and rangeland vegetation, disturbance, wildlife, recreation, ecosystem services, and

cultural heritage) (see appendix 1B for author affiliations). Each of the resource chapters includes a review of climate change effects, sensitivities, current management practices, and results of the adaptation strategies and tactics discussions.

Resource managers and other decision makers can use this publication in several ways. First, the vulnerability assessment will provide information on climate change effects needed for national forest and national park plans, project plans, conservation strategies, restoration, and environmental effects analysis. The assessment will be particularly useful for national forest and national park planning and management. Second, climate change sensitivities and adaptation options developed at the regional scale will provide the scientific foundation for subregional and national forest and national park vulnerability assessments, adaptation planning, and resource monitoring. We expect that over time, and as needs and funding align, appropriate adaptation options will be incorporated into plans and programs of federal management units. Third, we anticipate that resource specialists will apply this assessment in land management throughout the region, thus operationalizing climate-smart resource management and planning.

Adaptation planning is an ongoing and iterative process. Implementation may occur at critical times in the planning process, such as when managers revise USFS land management plans and other planning documents, or after the occurrence of extreme events and ecological disturbances (e.g., wildfire). We focus on adaptation options for the USFS and NPS, but this publication provides information that can be used by other land management agencies as well. Furthermore, the NRAP process can be emulated by national forests, national parks, and other organizations outside the Northern Rockies, thus propagating climate-smart management across larger landscapes (e.g., the Intermountain Adaptation Partnership in Utah, Nevada, and southern Idaho; <http://adaptationpartners.org/iap>).

ALL-LANDS APPROACH TO CLIMATE CHANGE ADAPTATION

The USFS and NPS climate change strategies identify the need to build partnerships and work across jurisdictional boundaries when planning for adaptation. This concept of responding to the challenge of climate change with an “all-lands” approach is frequently mentioned, but a process for doing so is rarely defined. Unique in its effort to implement an all-lands approach to adaptation for a specific region, NRAP

is an inclusive partnership of multiple agencies and organizations with an interest in managing natural resources in a changing climate. In addition to representatives from the national forests, grasslands, and parks, several other agencies and organizations participated in the resource sector workshops (see appendix 1A). This type of partnership enables a coordinated and complementary approach to adaptation that crosses jurisdictional boundaries. NRAP also provides a venue for agencies to learn from the practices of others so that the most effective adaptation strategies can be identified.

Risks and vulnerabilities resulting from climate change and gaps in scientific knowledge and policy need to be assessed. Adaptation is a prominent focus of the NRAP, with emphasis on creating resilience in human and natural systems. Communicating climate change information and engaging employees, partners, and the general public in productive discussions is also an integral part of successfully responding to climate change. The need for partnerships and collaborations on climate change issues was also identified in the NRAP. Sharing climate change information, vulnerability assessments, and adaptation strategies across administrative boundaries will contribute to the success of climate change responses in the Northern Rockies.

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Chapter 2: Biogeographic, Cultural, And Historical Setting Of The Northern Rocky Mountains

S. Karen Dante-Wood

The Northern Rocky Mountains Adaptation Partnership (NRAP) includes diverse landscapes, ranging from high mountains to grasslands, from alpine glaciers to broad rivers (fig. 1.1). This region, once inhabited solely by Native Americans, has been altered by two centuries of settlement by Euro-Americans, including extractive activities such as timber harvest, grazing, mining, and water diversions. Although urbanization is relatively small in this region, paved and unpaved roads and electrical transmission wires permeate much of the landscape. A significant portion of the Northern Rockies is owned and managed by federal agencies, including 15 national forests and 3 national parks.

Resource conditions, resource management issues, effects of climatic variability and change, and climate change adaptation options differ greatly from Idaho to North Dakota and from the Canadian border to Wyoming. In order to capture these differences, the NRAP climate change vulnerability assessment and adaptation strategy were conducted for five subregions: Western Rockies, Central Rockies, Eastern Rockies, Greater Yellowstone Area, and Grassland. These subregions are briefly described below.

WESTERN ROCKIES SUBREGION

The Western Rockies subregion occupies approximately 17 million acres across portions of Idaho and Montana, including the Idaho Panhandle, Kootenai, and Nez Perce-Clearwater National Forests and several Native American reservations (e.g., Nez Perce Indian Reservation, Coeur d'Alene Indian Reservation). Most of this subregion is extremely mountainous and heavily forested, the mountains broken by river and stream valleys and two large grassland ecosystems, Big Camas Prairie and Palouse country. The subregion also includes 1.7 million acres of wilderness lands.

The Rocky Mountains encompass a large area of Idaho and extend from the Idaho panhandle along the Wyoming border. To the west of the Rockies lie the prairie lands of Washington and Oregon, while the east is home to mountainous western Montana. A distinguishing feature of this region is the rugged mountains that extend lengthwise along the panhandle. The Bitterroot Mountains border the Idaho Panhandle along the Montana/Idaho border; the Coeur d’Alene Mountains lie in the northern portion of the panhandle from Lake Pend Oreille in the north to Lake Coeur d’Alene in the south; and south of the Coeur d’Alene Mountains are the Clearwater and Salmon River Mountains.

Continental glaciers shaped the topography of this panhandle region by excavating lake basins and depositing glacial till and outwash. The bedrock found here is composed of sedimentary rocks of the Belt Supergroup, deposited 1470-1400 million years B.P. Deposition took place in a large basin where space was not a limiting factor and the sediment was able to build up vertically (ISU 2014a). Due to this deposition, the Coeur d’Alene area contains large silver, lead, and zinc deposits.

The Western Rockies subregion contains numerous large rivers. Commonly referred to as the “River of No Return,” the Salmon River winds 425 miles through central Idaho and divides the northern and southern part of the state. The canyon gorge is deeper than the Grand Canyon of Colorado. It is one of the longest rivers in the state and renowned for its spawning beds for Pacific salmon species. The Clearwater River, also in Idaho, was fed by the Bitterroot Mountains and was preferred by explorers, trappers, miners, and loggers because it was easier to navigate than the turbulent Salmon River (ISU 2014b). Other rivers include the Kootenai and Pend Oreille, which flow into the Columbia River. The Clark Fork of the Columbia River feeds into Lake Pend Oreille and the Saint Maries, Saint Joe, and Coeur d’Alene Rivers flow into Lake Coeur d’Alene. Priest Lake and Hayden Lake near Pend Oreille are heavily used for recreation because of their scenic setting among forested mountains (ISU 2014b).

Since Idaho is only 300 miles east from the Pacific Ocean, its climate is affected by a maritime atmospheric pattern, bringing more precipitation to northern Idaho than southern Idaho. Summers are typically hot and dry, and winters are relatively cold due to the high amount of moisture carried through the Columbia River Gorge.

The most actively managed forests in the Western Rockies are found in northern Idaho, which is characterized as a steppe-coniferous forest alpine meadow province (Schnepf and Davis 2013). A 2012 Forest Service, U.S. Department of Agriculture report used Forest Inventory and Analysis data to describe various forest cover types in the subregion. The six most common forest groups include Douglas-fir (*Pseudotsuga menziesii*), subalpine fir (*Abies lasiocarpa*)/Engelmann spruce (*Picea engelmannii*)/mountain hemlock (*Tsuga mertensiana*), lodgepole pine (*Pinus contorta* var. *latifolia*), ponderosa pine (*Pinus ponderosa*), western hemlock (*Tsuga heterophylla*)/Sitka spruce (*Picea sitchensis*), and quaking aspen (*Populus tremuloides*)/paper birch (*Betula papyrifera*) (Sullivan et al. 1986). Commercially harvested coniferous species in this area include Douglas-fir, Engelmann spruce, grand fir (*Abies grandis*), lodgepole pine, ponderosa pine, subalpine fir, western hemlock, western larch (*Larix occidentalis*), western redcedar (*Thuja plicata*), and western white pine (*Pinus monticola*). Other species not used for wood products include whitebark pine (*Pinus albicaulis*), limber pine (*Pinus flexilis*), alpine larch (*Larix lyallii*), mountain hemlock, and western juniper (*Juniperus occidentalis*). Quaking aspen, black cottonwood (*Populus nigra*) and paper birch are also commonly found.

The western white pine is an important tree species to this region. It grows on a variety of soil types and slopes and can regenerate across a broad range of environments. Western white pine forests usually originate from wildfires and when the species matures, it can survive fire better than nearly all of its shade-tolerant competitors. While the species can survive to 300 to 400 years old, it unfortunately is declining due to white pine blister rust.

Common shrub species in the subregion include serviceberry (*Amelanchier alnifolia*), Redosier dogwood (*Cornus sericea*), oceanspray (*Holodiscus discolor*), Lewis mockorange (*Philadelphus lewisii*), huckleberries (*Vaccinium membranaceum*) and smooth sumac (*Rhus glabra*). Evergreen shrubs include Oregon-grape (*Berberis aquifolium*), snowbrush ceanothus (*Ceanothus velutinus*), and mountain lover (*Paxistima myrsinites*), and evergreen groundcovers include kinnikinnick (*Arctostaphylos uva-ursi*), and twinflower (*Linnaea borealis*) (Sullivan et al. 1986).

The ecologically diverse habitats in the Western Rockies subregion also support a large number of rare plant species. The warm, dry grassland areas in the western part of the subregion harbor populations of Spalding's catchfly (*Silene spaldingii*), a federally threatened species, and Palouse goldenweed (*Pyrrocoma liatrifomis*). In contrast, the much wetter forests in the Clearwater River drainage contain several narrowly endemic plants such as Constance's bittercress (*Cardamine constancei*), as well as a number of disjunct species that are geographically isolated from their main ranges in the Cascade Mountains, such as Pacific dogwood (*Cornus nuttallii*). In the northern part of the subregion, fens (groundwater-dependent wetlands where peat has accumulated) are uncommon habitats that support peripheral populations of more northern plant species such as spoon-leaved sundew (*Drosera intermedia*) and small cranberry (*Vaccinium oxycoccos*).

The Western Rockies provide habitat for over 300 animal species. Large mammal species include woodland caribou (*Rangifer tarandus caribou*), black bear (*Ursus americanus*), grizzly bear (*U. arctos*), whitetail deer (*Odocoileus virginianus*), mule deer (*O. hemionus hemionus*), elk (*Cervus elaphus*), moose (*Alces alces*), coyote (*Canis latrans*), gray wolf (*Canis lupus*), bobcat (*Lynx rufus*), cougar (*Puma concolor*), and wolverine (*Gulo gulo*). Smaller vertebrates include Coeur d'Alene salamander (*Plethodon idahoensis*) and pygmy shrew (*Sorex hoyi*).

A broad range of avian taxa include bald eagle (*Haliaeetus leucocephalus*), golden eagle (*Aquila chrysaetos*), osprey (*Pandion haliaetus*), many species of owls, wild turkey (*Meleagris gallopavo*), California quail (*Callipepla californica*), greater sage grouse (*Centrocercus urophasianus*), blue jay (*Cyanocitta cristata*), and calliope hummingbird (*Stellula calliope*).

Both native and nonnative fish are found in many of Western Rockies rivers and lakes, making it a popular area for angling and spawning. Fish species include native cutthroat trout (*Oncorhynchus clarkii*), rainbow trout (*O. mykiss*), and bull trout (*Salvelinus confluentus*), which is federally listed, and nonnative brook trout (*Salvelinus fontinalis*). The Kootenai River is home to the endangered white sturgeon (*Acipenser transmontanus*) and threatened burbot (*Lota lota*).

Wildfire is a dominant influence on the structure, function, and productivity of forest ecosystems in the Western Rockies. Fire frequency varies greatly depending on biogeographic conditions, with stand replacement fires occurring at 50-500 year intervals, and surface fires occurring in dry forests at 2-50 year intervals. Frequent fires keep many forests in the early stages of succession as indicated by high numbers of western larch and pine (Schnepf and Davis 2013), although fire exclusion during the past 80 years or so has reduced fire frequency in lower-elevation dry forests, resulting in dense stands and elevated accumulation of surface fuels.

Mountain pine beetles (*Dendroctonus ponderosae*) kill large numbers of lodgepole pine, often in outbreaks of thousands of acres, and they increasingly kill whitebark pine and limber pine (*Pinus flexilis*) at high elevation as the climate continues to warm. Western spruce budworm (*Choristoneura occidentalis*) causes sporadic outbreaks in Douglas-fir and true firs (*Abies*), and Douglas-fir tussock moth (*Orygia pseudotsugata*) is a prominent defoliator of Douglas-fir.

White pine blister rust (*Cronartium ribicola*), a nonnative fungus, causes mortality in five-needle pines (western white pine, whitebark pine, limber pine), and has greatly reduced the dominance of western white pine (Schwandt et al. 2013). Forests dominated by Douglas-fir and grand fir have increased as a result, accelerating forest succession toward shade tolerant, late-successional true firs, western hemlock and western redcedar (Bollenbacher et al. 2014). Attempts to control the spread of blister rust through removal of currant (*Ribes*), its alternate host, were mostly unsuccessful (Russell and Jain 2007).

Various root diseases kill and reduce the vigor of Douglas-fir and grand fir (*Abies grandis*), especially north of the Salmon River. Parasitic dwarf mistletoes (*Arceuthobium* spp.) reduce the vigor of and sometimes kill several species of conifers, including western larch, Douglas-fir, ponderosa pine, and lodgepole pine (Idaho Forest Products Commission 2011).

Several silvicultural treatments are used to reduce the effects of these disturbances and stressors, including thinning, mechanically mixing the soil, and prescribed burning to favor the regeneration of different species and reduce surface fuels (Graham and Jain 2005). Treatments can be targeted to modify different portions of forest stands, from the soil to the upper canopy. Harvesting larger trees can result in

the redistribution of fewer stems, create canopy openings, and encourage regeneration. Thinning to remove the mid-story of forests can result in a various species combinations. Ground-level vegetation treatments can increase the density of small trees and, creating a continuous distribution of low-stature fuels.

The economic structure of the Western Rockies integrates northern Idaho, northeastern Washington, and western Montana as “the inland empire.” In the early 1950s, the timber industry was the second largest after agriculture. Large-scale lumbering operations did not occur until after Weyerhaeuser Corporation opened up plants near Sandpoint and Moscow in northern Idaho. Before 1900, timber was used locally for lumber and fuel wood for homes, railroads, and fence posts. After outside markets developed, operating sawmills produced various products such as 2x4 studs, plywood, waferboard, particleboard, house logs, posts, poles, pulp and paper, wood beams, mobile homes, roof supports and much more. Although forest industry maintains a significant presence in the Western Rockies, it has declined in the past 20 years because of changing economic conditions, competition with other markets, and greatly reduced harvest on federal lands.

Agriculture is a dominant industry on private lands, and continuous cultivation and livestock grazing has occurred on fertile prairie lands since the 1860s. Mining, which began in the 1880s, is another important industry in some areas, especially the Coeur d’Alene region, which leads the nation in silver production and produces other nonferrous metals such as lead and zinc. Water that originates in high mountains of the Western Rockies is an extremely important resource because of its value for agriculture, hydroelectric power, industry, and municipal consumption. Forests are increasingly recognized and managed for their capacity to produce large amounts of clean water and to reduce erosion that would degrade water quality.

As extractive industries have declined in the past 30 years and affluence of human populations has increased, recreation and aesthetically based activities have increased in popularity and economic importance. Rugged topography, forests, lakes, and streams are a major attraction for primary residences, seasonal residences, and recreational travel (fig. 2.1). Hunting, fishing, hiking, mountain biking, off-road

vehicle use, and snow skiing are popular activities for local residents and visitors from throughout North America. Federal management increasingly focuses on providing opportunities for a broad range of recreational activities.

The Western Rockies has large populations of the Nez Perce, Kalispel, Kootenai, and Coeur d'Alene tribes who have lived for thousands of years in the terrestrial and aquatic ecosystems, and more recently urban areas, of this subregion. Most tribes in this area had many villages and camps. They lived in teepees during the warmer months, and in large camps, mainly underground houses, during the winter. Hunting, fishing (especially for salmon), and gathering of wild foods occurred year round, and men and women typically had separate duties. Men hunted and fished, and women gathered vegetables and fruits such as chokecherry (*Prunus virginiana*), huckleberry (*Vaccinium* spp.), wild strawberry (*Fragaria virginiana*), and common camas (*Camassia quamash*). Native people in this subregion excelled at basketry, which was used for collecting nuts, storing fruits and roots, and cooking food. Federal agencies increasingly collaborate with tribal partners to ensure that tribal values (including cultural) and access to resources are considered in land management planning.

CENTRAL ROCKIES SUBREGION

The Central Rockies subregion occupies approximately 12 million acres across portions of western Montana and Idaho and includes the Bitterroot, Flathead, and Lolo National Forests; Glacier National Park, and Flathead Indian Reservation (fig. 1.1). The subregion contains steep mountains, rolling meadows, large rivers and lakes (fig. 2.2), and alpine ecosystems that span the Sapphire Mountains, Bitterroot Mountains, Mission Mountains, and many other ranges. It also contains the largest contiguous area of designated wilderness in the United States outside of Alaska. The northern portion of the Central Rockies is referred to as the Crown of the Continent, which includes Glacier National Park and the Flathead National Forest.

The Bitterroot and Missoula Valleys located in west-central Montana experience an inland mountain climate. Air masses that develop over the Pacific Ocean release moisture in the Cascade Range and over the mountains of northern Idaho. West-central Montana occupies the rain-shadow area receiving dried-out

Pacific air and little moisture in the valley bottoms, approximately 13 inches annually (Lackschewitz 1991). Humidity is high in this region, except during the summer months, and winters are cold and moist. The climate in the Flathead and Glacier region is very similar, influenced by the Pacific Maritime atmospheric pattern with warm, dry summers and wet, cold winters.

Alluvial sediments filled the Bitterroot River valley during the Tertiary period, and glacial Lake Missoula drained and refilled several times as a section of a continental glacier repeatedly washed out and redeveloped. Glacial lake sediments of various depths and qualities cover the slopes, bottomlands and terraces in west-central Montana today (Lackschewitz 1991). During the Pleistocene era, low-elevation valleys were scoured by continental glaciers, while the mountains were shaped by alpine glaciers in the Flathead and Glacier region (Newlon and Burns 2009).

In the Central Rockies, microclimate has a big effect on the distribution, abundance, and productivity of vegetation. For example, steep south-facing slopes with low retention of snow and soil moisture in summer are generally less productive and have different species composition than north-facing slopes. The bottoms of mountain canyons support lush vegetation due to the high level of moisture, whereas ridge tops support vegetation that requires little moisture for growth and survival.

Due to the Pacific-influenced climate, forests found in the west-central region (Bitterroot and Missoula valleys) are drier than those in Idaho and northwestern Montana. Only a few species typical of the Pacific Coast are found here, such as western redcedar, western white pine, Pacific yew (*Taxus brevifolia*), bride's bonnet (*Clintonia uniflora*), American trail plant (*Adenocaulon bicolor*), and threeleaf foamflower (*Tiarella trifoliata*). Intermountain forest species dominate the west-central Montana landscape, including western larch, subalpine larch (*Larix lyallii*), ponderosa pine, mock azalea (*Menziesia ferruginea*), Hitchcock's smooth woodrush (*Luzula hitchcockii*), common beargrass (*Xerophyllum tenax*). Bottomland ponderosa pine and hardwood species are commonly found in moist sites, whereas different types of bunchgrass species (*Agropyron*, *Festuca*) and a mixture of ponderosa pine and bunchgrasses are found in dry sites. Douglas-fir, grand fir, and subalpine fir dominate at higher elevation (Lackschewitz 1991). Extensive stands of lodgepole pine are present at mid to upper elevations.

Much of the native vegetation in the lower Bitterroot and Missoula valleys have either been lost to pasture or urban development.

In the Flathead Valley and Glacier National Park, lower elevations are dominated by Douglas-fir, ponderosa pine, grand fir, Engelmann spruce, and western redcedar. Douglas-fir, western larch and subalpine fir are common at mid elevation, and whitebark pine is found at high elevation (Newlon and Burns 2009). Black cottonwood (*Populus trichocarpa*) and quaking aspen are common deciduous trees found at lower elevations near Glacier National Park, often along lakes.

Wildfire is a major disturbance in the Central Rockies. Fires were fairly regular at lower and middle elevations in the Bitterroot and Missoula valleys prior to 1900. Seral western larch and lodgepole pine previously dominated north-facing slopes, but fire exclusion has led to increased dominance of shade tolerant species. As a result, silvicultural and prescribed burning treatments are being used to increase the distribution and abundance of seral tree and shrub species (Lackschewitz 1991).

The Central Rockies contain over 60 species of mammals, with wilderness locations having relatively intact populations. Species include gray wolf (*Canis lupus*), Canada lynx (*Lynx canadensis*), cougar, elk, mountain goat (*Oreamnos americanus*), bighorn sheep (*Ovis canadensis*), northern bog lemming (*Synaptomys borealis*), grizzly bear, golden-mantled ground squirrel (*Callospermophilus lateralis*), and pygmy shrew. Canada lynx and grizzly bear are on the threatened species list, and gray wolf, bald eagle, and peregrine falcon (*Falco peregrinus*) have been removed from the federally threatened and endangered species list.

Hundreds of bird species are found in the Central Rockies, including killdeer (*Charadrius vociferus*) and spotted sandpiper (*Actitis macularius*) in riparian areas, song sparrows (*Melospiza melodia*) in grassland, willow flycatcher (*Empidonax traillii*) and MacGillivray's warbler (*Geothlypis tolmiei*) in shrubby habitat, and bald eagle and Bullock's oriole (*Icterus bullockii*) in mature forest canopy.

Diverse native cold-water fish and nonnative fish are abundant in Central Rockies rivers. For example, Flathead National Forest is well known for its populations of native bull trout and westslope cutthroat trout (*Oncorhynchus clarki lewisi*), which are found in Flathead Lake and the Flathead River.

The Bitterroot River is home to many native fish species including bull trout, westslope cutthroat trout, northern pike minnow (*Ptychocheilus oregonensis*), and largescale sucker (*Catostomus macrocheilus*). As a result of the diversity and abundance of fish species, angling is a popular recreational activity in this area.

Wildfires and insect outbreaks are disrupting ecosystems in the Central Rockies. Although wildfires play an important ecological role, with warmer spring and summer temperatures, there have been more occurrences of larger wildfires and longer wildfire seasons. These fires are becoming increasingly expensive to control as they make their way around the forested landscape but also as they enter the wildland-urban interface, the zone where housing borders forests and woodlands. Insect invasions in this subregion have also been known to damage and kill trees.

Mountain pine beetle is one of the most destructive bark beetles in North America and has caused serious damage and mortality to whitebark pine in this subregion. Lodgepole pine were affected by the beetle between 1911 and 1942 in the forests of Idaho and Montana. These outbreaks originally occurred at lower elevations and moved upwards into whitebark pine habitat. This occurred in the Flathead National Forest in the 1970s, where the mountain pine beetle invaded lodgepole pine forests first and then moved upward into whitebark pine (Bartos and Gibson 1990). White pine blister rust has caused extensive mortality in whitebark pine in the Central Rockies, especially in Glacier National Park and adjacent areas, where over 70 percent of the trees are infected and 30 percent have died.

Many of the aforementioned flora and fauna were documented by Meriwether Lewis and William Clark during their expedition in the early 1800s. The explorers travelled across the Bitterroot River and Lolo Creek valley twice and never passed through the Flathead valley. Other early explorers to the region included fur companies and independent trappers. Fur companies obtained fur during by trading goods for furs with Native Americans, employing hunters and trappers, and trading furs with hunters and trappers at trading posts (McKay 1994). Hudson's Bay Company, had a good rapport with the Flathead, Pend d'Oreille, and Kootenai tribes, trading products for bison provided by Native Americans.

In 1855, the Hellgate Treaty established the Flathead Indian Reservation for the Flathead, Pend d'Oreille, and Kootenai tribes. As the tribes began to live on the reservation, Euro-American settlement accelerated. Initially inhabited by quartz miners, fur trappers, and French Canadians, the upper Flathead valley was more heavily settled after the Northern Pacific Railroad connected with Missoula in 1883.

Timber harvest was a primary extractive activity in the Central Rockies in the late 1800s. With the passage of the 1891 Forest Reserve Act, the President had authority to create forest reserves to revise public land laws (McKay 1994), and various protections gradually spread across federal lands. Yellowstone was the first forest reserve established by President Harrison. In 1897, the Flathead, Bitterroot, Lewis and Clark, and Priest River became the first four reserves in the Northern Region established by President Cleveland. Much of the lower elevation land in the Central Rockies today has been converted to agriculture and urban and suburban development. The major industries are agriculture, ranching, forestry, and recreation/tourism.

EASTERN ROCKIES SUBREGION

The Eastern Rockies subregion occupies approximately 12 million acres in central, west-central, north-central, and southwest Montana (fig. 1.1). Included in this area are the Beaverhead-Deerlodge (eastern portion), Helena, and Lewis and Clark National Forests. These forests are mostly found on the eastern side of the Continental Divide. The subregion extends from high mountains (often exceeding 11,000 ft) in the west to broad plains in the east, including several large wilderness areas. It contains numerous mountain ranges—the Beaverhead, Bitterroot, Pioneer, Centennial, Bridger, Madison, Absaroka, Beartooth, Crazy, Gallatin, Elkhorn, and Big Belt Mountains—most of which have reasonably intact ecosystems at higher elevation.

Climate in the Eastern Rockies varies considerably, based on location relative to the Continental Divide. The western side receives more precipitation as air masses from the west cool and release moisture over the mountain ranges, whereas on the eastern side, the air becomes warmer and drier, often accompanied by downslope air movement known as Chinook winds that create a more moderate than that

of the Great Plains (Phillips 1999). In general, the eastern portion of the subregion experiences a drier continental climate.

The Rocky Mountains were developed from intense plate tectonic movement during the Jurassic, Cenozoic, and Laramide orogeny periods. The Laramide orogeny, which took place approximately 70-40 million years B.P., is responsible for elevating the Rocky Mountains. California, Oregon, and Washington were added to North America during the Mesozoic Era, whereas the Rockies were added to the continent much later (70 million years B.P.). Although mountain building usually occurs 200-400 miles inland from the boundary of a tectonic plate (the subduction zone), the Rocky Mountains are several hundred miles inland. In the Rockies, the oceanic plate sank beneath the continental plate at a flat angle that led to mountain building farther inland than might be expected (USGS 2014).

Numerous rivers flow through the Eastern Rockies, including the Missouri, Blackfoot, and Smith Rivers. The longest river in North America, the Missouri begins at the confluence of the Jefferson and Madison Rivers near Three Forks, Montana and includes three reservoirs (Canyon Ferry, Hauser, and Upper Holter). The Smith River is a tributary of the Missouri River and flows between the Little Belt and Big Belt Mountains. The Blackfoot River, a snow and spring fed river, begins at the Continental Divide in Lewis and Clark County, and is the river featured in the book *A River Runs Through It* by Norman Maclean. These rivers are known for their blue-ribbon trout fishery status, scenic floats, and other water-based recreational activities.

Vegetation in the Eastern Rockies varies primarily as a function of elevation and aspect. Lower elevations are dominated by grassland and sagebrush steppe that include needle-and-thread grass (*Hesperostipa comata*), Idaho fescue (*Festuca idahoensis*), sagebrush (*Artemisia* spp.), rabbitbrush (*Chrysothamnus* spp.), milkvetch (*Astragalus* spp.) and wildflowers such as lupine (*Lupinus*) and balsamorhiza (*Balsamorhiza* spp.). Fremont's cottonwood (*Populus fremontii*), yellow willow (*Salix lutea*), coyote willow (*S. exigua*), woods rose (*Rosa woodsii*), and golden currant (*Ribes aureum*) are commonly found along rivers and streams. Dominant species in foothills and woodlands include limber pine (*Pinus flexilis*), Rocky Mountain juniper (*Juniperus scopulorum*), Douglas-fir, and ponderosa pine trees.

Understory species include antelope bitterbrush (*Purshia tridentata*), mountain-mahogany (*Cercocarpus*), and skunkbrush sumac (*Rhus aromatica* var. *simplicifolia*). Douglas-fir and ponderosa pine dominate upper montane slopes, and lodgepole pine and Engelmann spruce common at high elevation (Phillips 1999).

Common wildlife species in the eastern Rockies include mountain goat, bighorn sheep, elk, cougar, Canada lynx, wolverine and black bear. Hunters from around the world have and continue to purchase tags to hunt in this subregion for many of the aforementioned big game species. Also common are bald eagle, greater sage grouse, peregrine falcon, and red-tailed hawk (*Buteo jamaicensis*). Fly fishing opportunities are plentiful due to abundant populations of westslope cutthroat trout, rainbow trout, brook trout, and northern pike (*Esox lucius*). There are a few populations of grizzly bear and gray wolf in the region, but these species are concentrated in the western section of the eastern Rockies, particularly in wilderness areas.

Forests in the Eastern Rockies have been subject to widespread drought, wildfire, and insect outbreaks over the past 20 years (Montana DEQ 2013). Several large wildfires have burned with uncharacteristic intensity because the absence of fire for several decades has resulted in elevated accumulation of fuels. Mountain pine beetle has caused extensive mortality of lodgepole pine and some ponderosa pine, the concurrence of older, non-vigorous stands being susceptible to elevated beetle populations caused by warmer temperature. Western spruce budworm has caused mortality and stunted growth in Engelmann spruce and Douglas-fir in some areas.

The travels of Meriwether Lewis and William Clark through the Eastern Rockies have created a prominent historical legacy (fig. 2.3). Their expedition began in 1804 near St. Louis, and in the spring of 1805, they traveled to Three Forks, Montana via the Jefferson River. On this route, the explorers interacted with Shoshone Indians, and after passing over the Bitterroot Mountains, they made their way down to Fort Clatsop on the Oregon side of the Columbia River (Perry 2010). The Lewis and Clark National Forest and other place names commemorate the expedition.

Thousands of years before Euro-Americans arrived, the Blackfoot, Sioux, Cheyenne, Flathead and Crow Indians used the area as hunting grounds and a place to winter. Prior to 1806, the Blackfoot had exchanged wolf and beaver pelts with Canadian and English settlers for guns and ammunition. The livelihoods and cultures of these tribes were highly dependent on hunting the American bison (*Bison bison*), which provided food, shelter, and clothing. After horses were introduced to the region in the mid 1700s, hunters had much greater mobility to pursue bison, and horses themselves became part of livelihood, commerce, and culture. The decimation of bison herds by Euro-Americans in the mid 1800s contributed to a rapid decline in Native American populations.

In the mid 1800s, mining for gold and other precious minerals was a common activity along the Continental Divide, particularly near the town of Helena, which was founded in 1864 and had the second largest placer gold deposit in Montana. Within four years, Last Chance Gulch (the original name for Helena) produced \$19 million of gold. Since the city was adjacent to major transportation routes, the mining town was able to persist through the gold rush (History 2009).

Agriculture is the largest industry in Montana, and Beaverhead County is the leading cattle and calves producer in the state, followed by Gallatin County, Jefferson County and Madison County (Ranch and Recreational Group 2011). In the past several years, ranchland has been increasingly at risk to subdivision development. The wave of development in this region has transformed the forests and grasslands landscape into one of towns, farms, and increasingly fragmented forested areas. Several organizations such as The Nature Conservancy are working with private landowners to add conservation easements on their lands to limit subdivisions from fragmenting wildlife landscapes and affecting ranching operations. The Forest Service often coordinates with the Bureau of Land Management and Montana Department of Fish, Wildlife and Parks on natural resource issues related to landscape connectivity and restoration.

GREATER YELLOWSTONE AREA SUBREGION

The Greater Yellowstone Area (GYA) subregion occupies approximately 23 million acres, extending across portions of Wyoming, Montana and Idaho. It includes both the country's first national park (Yellowstone) and first national forest (Shoshone), in addition to Grand Teton National Park and portions

of Bridger-Teton, Caribou-Targhee, Gallatin, Custer and Beaverhead-Deerlodge National Forests. One of the defining features of the subregion is a group of 24 conterminous mountain ranges that wrap around the Yellowstone Plateau (Morgan 2007).

The Yellowstone “hotspot” and associated geological activity have shaped the geography, topography, climate, soils, and biota of the GYA. The hotspot is a thermal disturbance fixed in the Earth’s mantle below the North American continental plate, moving to the northeast at the rate of one inch per year (Morgan 2007). This volcanic hotspot is responsible for eruptions that have left calderas in Oregon, Nevada, and Idaho and for creating the eastern Snake River plain. Volcanism formed the Yellowstone rhyolite plateau, and faulting formed sediment-filled basins and steep mountains such as the Teton Range/Jackson Hole and Madison Range/Madison Valley. Uplift contributed to the high altitude of the GYA and associated deep valleys (Morgan 2007). The heat of eruptions that created calderas originated in the Earth’s mantle, providing the source of heat for hot springs and geysers, one of the primary reasons that Yellowstone National Park was established; more geysers are found here than anywhere else in the world (USDI NPS 2015).

The GYA is the source of three major river systems—the Missouri/Mississippi, Snake/Columbia, and Green/Colorado. The Missouri River begins in the northwest corner of the GYA and merges into the Mississippi River, the Snake River begins in the southeast corner of the GYA and merges into the Columbia River, and the Green River is the main tributary of the Colorado River. Anglers are drawn to these river systems for their blue-ribbon fishing streams.

The GYA is one of the largest relatively intact and functional natural ecosystems in the temperate zone (Keiter and Boyce 1991). Abiotic factors such as topography and soils strongly influence vegetation composition and structure of the area. Differences in elevation strongly influence local climate, with valley bottoms experiencing substantially higher annual temperatures than higher elevations. Soils are deeper in valley bottoms than on the Yellowstone Plateau, which is more affected by nutrient-poor soils derived from the Yellowstone Caldera (Hansen et al. 1999). Valley bottoms are generally occupied by lodgepole pine (USDI NPS 2013), lower slopes and richer soils (on basaltic or andesitic volcanic rocks,

sedimentary rocks, and Precambrian crystalline rocks) support Engelmann spruce, subalpine fir, and Douglas-fir (Morgan 2007), and the highest elevations are dominated by whitebark pine (USDI NPS 2012). Quaking aspen, willows, and cottonwoods are also found on richer soils, such as valley toe slopes and bottoms.

In lodgepole pine forests, elk sedge (*Carex geyeri*) and grouse whortleberry (*Vaccinium scoparium*) are dominant understory plants, whereas understories of Douglas-fir forests are dominated by pinegrass (*Calamagrostis rubescens*). Utah honeysuckle (*Lonicera utahensis*), snowberry (*Symphoricarpos albus*), and buffaloberry (*Shepherdia canadensis*) are dominant understory species around the edge of the northern range of the GYA. Mountain big sagebrush (*Artemisia tridentata* var. *vaseyana*) and Idaho fescue dominate lower elevation grassland and meadows (NPS 2012).

The GYA appears to have retained most of its historical complement of vertebrate wildlife species (NPS 2013). The largest elk (*Cervus elaphus*) and bison (*Bison bison*) herds in North America and the United States, respectively, are found in the area. The northern range—the grassland in the northern part of Yellowstone National Park—sustains large populations of these animals. This ecosystem supports other charismatic megafauna such as grizzly bear (fig. 2.4), moose, white-tailed deer (*Odocoileus virginianus*), gray wolf, and coyote; distinctive avifauna such as trumpeter swan (*Cygnus columbianus*) and bald eagle; several hundred species of other small mammals and birds; and thousands of species of insects and other invertebrates (Keiter and Boyce 1991). This rich diversity of fauna allows for intact predator-prey interactions and other aspects of trophic dynamics.

Of the many fish species found in the GYA, westslope cutthroat trout and Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*) are keystone species preyed upon by many wildlife species, including grizzly bears (*Ursus arctos*). Cutthroat trout are currently at risk from hybridization and competition with nonnative lake trout (*Salvelinus namaycush*) (USDI NPS 2012). Apart from fishing pressure, water resources will become increasingly important if the population of the 21 counties in the GYA continues to increase.

Climate, soil and plant productivity are some of the many factors that influence where organisms are found. For example, many bird species are predominantly found at lower elevations, because primary productivity is highest there and climate is moderate (Hansen et al. 1999). In the GYA, plant assemblages dominated by lodgepole pine, cottonwood, quaking aspen, and willow have high bird abundance and diversity.

The topography of the GYA has influenced human use of the region for more than 10,000 years. Native Americans entered the Greater Yellowstone region soon after they entered North America 13,500-12,800 years B.P. For their survival, hunter-gatherer groups would forage for seeds, fruit, and animals at lower elevations and follow the maturation of plants and migration of animals into mountainous areas. Around 1872, Native Americans were moved to a reservation in central Wyoming. Soon after, roads were developed for gold camps in Montana. During the development of roads, Native Americans tried to protect their hunting grounds by constructing forts. Pioneering ranchers eventually settled into the lower valleys of the region. It was the construction of the railroad from Livingston, Montana to Yellowstone National Park that brought increasing numbers of tourists to the area (Morgan 2007).

Current land allocations and land use in the GYA indicate that human activities are prevalent at low elevations, similar to the abundance of native species. From the Yellowstone Plateau to the Gallatin Valley, land use transitions from timber management, grazing, and agriculture to rural and urban residences. Development in urban areas such as Bozeman has increased in the past several years where the majority of the population is concentrated along the foothills, near streams or transportation routes (Hansen et al. 1999).

The GYA has faced many land-use changes and disturbances, both natural and human caused. Wildfire has had an enormous impact, especially the fires of 1988, which burned over 1.2 million acres. These fires helped change how scientists, resource managers, and the general public think about the role of large fires in the fire ecology of Western forests. Mountain pine beetles have killed thousands of acres of lodgepole pine in the GYA, although the outbreaks have not been as extensive as in other areas of North America.

One of the most controversial issues in the region to date involves the restoration of wolves to the area. Many scientists consider the reintroduction of wolves to be successful in restoring ecological completeness in the GYA (USDI NPS 2013). However, others consider it to be a disruption to existing conditions and local resources, including big game species such as elk, and livestock in adjacent private and public lands. As of September 2014, the western gray wolves have been removed from the endangered species list and listed as a nonessential experimental population for the state of Wyoming.

The Yellowstone grizzly bear population is also of importance to this subregion (fig. 2.4). The U.S. Fish and Wildlife Service listed the grizzly bears as a threatened species in 1975 as the species range was reduced to two percent of its former range. To help the population recover, federal and state agencies implemented many actions such as placing a stop on grizzly hunting seasons, and establishing a Yellowstone grizzly bear recovery area, and two interagency teams – Interagency Grizzly bear Study Team and Interagency Grizzly Bear Committee – to coordinate management and increase communication. While the population has recovered to some extent, the species is back on the threatened species list today. Managers and scientists continue to monitor the population and strive to maintain a viable population (USDI NPS 2015).

The GYA attracts visitors from all over the world to tour the national parks and participate in recreational activities such as fishing, hunting, skiing, and hiking. The economy of the area is therefore driven by the character and quality of the natural and social environment, which draws visitors and permanent residents to the area. Communities such as Gardiner and West Yellowstone depend on Yellowstone National Park for economic activity, whereas communities such as Bozeman, Livingston, and Cody are less dependent on the park and have more diverse economies (Graff 2005).

GRASSLAND SUBREGION

The Grassland subregion occupies 119 million acres, extending across portions of Montana, Wyoming, North Dakota and South Dakota. The area includes portions of Custer National Forest, all of the Dakota Prairie National Grassland and several Indian reservations including the Crown Indian, Fort Peck, Standing Rock, Blackfoot, Cheyenne River and Spirit Lake.

The Wisconsinan glacier shaped the rolling and flat plains of North Dakota at the end of the last glacial period, approximately 12,000 years B.P. The southwestern corner of North Dakota was untouched by the glacier, which in turn led to the formation of the Little Missouri Badlands. Although this Ice Age glacier did not help shape the badlands, a previous glacier did. The Little Missouri River flowed northward up until 600,000 years B.P. until a glacier blocked its path and diverted its flow east (Herman and Johnson 2008a), creating a cycle of erosion and downcutting which led to the development of badlands.

Sedimentary layers found here are mainly continental sediments deposited by rivers and streams. Siltstone, claystone, sandstone, and lignite coal are common sediments in this environment (Bluemle 1996). Clinkers (or scoria), rocks produced by burning coal beds, are also commonly found in the badlands. They are mostly reddish in color but also include shades of pink to black. The landforms found in the Badlands—hills, valleys, cliffs, buttes—are a result of the differential hardness of minerals and their resistance to erosion (Bluemle 1996). As Theodore Roosevelt remarked, “The Badlands grade all the way from those that are almost rolling in character to those that are so fantastically broken in form and so bizarre in color as to seem hardly properly to belong to this earth.”

The rugged badlands were carved from rocks from the Late Cretaceous through the Eocene period. Cretaceous and Tertiary sedimentary formations mark the period when dinosaurs became extinct. The Hell Creek formation, located in the southern portion of the Little Missouri Badlands, has remnants of the last species of dinosaurs that existed on Earth, the most common of which was *Triceratops* spp. (Bluemle 1996). Along with dinosaur remains, other common fossils found in the area include those of fish, turtles, alligators, birds, and small mammals. Fossils of broad-leafed trees, cycads, palms, and ground ferns are also present, indicating the presence of a subtropical coastal plain environment during the Cretaceous period. Petrified wood is commonly found in the Badlands and is thought to be the remains mostly of dawn redwood (*Metasequoia glyptostroboides*) (Bluemle 1996).

The Missouri, Red, and Souris (or Mouse) Rivers are the three major river systems in the Dakota Prairie portion of the Grassland subregion. The Missouri River is the largest and longest in the state of

North Dakota. The Red River borders North Dakota and Minnesota, and the Souris River begins in eastern Saskatchewan, Canada and flows into North Dakota, after which it loops back into Canada. The Tongue and Powder Rivers are the major river systems that flow into the Yellowstone River in the southern portion of the Grassland subregion.

The subregion is characterized by three very different ecosystem types, badlands, prairie, and ponderosa pine forest. The pine forests are found in “islands of green in a sea of rolling prairie.” Most of the ponderosa pine forest in the Custer and Sioux National Forest burned in the last decade. Located mostly along the Little Missouri River, the badlands are a collection of rugged landscapes as described above. Sioux Indians, a group that lived in the region before Euro-American settlement, called the badlands “makosika” (land bad), and the French explorers called it “les mauvais terriers à traverser” which means bad lands to travel across (Bluemler 1996).

Most of the vegetation found in the badlands is native and consists of grasses, forbs, trees and shrubs. Shortgrasses are dominant because average precipitation is only 10-12 inches annually. Common bunchgrasses include little bluestem (*Schizachyrium scoparium*), blue grama (*Bouteloua gracilis*), and needle and thread (*Hesperostipa comata*). In areas where precipitation reaches close to 15 inches, western wheatgrass (*Pascopyrum smithii*) is fairly common. Open areas that can retain moisture throughout the year can support trees and shrubs. Deciduous trees include eastern cottonwood (*Populus deltoides*), green ash (*Fraxinus pennsylvanica*), boxelder (*Acer negundo*) and American elm (*Ulmus americana*), and ponderosa pine and Rocky Mountain juniper (*Juniperus scopulorum*) are common in some locations. Drainages dominated by trees also provide habitat for shrubs such as western serviceberry (*Amelanchier alnifolia*), chokecherry (*Prunus virginiana*), currant species, and American plum (*P. americana*). Shrubs found in drier locations include sagebrush, winterfat (*Krascheninnikovia lanata*), rabbitbrush, and buckbrush (*Ceanothus cuneatus*). Prairie wildflowers include gumbo lily (*Mentzelia decapetala*), scarlet globemallow (*Sphaeralcea coccinea*), soapweed yucca (*Yucca glauca*), and brittle pricklypear cactus (*Opuntia fragilis*) (Herman and Johnson 2008a).

The badlands landscape provides wildlife habitat in native prairie, sagebrush, woody draws, shrubby areas, and buttes. Large animals include bighorn sheep, pronghorn (*Antilocapra americana*), elk, white-tailed deer, and mule deer. When Lewis and Clark passed through North Dakota in 1804, the most abundant animal they encountered was bison followed by pronghorn. Populations of wildlife considered food and game species were greatly reduced after Euro-American settlement. Other mammals found in the Grassland include black-tailed prairie dog (*Cynomys ludovicianus*), cougar, porcupine (*Erethizon dorsatum*), cottontail rabbit (*Lepus sylvaticus*), and bobcat. Common reptiles include prairie rattlesnake (*Crotalus viridis*), bullsnake (*Pituophis catenifer*), and sagebrush lizard (*Sceloporus graciosus*), and common amphibians include Woodhouse's toad (*Anaxyrus woodhousii*), Great Plains toad (*A. cognatus*), and plains spadefoot toad (*Spea bombifrons*) (Herman and Johnson 2008).

The badlands support a diversity of bird species such as long-billed curlew (*Numenius americanus*), yellow-breasted chat (*Icteria virens*), mountain bluebird (*Sialia currucoides*), rock wren (*Salpinctes obsoletus*), western kingbird (*Tyrannus verticalis*), eastern kingbird (*T. tyrannus*), black-billed magpie (*Pica hudsonia*), prairie falcon (*Falco mexicanus*), and burrowing owl (*Athene cunicularia*). Greater sage grouse are found in southwestern North Dakota and depend on declining sagebrush habitat, and sharp-tailed grouse (*Tympanuchus phasianellus*) are found in similar sagebrush and prairie habitat (Herman and Johnson 2008a).

The native prairie component of the Grassland subregion is dominated by grasses and forbs (fig. 2.5) that tolerate low precipitation, strong winds, cold winters and hot summers, frequent fire, and herbivory. Native grasses have deep and extensive connected root systems that allow them to persist under stressful conditions (Herman and Johnson 2008b). Native prairie is divided into three tallgrass, mixed grass, and shortgrass. Tallgrass prairie, which dominates eastern North Dakota, requires the most moisture, and shortgrass prairie requires the least.

The largest remaining tallgrass prairie is in the Red River Valley, dominated by big bluestem (*Andropogon gerardii*), switchgrass (*Panicum virgatum*), Indian grass (*Sorghastrum*), and prairie dropseed (*Sporobolus heterolepis*) (NDGF 2012). Humus, which develops as grasses and forbs

decompose, helps retain soil moisture. This fertile soil led to the near extinction of the tallgrass prairie as farmers cultivated the land for wheat and other crops. The Sheyenne National Grassland contains most of the remaining tallgrass prairie in North Dakota today. Cedar River National Grassland, which connects with Grand River National Grassland in South Dakota, contains both tallgrass and shortgrass species. Warm and cool season grasses dominate this area, such as prairie junegrass (*Koeleria macrantha*), crested wheatgrass (*Agropyron cristatum*), green needlegrass (*Nassella viridula*), needle and thread, blue grama, little bluestem, and needleleaf sedge (*Carex duriuscula*). Dominant forbs include eastern pasque flower (*Anemone patens*), western wall-flower (*Erysimum asperum*), prairie smoke (*Geum triflorum*), blacksamson (*Echinacea angustifolia*) and common yarrow (*Achillea millefolium*) (Herman and Johnson 2008b).

Shortgrass prairie, found in the higher elevation region of the Missouri slope of North Dakota, is dominated by warm season species that require little rainfall, including spikemoss (*Selaginella*), blue grama, needleleaf sedge, threadleaf sedge (*Carex filifolia*), buffalo grass (*Urochloa mutica*), and needle and thread. These grasses are 3-7 inches tall. The Little Missouri National Grassland contains both mixed and shortgrass prairie. Common prairie forbs include wild prairie rose (*Rosa arkansana*), blacksamson, showy milkweed (*Asclepias speciosa*), soapweed yucca, gumbo lily, and tenpetal blazingstar (*Mentzelia decapetala*) (Herman and Johnson 2008b).

American bison was formerly the iconic “ruler of the prairies,” and Native Americans depended on bison for their livelihood. However, Euro-American settlement and hunting nearly drove the bison to extinction. Other mammals found in prairie habitat of the Grassland subregion include elk, red fox (*Vulpes vulpes*), coyote, American badger (*Taxidea taxus*), several species of ground squirrel (*Spermophilus* spp.) and pocket gopher (*Thomomys* spp.), white-tailed jackrabbit (*Lepus townsendii*), eastern cottontail (*Sylvilagus floridanus*), and meadow vole (*Microtus pennsylvanicus*) (Herman and Johnson 2008b).

Reptiles found in the prairie include garter snakes (*Thamnophis* spp.), smooth green snake (*Opheodrys vernalis*), and western hognose snake (*Heterodon nasicus*). Bird species include greater

prairie chicken (*Tympanuchus cupido*) in the tallgrass prairie, sharp-tailed grouse, greater sage grouse, upland sandpiper (*Bartramia longicauda*), nonnative ring-necked pheasant (*Phasianus colchicus*), and many songbird species (Herman and Johnson 2008b).

The Grassland subregion is home to over 100 species of fish, including northern pike, walleye (*Sander vitreus*), and sauger (*Sander canadensis*). Walleye inhabit large reservoirs such as Lake Sakakawea and Lake Oahe, while sauger are mostly found in the Missouri River (Herman and Johnson 2008c). In addition, this subregion contains a variety of endemic prairie fish assemblages, including sensitive species like northern redbelly dace (*Phoxinus eos*), a sensitive species, and associated native macroinvertebrates like fatmucket mussels (*Lampsilis siliquoidea*).

The Sioux, Assiniboine, Cheyenne, Mandan, Hidatsa, and Arikara were the first inhabitants of the land. In 1910, approximately 6,000 Native Americans lived in North Dakota. That number increased to over 25,000 in 1970 and over 30,000 today. Today, there are five federally recognized tribes in North Dakota: Fort Berthold, Lake Traverse Indian Reservation, Standing Rock Indian Reservation, Spirit Lake Reservation, and Turtle Mountain Reservation.

With the majority of the Grassland subregion located on fertile soil, agriculture drives the economy. Wheat, flaxseed, canola, peas, lentils, and oats are some of the many products grown here, especially in the Red River Valley (also known as “Breadbasket of the World”). Livestock production occurs on the less suitable lands and includes beef, dairy cattle, and hogs. North Dakota is currently in a boom phase of oil production, focused on the Bakken and Three Forks formations, making it the second largest oil-producing state. Petroleum refining and food processing are also major industries.

The declining sage-grouse population is of extreme concern to western states and is now a candidate species for listing under the Endangered Species Act. Over half of the greater sage-grouse habitat has been lost resulting in sage-grouse population numbers of 200,000 to 500,000. The Bureau of Land Management, U.S. Forest Service, U.S. Fish and Wildlife Service and the Natural Resources Conservation Service are working together to conserve the western sagebrush habitat. Several Environmental Impact Statements have been developed by these agencies to incorporate sage-grouse

conservation measures into land use plans (USDI BLM 2015). While agencies continue to monitor and evaluate the western landscape, a final decision on the species listing is forthcoming.

Many organizations such as the U.S. Forest Service, U.S. Fish and Wildlife Service, The Nature Conservancy, North Dakota Game and Fish Department, and Ducks Unlimited are working to protect existing grasslands and aquatic habitat. Although most of the land is under private ownership, many land owners have converted cropland to grassland under the Conservation Reserve Program, in which the federal government pays farmers to plant grass on less fertile lands. In many cases, reserve lands produce higher populations of white-tailed deer, ducks, ring-necked pheasant, and many non-game species. Unfortunately West Nile virus, oil and gas development, and conversion of sagebrush land to cropland have reduced greater sage-grouse range habitat and populations (USFWS 2014).

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DRAFT

Chapter 3: Historical and Projected Climate in the Northern Rockies

Adaptation Partnership Region

Linda A. Joyce, Marian Talbert, Darrin Sharp, Jeffrey Morisette, and John Stevenson

INTRODUCTION

Climate influences the ecosystem services we obtain from forest and rangelands. Climate is described by the long-term characteristics of precipitation, temperature, wind, snowfall, and other measures of weather that occur over a long period in a particular place. Day to day implementation of resource management practices are made in response to weather conditions; resource management strategies and plans are developed using our understanding of climate, the long-term average conditions. With the need to consider climate change in planning and management, an understanding of how climate may change in the future in a resource management planning area is valuable. In this chapter, we present the current understanding of the future changes in climate for the Northern Rockies Adaptation Partnership Region (NRAP).

CLIMATE MODEL PROJECTIONS: CMIP3 AND CMIP5

Global climate models have been used to understand the nature of global climate, how the atmosphere interacts with the ocean and the land surface. Scientists can use these models to pose questions about how changes in the atmospheric chemistry would affect global temperature and precipitation patterns. Given a set of plausible greenhouse gas scenarios, these models can be used to project potential future climate. These projections can be helpful in understanding how the environmental conditions of plants and animals might change in the future; how runoff and seasonal flows might vary with precipitation and timing of snowmelt, how wildfire, insects and disease outbreaks might be affected by changes in climate, and how humans might respond in their use of the outdoors and natural resources.

The Coupled Model Intercomparison Project (CMIP) began in 1995 to coordinate a common set of experiments for evaluating changes to past and future global climate (Meehl et al. 2007). This approach

allows comparison of results from different global climate models around the world and improves our understanding of the “range” of possible climate change. The third CMIP modeling experiments, or CMIP3, were used in the International Panel on Climate Change (IPCC) Fourth Assessment Report (Solomon et al. 2007), whereas CMIP5, the latest experiments, were used in the IPCC Fifth Assessment Report (Stocker et al. 2013).

A key difference between CMIP3 and CMIP5 is the set of emissions scenarios that drive, or force, the simulations of future climate (fig. 3.1, taken from Walsh et al. 2014). The CMIP3 simulations of the 21st century were forced with emission scenarios from the Special Report on Emissions Scenarios (SRES) (Nakićenović et al. 2000). The CMIP3 scenarios represent futures with different combinations of global population growth and policies related to alternative energy and conventional fossil fuel sources (Solomon et al. 2007). The CMIP5 simulations of the 21st century are driven by representative concentration pathways (RCP) scenarios (van Vuuren et al. 2011). The RCPs do not define emissions, but instead define concentrations of greenhouse gases and other agents influencing the climate system. RCPs present the range of current estimates regarding the evolution of radiative forcing, the total amount of extra energy entering the climate system throughout the 21st century and beyond. Projections made with RCP 2.6 show a total radiative forcing increase of 2.2 Wym² (Watts per square yard) by 2100; projected increased radiative forcing through the scenarios of RCP 4.5, RCP 6.0 and RCP 8.5 indicate increases of 4.5, 6.0, and 8.5 Watts per square meter, respectively (3.75, 5.0, and 7.1 Wym², respectively). Unlike the SRES scenarios used in CMIP3, the RCPs in CMIP5 do not assume any particular climate policy actions. Rather, policy analysts and social scientists are free to develop mitigation scenarios that lead to one of the RCPs. Comparisons between CMIP3 and CMIP5 model results for the states of Oregon and Washington are described in box 3.1.

CLIMATE OF THE NORTHERN ROCKIES ADAPTATION PARTNERSHIP REGION

Historical Climate

For historical data, we drew from and contrasted three common gridded historic datasets; Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM 2014), Maurer (Maurer et al.

2002), and TopoWx (Oyler et al. 2014). These three gridded historic products are knowledge-based systems that use point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based climatic parameters. Due to differences in the station data used by these gridded products as well as the models and assumptions used to interpolate to a grid, these climate models do not always agree on the historic climate or trend for a region. This is especially true in the western mountains where PRISM has been shown to have an artificial amplification in warming trend (Oyler et al. 2015). For this reason we chose to contrast all models rather than the trend and values produced by a single model.

Projected Climate

For an overview of projected climate in the NRAP region, we use downscaled CMIP5 projections based on RCP 4.5 and RCP 8.5 scenarios (fig. 3.2). Output from global climate models is at a scale too coarse to represent climate dynamics in subregions and management areas relevant for the NRAP. Many methods have been developed to bring climate projection information down to a scale that can be helpful to resource managers. We drew on climate projections that had been downscaled using the bias-correction and spatial disaggregation (BCSD) method (Maurer et al. 2007). We obtained the downscaled projection data from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. We use projections from 36 climate models for RCP 4.5 and 34 climate models for RCP 8.5 (table 3.1). The variables available for each BCSD climate projection include monthly precipitation and monthly surface air temperature for the 1950-2099 period. Spatial resolution of the data is 1/8-degree latitude-longitude (~7.5 mi by 7.5 mi) and covers the entire NRAP region. We use a base period of 1970-2009 for the historical climate, and compare projections for two periods (2030-2059, 2070-2099) with this historical climate. These time periods were selected in an attempt to summarize climate that has influenced the current conditions (base period) and two future periods that will be relevant to long-term management action (such as road construction, hydrological infrastructure, or vegetation planting).

The currently cooler climates associated with the Rocky Mountains are evident as are the warmer parts of eastern Montana and South Dakota (fig. 3.2). All areas warmed under both projections, with a greater warming in RCP 8.5. Average annual precipitation ranges from less than 6 inches to just over 85 inches with the wetter areas occurring in the northern parts of the mountains in Montana (fig. 3.3). See box 3.2 for key messages associated with these NRAP region maps.

COMPARISONS OF CMIP5 PROJECTIONS WITH THE CMIP3 PROJECTIONS USED IN THE RESOURCE CHAPTERS

The CMIP3 projections have been widely used in assessments, such as the National Climate Assessment (Walsh et al. 2014), and the Forest Service, U.S. Department of Agriculture Resource Planning Act Assessment (USDA Forest Service 2012). Since many of the resource chapters in this report use published literature using the CMIP3 projections developed by Littell et al. (2011), figure 3.4 compares the CMIP5 results used in this overview with CMIP3 projections of Littell et al. (2011) for use in natural resource assessments. There are many ways to compare projections; one such comparison involves comparing the change in temperature with the change in precipitation over a common period. The downscaled projections from Littell et al. (2011) did not cover the entire NRAP region (they cover the western area but stop at the continental divide). However, because we are interested in comparing the differences in temperature and precipitation between the CMIP3 and CMIP5 models for the entire region, we estimated the change in temperature and precipitation using global results for the models Littell et al. (2011) used - 10 CMIP3 model projections using the A1B scenario. We obtained these 1-degree global model projections for the entire NRAP region (Littell, written communication). Using these data we estimate the change in temperature and percent change in precipitation between a future period (2040-2060) and a historical period (1979-2009) for the models that Littell et al. (2011) used and the CMIP5 models that we are using in this study. In fig 3.4, the projected change in mean annual temperature is shown on the horizontal axis, and the percent change in precipitation is shown on the vertical axis. Change is described as the difference in temperature (future mean annual value minus historical mean

annual value) and percent change in precipitation ($100 \times [\text{future mean annual value minus historical mean annual value}] / \text{historical mean annual value}$).

Across all models, projected change in temperature by the 2040-2060 period ranges from just under 2 °F to nearly 8 °F (fig. 3.4). Generally, the projected change for models using the RCP 8.5 scenario (shown in red) is greater than the change projected for RCP 4.5 scenario (shown in yellow). Change in precipitation ranges across these CMIP5 models from a decrease of approximately 5 percent to an increase of 25 percent with a mean projected change of around 6 and 8 percent for RCP 4.5 and RCP 8.5 respectively. Change in the CMIP3 projections developed by Littell et al. (2011) is shown on this graph as pcm1, Ensemble (average of 10 model projections), and miroc_3.2 (where pcm1 and miroc_3.2 are individual climate models). We conclude that when this set of CMIP3 results (Littell et al. 2011) are compared with CMIP5 results for the NRAP region, the CMIP3 results are in the same temperature range for 2040-2060, although CMIP5 precipitation projections are slightly wetter in the future (fig. 3.4).

CLIMATIC VARIABILITY AND CHANGE IN NRAP SUBREGIONS

The following five sections summarize historical and projected climate for the five subregions in the Northern Rockies Adaptation Partnership: Western, Central, Eastern, Greater Yellowstone, and Grassland (see figure of subregions in chapter 2). Each section contains a set of figures based on a common template that we describe here. Key messages for each region are given in a series of boxes.

The first figure in each section shows the annual mean daily maximum temperature (°F), the annual mean daily minimum temperature (°F), and the total annual precipitation (inches) for 1949 to 2010. For this historical data, we drew from and contrasted three common gridded historic datasets; PRISM, Maurer, and TopoWx. In both temperature and precipitation there is variability, so we show the 10-year rolling average to highlight any short-term trends (bold lines).

The second figure in each section shows the historical modeled and projected annual mean of the daily maximum and minimum temperatures (°F), and total annual precipitation (inches) for the RCP 4.5 and the RCP 8.5 scenarios based on the CMIP5 1/8th degree BCSD data available on the Green Data Oasis (<https://computing.llnl.gov/resources/gdo/>). Typically, the higher emission scenario (RCP 8.5) will

show a higher temperature by 2100. In these figures, each model was backcast and we display the modeled historic data, which include all CMIP5 models that are bias corrected and downscaled in the same manner as the model projections. We overlay the 1/8-degree spatial resolution (about 7.5 mi) gridded historical observation dataset (blue line) (Maurer et al. 2002), which was used in the bias correction of the modeled data. The projections are shown in the colors used in figure 3.6, red for RCP 8.5 and yellow for RCP 4.5. The ensemble median from all models for each scenario is shown in the heavy line; the 5th and 95th percent quantiles for all models are shown by the shaded area. The precipitation projections have a greater variability than either temperature projection, and there is less confidence in any one particular model's projection for precipitation.

The third figure in each section shows the seasonal means of the daily maximum temperature (°F) for the historical and projected period. We use box plots here, where each box is an aggregation of 20 years of modeled historical or projected seasonal data. For example, the box labeled as 1960 represents the seasonal average of 1950 to 1969. The modeled historical boxes are grey, and boxes for projections use the same colors as in other figures: yellow for RCP 4.5 and red for RCP 8.5. The central line in each box is the median, indicating the same number of modeled historical or projections lie above and below this line. The hinges or edges of the boxes are the first and third quartiles. Whiskers extend past the first and third quartile by 1.5 times the interquartile range.

The fourth figure in each section shows the seasonal means of the daily minimum temperature (°F) for the historical and projected period 1950 to 2100. The figure is set up as the third figure description above. We do not show the seasonal mean precipitation values as there is large variability and no discernible trend and hence, less confidence overall in the finer scale precipitation projections.

Western Subregion

The primary results of analysis of historical and projected climate in the Western subregion are summarized in box 3.3, with specific detail in figs. 3.5, 3.6, 3.7, and 3.8.

Central Subregion

The primary results of analysis of historical and projected climate in the Central subregion are summarized in box 3.4, with specific detail in figs. 3.9, 3.10, 3.11, and 3.12.

Eastern Subregion

The primary results of analysis of historical and projected climate in the Eastern subregion are summarized in box 3.5, with specific detail in figs. 3.13, 3.14, 3.15, and 3.16.

Greater Yellowstone Subregion

The primary results of analysis of historical and projected climate in the Greater Yellowstone subregion are summarized in box 3.6, with specific detail in figs. 3.17, 3.18, 3.19, and 3.20.

Grassland Subregion

The primary results of analysis of historical and projected climate in the Grassland subregion are summarized in box 3.7, with specific detail in figs. 3.21, 3.22, 3.23, and 3.24.

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Chapter 4: Effects of Climate Change on Snowpack, Glaciers, and Water Resources in the Northern Rockies Region

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INTRODUCTION

Water is critical to life, and the effects of climate change on ecosystems are mediated through changes to hydrology. Changes in how snow accumulates and melts are one of the more consistently noted climate-induced changes to water in the western U.S. (Barnett et al. 2005; Service 2004), and these changes affect when water will be available for forests and fish alike. Changes in summer atmospheric circulation patterns may alter the ability of summer precipitation to allow midsummer respite from seasonal drought and dampening of wildfire spread (IPCC 2013; see chapter 8). Fish will be affected by both lower low flows with earlier snowmelt and higher midwinter floods caused by rain-on-snow events. Declining summer water supplies will likewise challenge municipal and agricultural water supplies. All of these meaningful effects can be traced to interactions between temperature and precipitation changes projected for the future and described in chapter 3. In this chapter, we describe mechanisms of hydrologic change, provide maps illustrating variations in effects across the region, and discuss some uncertainties relevant to effects. Effects of climate change on stream temperature are discussed in chapter 5.

Warming temperatures are the most certain consequence of increased CO₂ in the atmosphere. The hydrological consequences of warmer temperatures include less snowpack and greater evaporative demand from the atmosphere. Snowpack depth, extent, and duration are expected to decrease due to a combination of 1) less precipitation falling as snow (Pierce et al. 2008), and 2) slightly earlier melt (Luce et al. 2014). The degree of change expected as a result of warming varies dramatically over the landscape as a function of temperature (Luce et al. 2014). Places that are warm (near the melting point of snow) are expected to be more sensitive than places where temperatures remain subfreezing throughout much of the

winter despite warming (Woods 2009). In the coldest locations, snowpack may increase with increasing winter precipitation under changing climate (Hamlet et al. 2013).

The relationship of evapotranspiration to a warming climate is more complicated (Roderick et al. 2014). Warmer air can hold more water, which means that even if the relative humidity stays constant, the vapor pressure deficit, the difference between the actual water content of the air and the water content at saturation, increases. That difference between actual and saturation drives a water vapor gradient between leaves and the atmosphere that can draw more moisture out of the leaves. This has led many to expect greater evaporation during climate change (e.g., Cook et al. 2014; Dai 2013) using potential evapotranspiration formulations dependent on temperature, reflecting the increased “demand.”

Evaporation, however, is an energy intensive process, and there is only so much additional energy that will be available for evaporation. In addition, one needs to consider both the water balance and the energy balance when considering future warming (Roderick et al. 2015). The observation that temperatures are warmer during drought are more generally related to the lack of water to evaporate leading to warmer temperatures than to warmer temperatures causing faster evaporation (Yin et al. 2014). Unfortunately when potential evapotranspiration models based on air temperature (including Penman-Monteith) are applied as post-processing to general circulation model (GCM) calculations, an overestimate of increased evapotranspiration is likely, because the energy balance is no longer tracked (Milly 1992; Milly and Dunne 2011). The reality is that most of the increased energy from increased longwave radiation will result in warming rather than increased evaporation (Roderick et al. 2015).

Changing precipitation is more rarely discussed in climate change projections because it is more uncertain (Blöschl and Montanari 2010; IPCC 2013). Nevertheless, it has a much more direct impact on hydrologic process than temperature and cannot be ignored. On average, across many GCMs, precipitation is expected to increase very slightly in the Northern Rockies. The bounds are quite large, however, ranging from on the order of +30% to -20% (see chapter 3). Unfortunately, because many hydrologic processes are sensitive to precipitation (e.g., floods, hydrologic drought, snow accumulation), this represents a profoundly large uncertainty. As a consequence, the general approach in this and other

analyses is to use an ensemble average (i.e., average across many GCMs) precipitation outcome. In this report, we discuss some of the uncertainty surrounding that mean estimate to illustrate which processes or hydrologic outcomes are most uncertain and where. Not all processes are sensitive to precipitation, and uncertainty in outcomes caused by uncertainty in precipitation is not the same everywhere for a given process. Acknowledging the substantial quantitative disagreement among models in projected precipitation behavior, we now turn to discussion of the general physical mechanisms behind precipitation change, on which there is some agreement.

Two primary concepts are applied for precipitation change: 1) dynamic and 2) thermodynamic (Seager et al. 2010). Dynamic drivers of precipitation change include changes in global circulation patterns (e.g., the Hadley cell extent) and changes in mid-latitude eddies. Changes in teleconnection patterns, for example the North American Monsoon System (NAMS), would also fall into this category. Thermodynamic changes refer to the fact that the atmosphere can hold more water (Held and Soden 2006) according to a non-linear Clausius-Clapeyron relationship (saturation vapor pressure versus temperature), leading to a rough expectation on the order of seven percent increase in precipitation per 1.8 °F of temperature change. There are, however, other physical limits on the disposition of energy driving the cycling of water in the atmosphere, leading to lesser estimates on the order of 1.6 percent per 1.8 °F at the global scale, with individual grid cells being less or potentially negative, particularly over land (Roderick et al. 2014). Different approaches to scaling the thermodynamic contribution is one of the reasons for differences among models, although the dynamic process modeling differences can be great as well.

When considering the impacts of precipitation change on streamflow, the seasonality of precipitation is important. One key outcome of the thermodynamically driven changes is that when precipitation happens, it is expected to fall with greater intensity. In turn, this is expected to result in greater dry spell duration between events. This process can be important in determining drought duration (and consequently severity) in locations where summer precipitation is an important component of the summer water budget (Luce et al. 2016), such as much of eastern Montana, and low elevation stations in western Montana (fig. 4.1). Locations with more exposure to westerlies (e.g., Idaho stations and the Yellowstone

area), and high elevations in northern Montana, show a more pronounced winter-wet pattern, which is broadly more representative of high elevation stations than low elevation stations (figs. 4.1 and 4.2). It is specifically worthwhile noticing that much of the region has a substantially wetter May and June than July and August, and in some cases, the May through June precipitation is on a par with or exceeds the winter snowpack contribution to the annual water budget (fig. 4.2). In these locations, the snowpack changes may have less consequence than any circulation changes driving summer precipitation, such as expected shifts in NAMS (IPCC 2013). The May through June precipitation contributions, for example, can be an important determination of the severity of summer drought and the fire season (Abatzoglou and Kolden 2013). Pairing longer periods of precipitation deficit in summer with decreasing snowpack may be particularly challenging for vegetation and fishes.

Changes in orographic enhancement of precipitation over mountain areas in the Pacific Northwest is another effect within the class of dynamic effects. Historical changes in westerly windflows have led to a decrease in the enhancement of winter precipitation by orographic lifting over mountain ranges (Luce et al. 2013), raising the important question of whether such a pattern may continue into the future. Westerly winds across the Pacific Northwest are strongly correlated with precipitation in mountainous areas (fig. 4.3), but valley precipitation is not, nor is precipitation in much of eastern Montana. The historical trend in westerlies was driven by pressure and temperature changes spatially consistent with those expected under a changing climate, but were a consequence in part (~50%) of normal climate variability. Dynamic downscaling using a regional climate model (RCM) with small (~12.5 mi) cells provides a means to estimate orographically-induced precipitation (fig. 4.4b), which cannot be simulated with the large cell size of GCMs (fig. 4.4a). While the GCM shows general moistening over most of the area, the RCM shows a pattern of drying or no change on the upwind side of major mountain ranges, with moistening limited to valleys in the lee. Since precipitation falls mostly in mountain areas where streamflows originate, this is a potentially important aspect of future changes to consider. The variable infiltration capacity (VIC) model simulations detailed later in this chapter do not include this effect, so for purposes of general discussion, it can be lumped as an additional source of uncertainty for precipitation.

The range of potential changes to climate looks complex, particularly for such a varied landscape as the Northern Rockies. Perhaps the most important point to summarize from the above is that the current climatological settings vary over the landscape at both macroscales and fine scales. There are broad east-west changes in precipitation seasonality and amount, and local differences between nearby mountain and valley weather stations echo that pattern. Trends and drivers for climate variations will differ greatly from east to west. Fundamentally, topography is an important factor affecting seasonality, precipitation amount, and potential trends. Given that forests and much of the water supply generation are generally in mountain areas, it is important to recognize the role of topography in affecting the climate. Specific hydrologic outcomes of interest are changes to snowpacks and glaciers, streamflow, and drought.

SNOWPACK AND GLACIERS

Snowpack

Snowpack declines are among the most widely cited changes occurring with climate change, as warmer temperatures will reduce the fraction of precipitation falling as snow (Klos et al. 2014; Pierce et al. 2008). On the order of 70 percent of the water supply in the western U.S. is tied to mountain snowpacks (Service 2004), and thus changes in snowpack are particularly relevant to municipal and agricultural water timing (Stewart et al. 2005).

Historical trends in snowpack accumulation have been negative across much of the region (Mote et al. 2005; Regonda et al. 2005). Although earlier work has ascribed the changes primarily to warming temperatures, the interior parts of the Northern Rockies are cold enough to be relatively insensitive to warming and strongly sensitive to precipitation variation (Luce et al. 2014; Mote 2006). Consequently, interior snowpacks have likely responded primarily to reduced precipitation (Luce et al. 2013). In contrast, the low elevation mountains of northern Idaho, the western-most mountains in the region, are heavily influenced by a maritime snow climate (Armstrong and Armstrong 1987; Mock and Birkeland 2000; Roch 1949), and are still sensitive to temperature variability, particularly with respect to snow durability (Luce et al. 2014) (fig. 4.5).

Precipitation uncertainty can be substantial, but it does not translate into uncertainty in snowpack changes everywhere (fig. 4.6). An index of uncertainty can be calculated as a ratio of the effects of the likely range of precipitation values (about $\pm 7.5\%$ for one standard deviation across models) to the relatively certain temperature change (the timing is uncertain, but a change in temperature is certain as long as CO₂ concentrations continue to increase):

$$R_u = \frac{\Delta (\pm 7.5\%)}{\Delta}$$

Figure 4.6 shows strong certainty of large changes in April 1 snow water equivalent (SWE) for the Cascades but substantial uncertainty in outcomes for the Greater Yellowstone Area, where cold temperatures leave the snowpack more sensitive to precipitation than temperature changes. The uncertainty ratio in these areas suggests that relatively large increases in precipitation could counter the effects of warming on snowpack loss.

Glaciers

Glaciers are well known features in the Northern Rockies, with a large number located in and near Glacier National Park, on the northern edge of the region, and in the Wind River, Absaroka, and Beartooth ranges in and near Yellowstone National Park, at the southern edge. They are also found in several other mountain ranges in Montana and Wyoming (see <http://glaciers.research.pdx.edu/states-glaciers> for maps). Significant changes have been noted in the glaciers of Glacier National Park over the course of the 20th century (Fagre 2005), with the Grinnell Glacier having on the order of 10 percent of the ice that it had at its peak in 1850 (fig. 4.7). Declines have also been seen in the Wind River Range over the 20th century (Marston et al. 1991).

Estimating future changes in glaciers is complex (Hall and Fagre 2003), but empirical relationships derived for the glaciers indicate a brief future for them, with many glaciers becoming fragmented or disappearing by the 2030s. Increasing temperatures yield a rising equilibrium line altitude (ELA), decreasing the effective contributing area for each glacier as warming progresses. A 5.4 °F warming can translate into between 500 and 300 m of elevation rise in snow-rain partitioning and summer

temperatures. Unfortunately, for simplicity's sake, those changes do not directly equate to shift in ELA, which depends on the geometry and topography of the contributing cirque. Temperate alpine glaciers are well known for being as, or more, sensitive to precipitation variations as they are to temperature changes (McCabe and Fountain 1995), which has likely contributed to changes in glaciers across the Pacific Northwest. Westerlies and their contribution to winter precipitation have changed over the Glacier National Park region since the 1940s (fig. 4.3) and April 1 SWE at these elevations and latitudes is relatively insensitive to temperature. However, it is important to note that this area receives significant spring and summer precipitation (fig. 4.1), and changing summer temperatures affect both the melt rate and additional summertime mass contributions (new snow) in these glaciers. Thus, summer temperature is a strong predictor of their behavior, and regardless of changes in precipitation, significant reduction in area of glaciers is expected by the end of the 21st century (Hall and Fagre 2003).

STREAMFLOW

Streamflow changes of significance for aquatic species, water supply, and infrastructure include:

- Annual yield
- Summer low flows – average and extreme
- Peakflows – scouring floods
- Peakflow seasonality
- Center of runoff timing

Annual yield, summer low flows, and center of runoff timing are all important metrics with respect to water supply. Irrigation water for crops and urban landscapes is typically needed in summer months, and these metrics are most relevant to surface water supplies rather than groundwater supplies, although changes in long-term annual means could be informative for the latter. For summer low flows, two metrics are used, the mean summer yield (June through September), and the minimum weekly flow with a 10-year recurrence probability (7Q10). Center of runoff timing refers to the timing of water supply, and shifts in runoff earlier in the winter or spring disconnect streamflow timing from water supply needs. Center of timing can be redundant with other metrics that measure impact more directly, but with care in

interpretation, it can help clarify different potential causal mechanisms, changing precipitation versus changing temperature.

Peakflows are important to fishes and infrastructure. Scouring flows can damage eggs in fish redds if they occur while the eggs are in the gravel or alevin are emerging (DeVries 1997; Goode et al. 2013; Montgomery et al. 1996; Tonina et al. 2008;). Winter peakflows can affect fall spawning fish (chinook, bull trout, brook trout) while spring peakflows affect spring spawning cutthroat trout, steelhead, and resident rainbow trout (Wenger et al. 2011a,b). Spring peakflows associated with the annual snowmelt pulse are typically muted in magnitude in comparison to winter rain-on-snow events, because the rain-on-snow events tend to affect much larger fractions of a basin at a time, so scouring is less of a risk to spring spawning fishes. Consequently, a shift to more mid-winter events can yield greater peakflow magnitudes, which can threaten infrastructure such as roads, recreation sites, or water management facilities (diversions, dams).

Historical changes in some of these streamflow metrics have been examined in some of the western and southern basins in the Northern Rockies. For instance earlier runoff timing was noted by Cayan et al. (2001) and Stewart et al. (2005), and declining annual streamflows were noted by Luce and Holden (2009) and Clark (2010). Declining low flows (7Q10) have also been seen in the western half of the Northern Rockies (Kormos et al. in review) associated more with declining precipitation than warming temperature effects for the historical period. Low flow changes and timing changes in projections are generally associated with the expected changes in snowpack related to temperature (e.g., more melt or precipitation as rain in winter yielding a longer summer dry period).

Streamflow Projections

Streamflow projections were produced from the VIC model (Liang et al. 1994) for the western U.S. (available online, Western U.S. Hydroclimate Scenarios Project, <https://cig.uw.edu/datasets/wus/>). Climate projections are based on Coupled Model Intercomparison Project Phase 3 (CMIP3) GCM runs, the full details of which are discussed in Littell et al. (2011). Differences between the climate described by CMIP3 and CMIP5 are provided in chapter 3. The gridded data were used to estimate streamflow by

using area-weighted averages of runoff from each VIC grid cell within a given basin, following the methods of Wenger et al. (2010), to accumulate flow and validate. Streamflow metrics were calculated for stream segments in the NHD+ V2 stream segments (http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml).

Uncertainty in climate model inputs can be a significant factor in uncertainty for outcomes for natural resources (e.g., Wenger et al. 2013). Besides showing the projected change from the ensemble average, metrics were calculated for two additional climate scenarios; MIROC 3.2 and PCM GCMs were chosen to show warmer-drier and cooler-wetter summers than the ensemble mean, respectively (Littell et al. 2011). The difference between these two runs is shown in the second panel of the figures for each metric to give a sense of the certainty with which the change is projected in a given basin. Downscaling for these runs was done statistically, so GCM expectations for precipitation are implicit. No effects of change in orographic enhancement (e.g., fig. 4.4) are inherent in these images, so readers may wish to consider an additional degree of uncertainty (in a drier direction) on the windward side of mountain ranges.

Although calculations were made for all 6th-Digit Hydrologic Units in the Northern Rockies, only the western half of the region is shown in figures 4.8-4.14. Trimming the domain allows easier comparison of the uncertainty map to the ensemble mean projection, at the loss of display for eastern Montana and western North Dakota. Fortunately, the easternmost part of the maps that are shown show little change going east.

Mean annual flow (fig. 4.9) shows minor increases in the western and southern portions of the domain, with lesser changes across eastern Montana. Higher mountains in northern Idaho and northwestern Montana show substantial uncertainty in the annual scale water yield compared to the size of the change. Over much of the rest of the domain, the range of uncertainty is on par with the magnitude of the expected change in runoff. Changes in the ensemble mean are comparable to ensemble changes in precipitation.

Despite projections of increased annual flow, low flows are expected to decline (figs. 4.10 and 4.11). Uncertainty is low compared to the magnitude of changes, particularly in mountain areas. Patterns are

1948 nominally similar, with relatively uniform changes, though with somewhat more pronounced changes in
1949 mountain areas, particularly in wetter ranges. By and large, those areas showing more pronounced change
1950 in low flows show a large shift in timing (on the order of two months; fig. 4.12), again with uncertainty
1951 generally lower than change magnitudes in mountain areas, and stronger changes in mountains with
1952 greater precipitation. The primary mechanism expected to drive lower low flows is reduced snowpack in
1953 winter, leading to less stored water.

1954 Summer wet portions of the region are more likely to see low flows affected by summer precipitation
1955 patterns. Shifts in circulation that affect how moisture flows from the Gulf of Mexico during summer
1956 months are expected to negatively affect precipitation, on the net, and there will also likely be increased
1957 spacing between precipitation events (IPCC 2013; Luce et al. 2016). These summer wet areas are also
1958 more likely to see greater losses in precipitation with increased evaporation, but it is critically important
1959 to recognize the energy balance constraints when estimating the degree of loss (Roderick et al. 2014).
1960 This is not done in the VIC modeling, which uses only the temperature outputs from GCMs without
1961 reevaluating the change in energy balance from a different hydrological formulation, which is known to
1962 potentially lead to overestimation of loss (Milly and Dunne 2011).

1963 Changes to flood magnitude across the region are substantially more uncertain and spatially
1964 heterogeneous at fine scales (fig. 4.13). The second metric on flood timing shows changes in the number
1965 of days in winter that are in the top five percent of flows for the year (a maximum of 18.25 days on
1966 average; fig. 4.14). Bull trout are sensitive to this metric and tend to be rare when values exceed five percent
1967 (Wenger et al. 2011a,b). The shift to more midwinter rain and more rain-on-snow flooding depends
1968 strongly on the elevation range of each given basin. Generally, the maps reflect strong declines in flood
1969 magnitude in higher elevation basins near the crest of major mountain ranges, with strong increases at
1970 middle elevations and little change below that. This matches well with the information on number of
1971 midwinter events, which shows the greatest increases at middle elevations and less pronounced changes at
1972 both higher and lower elevations. While there is less snow and more rain at higher elevations, it is
1973 probably more a process of shifting shoulder seasons (Woods 2009) than more midwinter flood events,

thus producing more rain or rain-on-spring snowmelt floods, which tend to be less severe (MacDonald and Hoffman 1995). With less snow accumulating, the annual snowmelt and rain events during snowmelt are likely to be smaller, because less area will be snow-covered. At mid-elevations, temperatures will increase enough that rain is likely on snowpacks, even in midwinter. Uncertainty in peakflow magnitudes are generally as large as or larger than the expected magnitude of the change. Uncertainty in the amount of flooding occurring in mid-winter is less uncertain.

ADAPTING WATER RESOURCES TO CLIMATIC VARIABILITY AND CHANGE IN THE NORTHERN ROCKIES

With many potential changes in water resources, there are naturally questions about what we might be able to do to shift water and land management practices to reduce the impacts or consequences of a changing climate on water resources. Since the NRAP region includes a broad diversity of topography, geology, watershed configurations, and ecosystems, adaptation responses to climatic variability and change vary considerably across the region. However, several themes prevail across most of the region in response to dominant sensitivities to climate change (table 4.1). Many of these strategies and tactics may do little to alleviate some of the more direct consequences of shifting precipitation, snowpack timing, and temperature changes to forests during drought conditions (e.g., Vose et al. 2016); they are largely directed toward affecting downstream water availability and consequences of hydrologic drought.

Of greatest concern is reducing the vulnerability of roads and infrastructure to flooding, a phenomenon that is expected to increase considerably as snowpack declines and snow:rain ratios increase. National forests in particular contain thousands of miles of roads, mostly unpaved. Damage to those roads and associated drainage systems reduce access by users and is extremely expensive to repair. Road damage often has direct and deleterious effects on aquatic habitats as well, particularly when roads are adjacent to streams. Resilience to higher peakflows and frequency of flooding can be increased by (1) maintaining the capability of floodplains and riparian areas to retain water, (2) conducting a risk assessment of vulnerable roads and infrastructure, and (3) modifying infrastructure where possible (e.g., increasing culvert size, improving road drainage, relocating vulnerable campgrounds or road segments).

Climate-induced occurrence of disturbances such as drought and flooding are expected to increase, thus reducing water quality. Building an information base on potential locations of and responses to disturbances will help ensure informed and timely decision making when disturbances occur. Within this overall strategy, tactics include (1) prioritizing data collection based on projections of future drought, (2) collecting pre-disturbance data on water resources, and (3) developing a clearinghouse for programs related to fire and other disturbance. All tactics are focused on federal lands (table 4.1).

In contrast to the effects of winter peakflows, reduced overall base flows (especially in summer) are expected to reduce riparian habitat, water storage, and shallow aquifers. The primary adaptation strategies in this case are to increase natural storage and build storage where appropriate, as well as increase knowledge about groundwater. Specific tactics focus on (1) increasing storage with constructed wetlands, beavers, and obliterated roads, and (2) considering small-scale storage in dams, retention ponds, and swales, where appropriate. In addition, it will be important to map aquifers and alluvial deposits, improve monitoring to provide feedback on water dynamics, and understand the physical and legal availability of water for aquifer recharge.

Public lands are a critical source of municipal water supplies, for which both quantity and quality are expected to decrease as snowpack declines. A critical adaptation strategy is to reduce erosion potential to protect water quality, as well as prioritize municipal water supplies. Water quality can be addressed by: (1) reducing hazardous fuels in dry forests to reduce the risk of crown fires, (2) reducing other types of disturbances (e.g., off-road vehicles, livestock grazing), and (3) using road management practices that reduce erosion. These tactics should be implemented primarily in high-value locations (near communities and reservoirs) on public and private lands.

Harvesting trees to increase water yield has been a practice of interest for some time (e.g., Bates and Henry 1928). Trees use water, so it is not surprising that water yields generally increase after canopy loss (Brown et al. 2005; Jones and Post 2004; Troendle and King 1987; Troendle et al. 2010). There are, however, certain caveats to be considered. For example, increases in water yield are generally greater in moister environments or years, with less increase in drier locations or years (e.g., Brown et al. 2005), and

in some circumstances in drier climates, decreased yields may be seen (Adams et al. 2011; Guardiola-Claramonte et al. 2011). In broad terms, the general places and times one would want to see increases in water yield are the places and times when forest harvest is least effective (Troendle et al. 2010; Vose et al. 2012). Furthermore, thinning has proven to be ineffective in increasing water yield (Lesch and Scott 1997; Wilm and Dunford 1948). However, it can be useful in augmenting snow accumulation depths, for example for wildlife or recreation benefit (Sankey et al. 2015; Wilm 1944).

Canopy removal for streamflow augmentation is likewise not all positive. A negative effect of canopy reduction treatments is that they advance the timing of runoff (Luce et al. 2012). An example of large scale canopy loss in an area with similar vegetation and climate is the Boise River Basin, where about 45 percent of one basin burned while the other was left relatively unchanged after 46 years of calibration. This allowed for detection of a five percent increase in water yield from the 494,211-acre basin, providing an average of an additional 50,000 acre-feet each year. However, the average timing of release advanced by two weeks because the exposed snowpack melted faster, and most of the additional runoff was available prior to April, when it would be of little use in bolstering low flows. In warmer regions of the Northern Rockies, such large scale canopy removal could increase the magnitude of mid-winter rain-on-snow floods (Marks et al. 1998; Tonina et al. 2008). There are also water quality consequences to large scale canopy treatments, such as warming stream temperatures (Isaak et al. 2010) or sediment from increased road construction and use (Black et al. 2012; Luce and Black 1999).

Conceptually, replacing snowpack storage with storage in constructed reservoirs to carry over water from the winter wet season into the summer could be beneficial to irrigators in regions with significant irrigated agriculture. The degree of potential benefit, however, varies substantially with context of existing water right regulations, reservoir operating rules, snowpack sensitivity to temperature and precipitation, expectations for future precipitation, and the role and future of summer precipitation. The benefits of replacing snowpack storage with reservoir storage are somewhat built around the notion that the only thing changing is timing and that total volumes are unchanged. If, for instance, precipitation rises, temperature induced changes could be compensated for in relatively cold regions (Luce et al. 2014),

such as those found across most of the Northern Rockies. If, on the other hand, precipitation declines, total flow volume will be reduced, and it will be harder to fill reservoir storage because of other rights for water further downstream that might not be fulfilled. Ironically, this would be most difficult in dry years when the timing would be most strongly shifted because of the effect of snow water equivalence on duration of the melt period (Luce and Holden 2009). Given the large expenses, both financial and ecological, of dam construction, and that the precipitation uncertainties are considerable, it is likely worthwhile to perform a detailed economic and ecologic analysis before dam construction is seriously considered.

Shifting dam operation is another possibility, which would cost significantly less, but still require some infrastructure investment in upstream snowpack, soil, and weather monitoring. Streamflow forecasting allows more informed management of the tension between water storage for irrigation and maintaining empty reservoirs to buffer potential flooding (e.g., Wood and Lettenmaier 2006). Information on current state of the snowpack is a great boon to runoff forecasting in basins with substantial snowmelt contributions (Wood et al. 2015), even more so than climate and weather forecasting. Under such circumstances, it is reasonable to taper reservoir filling in such a way as to bring the reservoir to operational levels without undue flood risks, because later in the season, snowpack area is substantially reduced and rain-on-snow during the spring is generally less severe (or variable) than midwinter events when snowpack coverage over the basin is greater (MacDonald and Hoffman 1995). Predictability is declining in some regions as we lose snowpack, but the Northern Rockies region will still retain significant snowpack, making improved forecasting through investment in instrumentation a viable alternative. Note that besides informing reservoir operation, improved forecasting can also be used to better determine downstream financial investments in crops and community choices in how to invest water (Broad et al. 2007).

A final strategy for addressing water availability is to reduce water use by increasing efficiency, an important connection between the source of water on public lands and use of water downstream on public and private lands. First, it will be helpful to identify effective water-saving tactics and where they can be

successfully implemented. Second, low water-use appliances can be installed at administrative sites (e.g., restrooms), and drought tolerant plants can be used for landscaping (e.g., adjacent to management unit buildings). Third, the benefit of water conservation can be communicated to users of public lands (e.g., in campgrounds). These tactics demonstrate leadership in water conservation as an agency, providing outreach and public relations that extend to local communities.

More specific details on adaptation strategies and tactics for each NRAP subregion are in Appendix 4A.

CONCLUSIONS

Changes in climate over the Northern Rockies are likely to have substantial impacts on hydrology. A primary change will be shifts in snowpack storage, though other changes in precipitation and atmospheric circulation could have significant consequences for forests, grasslands, streams, fishes, and agriculture in the region. Information is still the best tool for adaptation to a changing climate, and summaries provided here give a sense of both the general expectation for change as well as uncertainties that need to be considered in adaptation planning.

A range of adaptation options exist for the future of water resources, and while there is a bias in human nature toward taking action, information may yet be one of our better choices for future adaptation to an uncertain and varying climate. If we continue to invest in monitoring to track changing climate and outcomes, we can be better prepared, as what are now challenges of the future become current challenges. Armed with a better knowledge of how shifting temperatures and circulation have played out on our landscapes, snowpacks, and streams, we can make better decisions.

This effort illustrated that adapting to climate change does not necessarily entail drastically different management actions than those that are currently implemented. Many of the current federal agency management actions to improve and restore watersheds and riparian areas are consistent with the adaptation strategies and tactics identified here, as fully functional watersheds and riparian areas are more resilient to change. Thus, in many cases, adaptation to climate change involves increasing restoration

activities and re-prioritizing actions, and agencies are well-prepared for these types of shifts in management.

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Chapter 5: Climate Vulnerability of Native Cold-Water Salmonids in the Northern Rockies

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INTRODUCTION

During the 21st century, climate change is expected to alter aquatic habitats throughout the Northern Rocky Mountains, intermountain basins, and western Great Plains. Particularly in montane watersheds, direct changes are likely to include warmer water temperatures, earlier snowmelt-driven runoff, earlier declines to summer baseflow, downhill movement of perennial channel initiation, and more intermittent flows (see chapter 4), as well as indirect changes attributable to altered and perhaps novel disturbance regimes. For animals restricted to freshwater aquatic environments for most or all of their lives—fishes, amphibians, crayfish, mussels, and aquatic macroinvertebrates—changes in habitat and in hydrologic regimes are likely to lead to marked shifts in their abundance and distribution. This is primarily because many of these species are ectothermic (cold blooded), thus environmental conditions dictate their metabolic rates and nearly every aspect of their life stages, including growth rate, migration patterns, reproduction, and mortality (Magnuson et al. 1979).

A vast and growing literature describes the myriad interactions between climate change, aquatic environments, and biotic communities. Rather than revisit this topic, we refer the reader to syntheses of the nexus between climate change and aquatic species in the northwestern United States (especially Rieman and Isaak 2010, but also Isaak et al. 2012a,b; ISAB 2007; Mantua et al. 2010; Mantua and Raymond 2014; Mote et al. 2003) and beyond (Ficke et al. 2007; Furniss et al. 2010, 2013; Luce et al. 2012; Poff et al. 2002; Schindler et al. 2008). However, assessments rarely provide

empirically based, spatially explicit, and precise climate change projections for species across broad geographic regions.

To address this gap, we developed high-resolution stream temperature and flow scenarios that translate outputs from global climate models (GCMs) into reach-scale habitat factors relevant to aquatic biota (Isaak et al. 2015). Those scenarios were coupled with species distribution datasets crowdsourced from the peer-reviewed literature and state and federal agency reports to develop accurate species distribution models for contemporary relationships between climate and biology. These models were used to project the probability of species habitat occupancy in streams throughout the inland northwestern United States, facilitating the identification of streams that are most likely to be occupied in the future and serve as invasion-resistant climate refugia.

We focused on climate vulnerabilities and current and projected distribution of two native salmonid fishes—bull trout (*Salvelinus confluentus*) and cutthroat trout (*Oncorhynchus clarkii*)—because of their importance to society, the large amount of data on their distribution and abundance, and their sensitivity to warm stream temperature (Eby et al. 2014; USDA FS 2013). We confined our inferences to suitable habitat for juveniles of each native species, because they are more thermally constrained than are adults. We directly addressed how the presence of nonnative species, such as brook trout (*S. fontinalis*), brown trout (*Salmo trutta*), and rainbow trout (*Oncorhynchus mykiss*) (the latter native to a portion of the analysis area) further restricts climate-suitable habitats for native species now and in the future. A full explanation of our rationale, approach, and results are in Isaak et al. (2015). The associated Climate Shield website (<http://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html>) provides access to a comprehensive archive of user-friendly digital maps and ArcGIS databases showing stream-specific model projections for multiple climate and brook trout invasion scenarios across most of the northwestern and interior western United States.

In this assessment, we summarize information for stream populations of bull trout and cutthroat trout in the Northern Rockies and briefly discuss adaptation measures and future research directions

(see Rieman and Isaak 2010 for a more comprehensive discussion). We regard our inferences as robust, but foresee the arrival of improved models fostered by ongoing improvements in measuring and modeling the attributes of populations and streams. Databases describing the distributions of many aquatic species via rapid, cost-effective environmental DNA surveys (McKelvey et al. 2016a; Wilcox et al. 2016) are rapidly proliferating and can be used with new geostatistical stream models (Isaak et al. 2014; Ver Hoef et al. 2006) to develop more precise information for many aquatic taxa. This combination of advanced survey methods and more sophisticated stream network models has already been adopted for assessing the validity and refining the predictions of the Climate Shield model for bull trout (M. Young, K. McKelvey, and D. Isaak, unpublished data).

ANALYSIS AREA AND METHODOLOGY

This assessment encompasses all streams in national forests and national parks encompassed by the Forest Service, U.S. Department of Agriculture Northern Region (fig. 5.1). To delineate a stream network for this area, geospatial data for the 1:100,000-scale National Hydrography Dataset (NHD)-Plus were downloaded from the Horizons Systems website (<http://www.horizon-systems.com/NHDPlus/index.php>; Cooter et al. 2010) and filtered by minimum flow and maximum stream slope criteria. Summer flow values predicted by the Variable Infiltration Capacity hydrologic model (VIC; Wenger et al. 2010) were obtained from the Western United States Flow Metrics website (http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml) and linked to individual stream reaches through the COMID field.

Stream reaches with summer flows less than $0.2 \text{ ft}^3 \text{ s}^{-1}$), approximating a wetted width of 3.3 ft (based on an empirical relationship developed in Peterson et al. 2013b), or with slopes greater than 15 percent were trimmed from the network because they tend to be unoccupied or support very low numbers of fish (Isaak et al. 2015). In the case of the stream slope criterion, reaches steeper than 15 percent occur at the top of drainage networks where slopes become progressively steeper, and populations are more vulnerable to disturbances (e.g., post-wildfire debris torrents) that result in periodic extirpations (Bozek and Young 1994; Miller et al. 2003). The slope and flow criteria were

set liberally to minimize the exclusion of fish-bearing reaches from the analysis, but doing so results in the inclusion of many reaches with intermittent flows or migration barriers that prevent fish access. Thus, the network extent of 113,733 mi used as baseline habitat in this assessment probably overestimates potential habitat, but the current resolution of the NHDPlus hydrology layer and VIC flow model prevent further refinement.

Climate Scenarios

Average summer flow values for three 30-year climate periods were available from the flow metrics website: a baseline period (1970–1999, hereafter 1980s) and two future periods (2030–2059, hereafter 2040s; 2070–2099, hereafter 2080s) associated with the A1B (moderate) emission scenario. An ensemble of 10 global climate models (GCMs) that best represented historical trends in air temperatures and precipitation for the northwestern United States during the 20th century was used for future projections (table 5.1). Due to the significant uncertainties concerning the timing of change in the future, we deemphasize the dates associated with scenarios and refer to them instead as baseline (1980s), moderate change (2040s), and extreme change scenarios (2080s). With respect to scenarios used in other chapters of the NRAP assessment, the A1B scenario is similar to the RCP 6.0 scenario associated with Coupled Model Intercomparison Project 5 (CMIP5) simulations (see chapter 3).

To complement the streamflow information, geospatial data for August mean stream temperatures were downloaded for the same A1B trajectory and climate periods from the NorWeST website and linked to the stream hydrology layer (www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html). Within the study area, the NorWeST scenarios were developed using spatial statistical network models (Isaak et al. 2010; Ver Hoef et al. 2006) applied to 11,703 summers of monitoring data at 5,461 unique stream sites monitored with digital sensors from 1993 to 2011. The density and spatial extent of the temperature dataset, combined with the predictive accuracy ($r^2 = 0.91$; RMSE = 1.8 °F) and resolution (~0.62 mi) of the NorWeST model across those sites, was deemed sufficient for this assessment. Details about the

rationales associated with climate scenarios and the stream temperature model are discussed in Isaak et al. (2015).

Focal Species

Bull trout in the Northern Rockies are largely from an inland lineage (Ardren et al. 2011) primarily west of the Continental Divide (USFWS 2014). Bull trout may exhibit migratory or resident life histories. Migratory fish travel long distances as subadults to more productive habitats and achieve larger sizes and greater fecundity as adults before returning to natal habitats to spawn. Resident fish remain in natal habitats and mature at smaller sizes, although often at the same age as migratory adults. Adults spawn and juveniles rear almost exclusively in streams with average summer water temperatures less than 54 °F and flows greater than 1.2 ft³ s⁻¹ (Isaak et al. 2010; Rieman et al. 2007). Relative to its historical distribution, this species has undergone substantial declines because of water development and habitat degradation (particularly activities leading to water temperature increases, but also cumulative losses of in-channel habitat complexity), elimination of migratory life histories by human-created barriers, harvest by anglers, and interactions with introduced nonnative fishes (Rieman et al. 1997). Nonnative species such as brook trout, brown trout, and lake trout (*Salvelinus namaycush*) may compete with or prey on bull trout (Al-Chokhachy et al. 2016; Martinez et al. 2009), or lead to wasted reproductive opportunities (Kanda et al. 2002). As a consequence, bull trout were listed as threatened under the U.S. Endangered Species Act (ESA) by the U.S. Fish and Wildlife Service in 1998 (USFWS 2015).

Cutthroat trout are represented by two subspecies. Westslope cutthroat trout (*Oncorhynchus clarki lewisi*) has a complicated lineage structure that can be roughly broken into a single lineage in the north and east that occupied and colonized river basins directly influenced by glaciation or glacial dams, and a southern and western group of several presumably older lineages in basins never directly influenced by glaciation (M. Young, unpublished data). These fish also exhibit resident and migratory life history strategies. Spawning and juvenile rearing can occur in streams smaller (<2 ft wide) and warmer (up to 57 °F) than those used by bull trout (Isaak et al. 2015; Peterson et al.

2013a,b; M. Young, unpublished data). Yellowstone cutthroat trout (*O. c. bouvieri*) has an unresolved distribution because certain lineages are found in portions of the Bonneville basin (Campbell et al. 2011; Loxterman and Keeley 2012), probably because of periodic hydrologic connectivity between the Bonneville and upper Snake River basins associated with passage of the North American plate across the Yellowstone mantle plume, Basin and Range faulting, and stream drainage reversals (Smith et al. 2002). Undisputed members of this taxon are represented by a single mtDNA clade found throughout the analysis area in the Yellowstone River basin (Campbell et al. 2011). For this analysis, we assume that life histories and presumably spawning and juvenile habitats are the same as for westslope cutthroat trout.

The distributions of both subspecies have declined substantially (>50 percent) in response to the same stressors affecting bull trout (Gresswell 2011; Shepard et al. 2005), although each subspecies appears to occupy a larger proportion of its historical habitat and is often found in larger populations at higher densities than are bull trout. Both subspecies of cutthroat trout have been petitioned under the ESA, but found not warranted for listing. Brook trout have replaced cutthroat trout in many waters in the region, disproportionately so in the upper Missouri River basin (Shepard et al. 1997). These invasions in part seem influenced by the distribution of low-gradient alluvial valleys that may serve as nurseries for brook trout (Benjamin et al. 2007; Wenger et al. 2011a). Where rainbow trout have been introduced outside their native range, introgressive hybridization occurs with both taxa of cutthroat trout at lower elevations and in warmer waters (Rasmussen et al. 2012), similar to patterns where westslope cutthroat trout occurred historically with native rainbow trout (the Clearwater River basin in Idaho and the Kootenai River basin in Idaho-Montana; McKelvey et al. 2016b). Yellowstone cutthroat trout have also been widely stocked throughout the historical range of westslope cutthroat trout (Gresswell and Varley 1988) and these two taxa readily hybridize to form hybrid swarms (Forbes and Allendorf 1991; McKelvey et al. 2016b). Lake trout predation decimated adfluvial populations of Yellowstone cutthroat trout in Yellowstone Lake at the beginning of the 21st

century, but predator control efforts are enabling cutthroat trout populations to rebound (Syslo et al. 2011).

Trout Distribution Models

Species distribution models were developed that predicted the occurrence probabilities of juvenile bull trout and cutthroat trout. We focused on juveniles as indicators of important natal habitats and the presence of locally reproducing populations (Dunham et al. 2002; Rieman and McIntyre 1995). This approach provides more precision than also considering distributions of subadults and adults, which migrate widely, occupy an array of habitats, and occur with many other fish species (Behnke 2010). Juvenile distributions, by contrast, are restricted in ecological scope and geographic extent, especially with respect to temperature (Elliott 1994). For example, juvenile bull trout are rarely found where mean summer temperatures exceed 54 °F (Dunham et al. 2003; Isaak et al. 2010), whereas adult bull trout sometimes occupy habitats as much as 9–18 °F warmer (Howell et al. 2010). Similar patterns are evident with cutthroat trout (Peterson et al. 2013a; Schrank et al. 2003), so we used a thermal criterion to delimit potentially suitable habitats for juvenile native trout.

Temperature Criterion for Juvenile Trout Habitats

A mean August stream temperature of 52 °F was selected as the temperature criterion from a set of standardized thermal niches that were developed by cross-referencing thousands of species occurrence locations in Montana, Idaho, and Wyoming with the NorWeST baseline scenario (fig. 5.2). Fish data were contributed by national forest monitoring programs; Idaho Department of Fish and Game; Montana Fish, Wildlife and Parks; and Wyoming Game and Fish Department (Isaak et al. 2015). These niches revealed that most juvenile native trout (90 percent of bull trout observations and 75 percent of cutthroat trout observations) occurred at sites less than 52 °F, whereas nonnative species like brown trout and rainbow trout were rare at those sites. The thermal niche of brook trout overlapped that of the native species, but its occurrence peaked at a slightly warmer temperature and declined thereafter. Since especially cold temperatures limit rainbow trout incursions, colder temperatures also restrict introgression with rainbow trout, such that stream reaches with

temperatures less than 48 °F usually support only genetically pure cutthroat trout (McKelvey et al. 2016b; Rasmussen et al. 2012; Yau and Taylor 2013; M. Young unpublished data).

Habitat Attributes and Logistic Regression Models

Spatially contiguous 0.6-mile (1-km) reaches of stream with temperatures less than 52 °F were aggregated into discrete cold-water habitats (CWHs), and occupancy status (present or absent) of native trout juveniles and brook trout within a subset of those CWHs (bull trout, $n = 512$; cutthroat trout, $n = 566$) was determined using the fish survey database described above. Logistic regressions were used to model the probability of native trout occupancy as a function of CWH size, stream slope, brook trout prevalence, and stream temperature. Habitat size was represented as the channel length of each CWH, stream slope as the average value across all the reaches within a CWH, and brook trout prevalence as the percentage of sample sites within a CWH where they occurred. Temperature was represented as mean August temperature averaged across all 0.6-mi sections constituting a CWH or the lowest mean temperature of any 0.6-mi section within a CWH.

The four variables were good predictors of juvenile trout occurrence within the training dataset; classification accuracy of the models at a 50 percent occupancy threshold was 78.1 percent for bull trout and 84.6 percent for cutthroat trout. The final logistic regression models included the four main predictor variables and some interactions among those variables. Plots of species response curves from the final models matched expectations based on the ecology of bull trout and cutthroat trout, but also revealed important differences between the species (fig. 5.3). Habitat occupancy for both native trout was positively related to CWH size, but bull trout required habitats five times larger than cutthroat trout to achieve comparable probabilities of occupancy. Bull trout occupancy declined as minimum temperature warmed, whereas cutthroat trout occupancy was positively related to mean temperature. Stream slope negatively affected both species, as did their co-occurrence with brook trout, especially in small streams. The presence of brook trout masked the apparent preference of cutthroat trout for habitats with low slopes. Additional details on modeling procedures and variable selection are summarized in Isaak et al. (2015).

Application of Models for Status and Vulnerability Assessment

The logistic regression models were applied to the full set of CWHs within the historical range of each native species across the Northern Rockies to project probabilities of native trout occupancy. Projections were made for the baseline and future climate periods. To account for uncertainties in brook trout distributions, occupancy probabilities were calculated and mapped for a pristine scenario (no brook trout) and a broad invasion scenario that assumed brook trout would be present at half the sites within each CWH (50 percent brook trout). For this exercise, we did not map a scenario in which brook trout were present at all sites, because their prevalence rarely exceeded 50 percent in the large CWH (i.e., greater than 25 mi) that were most likely to serve as strongholds for native trout (Isaak et al. [2015] show brook trout prevalence in over 500 streams), and because not all locations appear suitable for brook trout (Wenger et al. 2011a). In some small streams with native trout brook trout prevalence occasionally reaches 100 percent, so probabilities for a full range of invasion scenarios were integrated into the ArcGIS databases at the Climate Shield website (<http://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html>) and can be used for stream-specific assessments of brook trout invasions.

After species probability maps were developed for all streams, the information was cross-referenced with land administrative status using geospatial data from the U.S. Geological Survey Gap Analysis Program (Gergely and McKerrow 2013). The total length and percentage of CWHs and stream temperatures were summarized by jurisdiction for different climate periods. Also noted were the proportions of CWHs that were administratively protected within national parks and wilderness areas. Finally, we denoted those CWHs with probabilities of occupancy exceeding 90 percent as climate refugia.

NATIVE TROUT VULNERABILITY TO CLIMATE CHANGE

Stream Temperature Status and Projected Trends

Considerable thermal heterogeneity exists across Northern Rockies streams because of the complex topography and range of elevations in this region (fig. 5.4). Of the 114,000 miles of stream

habitat within the analysis area, 43,000 mi (38 percent) had mean temperatures less than 52 °F (table 5.2). Most of those cold-water habitats (86 percent) were in publically administered lands, primarily (69 percent) in national forests. Areas with concentrations of cold streams were generally associated with high-elevation, high-relief mountain ranges in Montana (e.g., Whitefish Range, Mission Mountains, Swan Range, Flathead Range, Lewis and Clark Range, Sawtooth Range, Anaconda Range, Flint Creek Range, Big and Little Belt Mountains, Crazy Mountains, and ranges associated with the topographic rise produced by the Yellowstone mantle plume). In contrast, comparable mountain ranges and clusters of cold-water habitats are absent in most of northern Idaho.

Mean August stream temperatures were projected to increase across the Northern Rockies by an average of 2.2 °F in the 2040s and 3.6 °F in the 2080s (table 5.1, fig. 5.4). Larger than average increases are expected in the warmest streams at low elevations, and smaller than average increases are expected for the coldest streams. Differential warming occurs because cold streams tend to be buffered by local influxes of groundwater (Luce et al. 2014), a trend represented in the NorWeST scenarios we used. Averaged across all streams, future projections imply faster rates of warming (0.4–0.5 °F per decade) than were observed in recent decades (0.2–0.3 °F per decade; Isaak et al. 2012a). If future projections are accurate, the length of streams with temperature less than 52 °f will decrease to 27,000 mi in the 2040s and 17,000 mi in the 2080s (table 5.3). In both scenarios, over 75 percent of these cold streams are in national forests. Groups of exceptionally cold streams still likely to host bull trout or cutthroat trout would originate from the Sawtooth and Lewis and Clark Ranges along the Continental Divide in northern Montana, several smaller mountain ranges scattered throughout central Montana, and along the northern flank of the Yellowstone topographic high (fig. 5.4). Persistent CWHs are more isolated elsewhere.

Cutthroat Trout Status and Projected Trends

The historical range of cutthroat trout extends through most of the Northern Rockies. The number of discrete CWHs for cutthroat trout during the baseline climate period was estimated to exceed 5,000 and encompass over 28,000 mi of streams (table 5.4, fig. 5.5). Over 90 percent of the

CWHs were predicted to have probabilities of occupancy exceeding 50 percent (table 5.4), largely because of the relatively small stream networks (6 mi is associated with a 90 percent probability of occupancy) that cutthroat trout populations require for persistence (Peterson et al. 2013a) (fig. 5.3). Nonetheless, the largest CWHs accounted for a disproportionate amount of the habitat most likely to be occupied; 32.6 percent of CWHs were climate refugia, but these accounted for 70.7 percent of the length of CWHs. As expected, the number and extent of CWHs decreased 20–60 percent in future periods, but nearly 3,500 potential habitats encompassing over 12,000 mi were projected to remain under the extreme scenario.

Since some streams are currently too cold for cutthroat trout, future warming will increase the probability of occupancy in some basins (e.g., the Teton River basin along the Rocky Mountain Front and streams in the northern portion of Yellowstone National Park). Assuming that brook trout were present within half of each CWH did not affect the number or amount of CWHs, because the habitats remained potentially suitable for cutthroat trout, but occupancy probabilities declined (table 5.4). Reductions were particularly severe in categories with the highest probabilities of occupancy (greater than 75 percent). The sensitivity of streams to brook trout invasions varied with local conditions, but reductions were most pronounced in small streams with relatively low slopes.

Bull Trout Status and Projected Trends

The historical range of bull trout occupies a smaller portion of the Northern Rockies than cutthroat trout, but the number of discrete CWHs for bull trout during the baseline climate period was still estimated to exceed 1,800 and encompass over 14,000 mi (table 5.5, fig. 5.6). Probabilities of occupancy for most bull trout CWHs were less than 50 percent because of the relatively large stream networks that bull trout require for persistence (30 mi is associated with a 90 percent probability of occupancy; fig 5.3). Although fewer than six percent of CWHs constituted climate refugia, they provided 30 percent of the total length of CWH, emphasizing the contribution of large CWH to the amount of habitat projected to be occupied. The requirement for larger CWHs caused projected decreases in the number and network extent of bull trout CWHs to be more substantial (38-

71 percent) than those for cutthroat trout, particularly for the CWHs with the highest probabilities of occupancy. More than 800 CWHs representing over 4,200 mi were projected to remain, even in the extreme scenario.

Brook trout invasions reduced bull trout occupancy rates. These declines were more pronounced for bull trout than cutthroat trout, especially in the CWHs most likely to be occupied (those with greater than 50 percent probability of occupancy); fewer than 10 climate refugia for juvenile bull trout are projected to remain under any warming scenario if brook trout occupy half of each CWH. However, many of the large habitats bull trout require appear less susceptible to broad-scale brook trout invasions (Isaak et al. 2015). As expected, CWHs with the highest bull trout occupancy probabilities during all climate periods and brook trout invasion scenarios coincided with river networks with the largest number of cold streams: headwater portions of the North and Middle Forks of the Flathead River, the Whitefish River, and the North Fork Blackfoot River (figs. 5.4, 5.6). Due to the lower elevations and warmer streams in northern Idaho, few or no climate refugia were projected to remain under either warming scenario.

Additional Fish Species

See boxes 5.1 and 5.2 for narratives on additional fish species in the Northern Rockies that are at risk from climate change and are candidates for the habitat occupancy-climate vulnerability approach described here.

INTERPRETING AND APPLYING THE ASSESSMENT

The assessment described above provides accurate, spatially explicit projections of habitat occupancy in the Northern Rockies by combining (1) ecological understanding of cutthroat trout and bull trout, (2) distribution data from public data sources, and (3) broad-scale, high-resolution stream temperature and flow projections. Assuming that species responses are related to the effects of climate on stream ecosystems—and the accuracy of the models supports this contention—the models also provide reasonably robust projections of habitat occupancy in light of anticipated climate change. These projections have several implications for the future viability of native fish populations

in the Northern Rockies and for developing management strategies targeted at conservation of these species.

Although both native trout species require cold-water habitat, their response to a changing climate is expected to differ. Bull trout, and most members of the genus *Salvelinus*, are adapted to some of the coldest freshwater environments in the Northern Hemisphere (Klemetsen et al. 2003). These species also tend to inhabit variable environments, often with strong gradients in productivity that appear to favor migration as a life history tactic (Klemetsen 2010). It is unsurprising that a species near the southern end of its distribution that relies on large amounts of cold-water habitats and is often found at low density (High et al. 2008) would be susceptible to range contraction as temperatures warm. In the Northern Rockies, we anticipate large declines in their distribution because relatively few areas have the capability to serve as climate refugia. Nevertheless, retention of at least some climate refugia implies that bull trout will not be extirpated from the region. However, the conditions favoring migratory or resident life histories may change, although how to accommodate or exploit this is uncertain. As we learn more about the extent and prevalence of populations occupying cold-water habitats with varying probabilities of occupancy, a better understanding of environmental drivers of bull trout life history may emerge.

By contrast, cutthroat trout can accommodate a wider range of thermal environments, commensurate with its broad latitudinal distribution and an evolutionary history (since the late Miocene or early Pliocene) that exposed them to fluctuation in warm/arid and cold/moist periods in western North America (McPhail and Lindsey 1986; Minckley et al. 1986). They are relatively flexible with respect to life history strategies, ranging from highly migratory populations dependent on large rivers or lakes for growth and fecundity, to resident populations that move little and have been isolated for many decades, (Northcote 1992; Peterson et al. 2013a). Although we anticipate net losses in their distribution within the Northern Rockies, they are not expected to be as severe as for bull trout, and some basins that are currently too cold to support cutthroat trout will become high-quality climate refugia (Coleman and Fausch 2007; Cooney et al. 2005). Of greater importance may

be how nonnative salmonids, which often displace or replace cutthroat trout, respond to warming conditions (Wenger et al. 2011a).

The presence of brook trout is problematic for both native species. Brook trout's tolerance of cold temperature is nearly equivalent to that of cutthroat trout, and they favor the low-gradient environments preferred by cutthroat trout and bull trout (Wenger et al. 2011a). Nonetheless, larger habitats (e.g., those > 40 mi long) appear less susceptible to invasion by this species, which may be attributed to their preference for small streams but also to the likelihood that large systems will contain other salmonid species, such as rainbow trout or brown trout, that constrain brook trout distributions in their native range in eastern North America (Fausch et al. 2009). Rainbow trout and brown trout are expected to shift their distribution upstream as temperature isotherms optimal for these species move in that direction (Isaak and Rieman 2013; Wenger et al. 2011b). Both species appear to have negative effects on cutthroat trout, but cold headwaters that resist their invasions are expected to remain widespread.

Most cold-water habitats in the Northern Rockies are in national forests (tables 5.2, 5.3). This emphasizes the critical role that the U.S. Forest Service will play in the conservation of populations of native fish. Active management that conserves native fish will be possible, because most of the cold-water habitats are outside designated wilderness areas and national parks that limit many management activities. Conservation options will vary by location. For example, even under extreme warming, some cold-water habitats are expected to persist in some river basins in Montana. Maintaining those conditions may be all that is necessary to ensure the persistence of native fish populations. By contrast, very few habitats regarded as climate refugia are anticipated to remain in the Clearwater, Spokane, and Kootenai River basins in Idaho. Those circumstances favor more active yet strategic management to promote population persistence through manipulation of habitat, fish populations, or both. Many cold-water habitats in Montana and Idaho are situated in landscapes where multiple resource values and ecosystem services are important (see chapter 11), so fish conservation strategies that are compatible with other resource objectives will be an important issue

in public land management (Rieman et al. 2010). Retaining native trout populations in some areas may require conservation investments that are unacceptably high or could prove ineffective as climate warms. In these circumstances, reallocating those investments to areas where native populations are more likely to persist may be preferable.

The model projections described above contain uncertainties associated with emission scenarios and unanticipated characteristics of future climate (Hallegatte et al. 2012). The future scenarios we considered reflect qualitatively similar trends to those that have been occurring in the Northern Rocky Mountains during the last 50 years: summer streamflow decreases, air temperature increases, and stream temperature increases (Isaak et al. 2010, 2012a,b; Leppi et al. 2012; Luce and Holden 2009). Consequently, these estimates of occupancy probabilities should be a biologically robust and spatially explicit ranking of habitats critical to the persistence of native trout. The Climate Shield fish distribution maps (fig. 5.7) and databases developed in association with this project were designed for ease of use, allowing users to gauge the amount, distribution, and persistence of native trout habitats. In addition, this information can be summarized for multiple spatial scales and biogeographic entities (e.g., stream, river network, national forest, species or subspecies, state, region).

As with all models, current predictions and future projections of occupancy by juvenile native trout are estimates. These projections could be improved by including more local information on habitat conditions (Peterson et al. 2013a), the presence of barriers that influence habitat size and connectivity among populations (Eros et al. 2012), and the application of spatial statistical network models (Isaak et al. 2014). The potential for improvement notwithstanding, the accuracy of these simple models suggests that environmental gradients are the primary drivers of habitat occupancy by juvenile native trout.

The next step in an ongoing assessment process is to continue to reduce uncertainties associated with the distribution of aquatic species and their responses to a changing climate. Although we used data from thousands of sites to develop occupancy models, data on thousands of additional sites

would improve existing models and help build new ones for additional species. Compiling a comprehensive aquatic species database from all national forests has the potential to provide information on the recent presence of species in locations from which they may have disappeared, or from which they may have been absent but now exist. These data, and outputs from occupancy models, form the basis for projecting and detecting trends in aquatic species distributions, especially if coupled with new surveys, such as those based on rapid and reliable environmental DNA surveys (McKelvey et al. 2016a). Although DNA surveys are often conducted with one or a few species in mind, the samples constitute a snapshot of the entire aquatic community and can be archived to support future analyses of multiple species. Finally, better distribution data, an understanding of changes in occupancy, and geospatial analysis will improve the accuracy of existing species occupancy models and facilitate the development of new ones, ranging from an individual reach to an entire species range.

ADAPTING FISHERIES TO CLIMATIC VARIABILITY AND CHANGE

Adaptation Strategies and Tactics

Many options are available to facilitate climate change adaptation and improve the resilience of fish populations, perhaps more options than for any other resource assessed in the Northern Rockies Adaptation Partnership. Adaptation for fish conservation has been the subject of comprehensive reviews, including for the Northern Rockies (Rieman and Isaak 2010, especially table 2) and other parts of the Northwest (Beechie et al. 2013; Isaak et al. 2012a; ISAB 2007; Luce et al. 2013; Williams et al. 2015). Having a relatively well-known set of climate sensitivities and adaptation options (Isaak et al. 2015; Mantua and Raymond 2014; Rieman et al. 2007) provides for credibility and consistency in sustainable management of fisheries in the Northern Rockies and beyond.

The Western, Central, Eastern, and Greater Yellowstone subregions within NRAP all have steep mountain topography, complex stream systems, and cold-water fish populations. Therefore, climate change sensitivities and adaptation options across this broad area tend to be similar (table 5.6), although the effects of livestock grazing as a stressor are more important in the Eastern subregion.

The Grassland subregion has no cold-water fish species and is dominated by warm-water species many of which are nonnatives. Although some concern exists about aquatic systems in this subregion, no adaptation options were developed for fisheries at the Grassland workshop (but see box 5.2).

Reduced snowpack is one of the best-documented effects of warmer temperatures in mountainous regions (see chapter 4), resulting in lower summer streamflows and warmer stream temperatures. Adaptation strategies can attempt to either maintain higher summer flows or mitigate the effects of lower flows (table 5.6). Specific adaptation tactics include pulsing flows from regulated streams when temperature is high, reducing water withdrawals for various human uses, and securing water rights for instream flows to maintain more control of overall water supply.

Another strategy is to increase cold-water habitat resilience by maintaining and restoring the structure and function of streams. Specific tactics include restoring the functionality of channels and floodplains to retain (cool) water and riparian vegetation, and ensuring that passages for aquatic organisms are effective. These tactics could be particularly appropriate in areas where restoration activities are already underway and where habitat is limiting or declining, especially near roads and where high peakflows are frequent. In addition, accelerating riparian restoration may be a particularly effective and long-lasting way to improve hydrologic function and water retention. Maintaining or restoring American beaver populations provides a “natural” engineering alternative for cool water retention. In conjunction with restoration, road removal and relocation from sensitive locations near stream channels and floodplains can significantly improve local hydrologic function.

Interactions with nonnative fish species and other aquatic organisms are a significant stress for native cold-water fish species in the Northern Rockies. One adaptation strategy is to facilitate movement of native fish to locations with suitable stream temperatures. Adaptation tactics include increasing the patch size of suitable habitat, modifying or removing barriers to fish passage, and documenting where groundwater inputs provide cold water. All of these tactics will be more effective if native fish populations are healthy and nonnatives are not already dominant. Another

adaptation strategy is to focus management on reduction of nonnative fish species. Adaptation tactics include increased harvest of nonnative fish (e.g., sport fishing), manual or chemical removal of nonnatives, and excluding nonnatives with physical or electrical barriers where feasible. These tactics will generally be more effective if nonnatives are not already well established.

In stream systems adjacent to grasslands and shrublands, livestock grazing can damage aquatic habitat, causing stress that may be compounded by warmer stream temperatures. An important adaptation strategy is to manage grazing to restore as much ecological and hydrologic function of riparian systems as possible. Specific adaptation tactics include ensuring that standards and guidelines for water quality are adhered to and monitored, making improvements that benefit water quality (e.g., fencing), and reducing the presence of cattle through the retirement of vacant grazing allotments. It will make sense to prioritize these actions for locations that have high ecological value.

In a warmer climate, it is almost certain that increased wildfire occurrence will contribute to erosion and sediment delivery to streams, thus reducing water quality for fisheries. Increasing resilience of vegetation to wildfire may reduce the frequency and severity of fires when they occur. Hazardous fuel treatments that reduce forest stand densities and surface fuels are an adaptation tactic that is already widely used in dry forest ecosystems. Disconnecting roads from stream networks, another tactic already in practice, is especially important, because most sediment delivery following wildfire is derived from roads. Finally, erosion control structures can reduce postfire sediment delivery and are often a component of Burned Area Emergency Rehabilitation on federal lands.

More specific details on adaptation strategies and tactics for the subregions are in appendix 5A. The process used to elicit adaptation options differed among subregions, with some information being general and some being geographically specific.

Toward Climate-Smart Management

The broad range of adaptation options summarized in table 5.6 and appendix 5A provide a diverse toolkit for fisheries managers. In addition to specific strategies and tactics, several overarching issues help guide applications in federal lands.

Be Strategic

Prioritizing watershed restoration such that the most important work is done in the most important places is critical, because funds, labor, and time for management of native fish populations are limited (Peterson et al. 2013b). For example, climate refugia for native trout in wilderness areas may not require or be amenable to habitat modification to ensure the persistence of those populations. Similar refugia outside wilderness might be targeted to improve habitat conditions or reduce nonnative species, particularly if doing so increases the probability of occupancy of such habitats. Regardless of such efforts, some basins are unlikely to provide suitable habitat for native trout in the future, so directing conservation investments elsewhere, or for other species, may be prudent.

Implement Monitoring Programs

Being strategic means reducing current and future uncertainties for decision-making. In the case of fisheries, more data are needed for streamflow (more sites), stream temperature (annual data from sensors maintained over many years), and fish distributions. These data can be used for better status-and-trend descriptions, and to develop robust (more accurate and precise) models for species to understand the interaction of climate change, natural variation, and land management. The feasibility of monitoring at small to broad scales is increasing with the advent of rapid, reliable eDNA inventories of aquatic organisms (Thomsen et al. 2012) and the availability of inexpensive, reliable temperature and flow sensors (USEPA 2014).

Restore and Maintain Cold Stream Temperature in Summer

Persistence of native trout species will depend on a variety of management techniques to restore and maintain stream shade and narrow unnaturally widened channels. Actions may include relocating roads away from streams, limiting seasonal grazing in some areas, and managing streamside riparian forest buffer zones to maintain effective shade and cool, moist riparian microclimates. Tactics described above have implications and consequences far beyond enhancing

the persistence of native fish populations, but being open to opportunities to do so are part of strategic thinking.

Manage Connectivity

Beyond climate change concerns, obstacles to fish migration are often removed in hopes of enhancing the success of migratory life history forms, or permitting native species to reoccupy former habitat or supplement existing populations. However, this presents a dilemma: accessible waters can be invaded by nonnative fish species that can replace natives (Fausch et al. 2009). In some cases, barriers can be installed to prevent these invasions. Native populations above barriers may be secure if they can adopt resident life histories, but could be susceptible to loss from extreme disturbance events in small habitats, requiring human intervention re-establish or supplement populations. Barriers are usually temporary, and may require reconstruction if nonnative species still remain downstream.

Remove Nonnative Species

Removal of nonnative fish species, although challenging in some locations, may be the best option for maintaining or restoring some native fish populations. These efforts typically consist of chemical treatments or electrofishing, and both tend to be feasible only in smaller, simpler habitats. Both are also costly, in part because they need to be conducted on multiple occasions to be effective. Chemical treatment can be controversial because of its perceived effects on water quality. Furthermore, any method of removal is successful only if the source of nonnative species is removed, often by installation of a migration barrier (see above). Public resistance to removal of nonnative fishes may also be an obstacle, particularly if sport fish are involved. Unauthorized introductions are also common, and can undermine conservation efforts. Finally, using control measures to manage the abundance of nonnative species rather than removing all of them has been helpful in some areas (e.g., removal of lake trout to promote bull trout persistence, electrofishing to depress brook trout and favor cutthroat trout). Such activities will be successful only if conducted at

regular intervals for the foreseeable future, which assumes social acceptance and that project funding will be available indefinitely.

Implement Assisted Migration?

Moving native fish species from one location to another, a historically common activity in fish management, has typically been used to found populations in previously fishless waters. This practice, alternately termed assisted migration or managed relocation, has become controversial for some taxa in recent years. However, assisted migration may be useful in the Northern Rockies where basins are currently fishless (or host only nonnative species in limited numbers) because of natural barriers such as waterfalls, and may constitute high-quality climate refugia in the future. Moving native fish to such areas is feasible, but potential effects on other native taxa (e.g., amphibians or invertebrates) must be considered. Reintroductions of native species may also be warranted when natural refounding is not an option, such as when populations in a specific location are isolated and periodically fail or suffer population bottlenecks (Dunham et al. 2011). This degree of management intervention requires a thorough understanding of genetic principles and broodstock establishment.

In conclusion, fisheries managers responding to the environmental trends associated with climate change will require a diverse portfolio comprised of many of the actions described in this chapter. Equally important is adapting our mindsets—and our administrative processes—to a new paradigm of dynamic disequilibrium for the 21st century. Under this paradigm, stream habitats will become more variable, undergo gradual shifts through time, and sometimes decline. Many populations will retain enough flexibility to adapt and track their habitats, but others could be overwhelmed by future changes. It is unlikely that we will be able to preserve all populations of all fish species as they currently exist. However, as better information continues to be developed in the future, managers will have increasingly precise tools at their disposal to know when and where resource commitments are best made to enhance the resilience of existing fish populations or to benefit other species for which management was previously not a priority. There is much to do as climate change adaptation

continues in future years, and federal lands will play a critical role in providing important refuge habitats for aquatic resources.

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Chapter 6: Climate Change Effects on Forest Vegetation in the Northern Rocky Mountains

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INTRODUCTION

The projected rapid changes in climate will impact the unique vegetation assemblages of the Northern Rockies in myriad ways, both directly through shifts in vegetation growth, mortality, and regeneration, and indirectly through changes in disturbance regimes and interactions with changes in other ecosystem processes, such as hydrology, snow dynamics, and exotic invasions (Bonan 2008; Hansen and Phillips 2015; Hansen et al. 2001; Notaro et al. 2007). These impacts, taken collectively, could change the way vegetation is managed by public land agencies in this area. Some species may be in danger of rapid decreases in abundance, while other may experience range expansion (Landhäusser et al. 2010). New vegetation communities might form, while historical vegetation complexes may simply shift to other areas of the landscape or become rare. Juxtaposed with climate change concerns are the consequences of other land management policies and past activities, such as fire exclusion, fuel treatments, and grazing. A thorough assessment of the responses of vegetation to projected climate change is needed, along with an evaluation of the vulnerability of important species, communities, and vegetation-related resources that may be impacted by the effects, both direct and indirect, of climate change. This assessment must also account for past management actions and current vegetation conditions and their interactions with future climates.

This chapter addresses the potential impacts of climate change on forest vegetation in the Forest Service, U.S. Department of Agriculture (USFS) Northern Region and the Greater Yellowstone Area (GYA), hereafter called the Northern Rockies (NR) assessment area (fig. 6.1). Then, based on the climate impacts assessment, we present an evaluation of the vulnerability of important tree species, vegetation

types, and resources of concern to projected climate change effects. And last, we present various adaptation actions to address climate change vulnerabilities.

This chapter includes six major sections. In the introductory section, we define terminology used throughout the chapter and provide background material on the details of the assessment including the scales, geographic areas, and pertinent information used to make our assessments. We also included discussion on how to evaluate uncertainty in climate change projections and vegetation response. We also summarize the methods used to make projections of vegetation response to changing climate. The second section contains important ecological background information that was used to assess climate change impacts and projected climate change responses for 17 tree species, five forest vegetation types, and three resources of concern. The third section is comprised on information on the tree species, types, or resources of concern that are important when evaluating climate change responses. In the fourth section, we then rate the vulnerability of the species, vegetation types, and resources of concern to climate change using information presented in section three. In the fifth section, we discuss adaptation strategies and management actions that can be used to address likely impacts of climate change. The final section is a concluding discussion.

This chapter utilizes the best-available information of climate change impacts on vegetation in the NR assessment area. We have integrated broad scale modeling results with a detailed synthesis of climate change literature for the NR area. This chapter was written to aid land managers in addressing climate change impacts on forest vegetation in land management planning and development of management strategies. This chapter does *not* include the detail needed to address climate change impacts at the project level, but it does include valuable information and syntheses that can be used in project planning and in addressing broad concerns at a landscape and project scale.

Terminology

Climate

Evaluations of climatic trends can be quite confusing, mostly because weather and climate vary at different spatial and temporal scales. To reduce this confusion, it is often helpful to clearly define the

terms and explain the scales that distinguish weather, climate variability, and climate change. *Weather* is the hourly, daily, weekly or monthly summaries in temperature, precipitation, wind, humidity, and other atmospheric conditions observed at a given place or across a large region. Weather changes at relatively small temporal scales (quickly) and it can change significantly as one moves north or south, east or west, or up and down in elevation. Weather is difficult to predict more than a few days in advance. *Climate* is a statistical characterization of the weather, averaged over many years. The World Meteorological Association defines it as the average 30-year weather patterns of a region. *Climate variability* is the variation in weather statistics over relatively broad regions and long time periods. Climate variability can be caused by underlying climatic processes, such as changes in patterns of ocean temperatures. The El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), for example, are two sources of climate variability in western North America (Newman et al. 2003). ENSO oscillations occur over two to seven year periods (Gershunov and Barnett 1998), while PDO oscillations occur on a longer cycle (20 – 50 years) (Heyerdahl et al. 2002). External forcings, such as changes in solar radiation, large volcanic eruptions, and increasing concentrations of greenhouse gases in the atmosphere, also influence climate variability. *Climate change* is a non-random change in climate that is measured over several decades or longer. It is technically defined as a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (decades or longer). Like climate variability, climate change may be due to natural internal processes or to external forcings. A *climate scenario* is a plausible and often simplified representation of one possible future climate, based on a consistent set of known principles about the climate system used as input to climate models.

Vegetation

There are several general terms that are used in vegetation ecology to describe how ecosystems respond to climate change (IPCC 2007). *Adaptive capacity* is the ability of a plant, species, or system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. *Exposure* is the nature and degree to which a system is exposed to significant climate variations (Glick and Stein 2010). *Sensitivity* is the

degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effect may be direct, such as crop yield decreases in response to a higher temperature, or indirect, such as damages caused by an increase in the frequency of coastal flooding due to sea-level rise. *Resilience* is the degree to which ecosystems can recover from one or more disturbances without a major shift in composition or function, while *resistance* is the ability of an organism, population, community, or ecosystem to withstand perturbations without significant loss of structure or function (i.e., remain unchanged) (Holling 1973; Seidl et al. 2016). From a management perspective, resistance includes both (1) the degree to which communities are able to resist change, such as that from warming climates, and (2) the manipulation of the physical environment to counteract and resist physical and biological change (i.e., cutting, burning, harvest treatments). *Vulnerability* is the degree to which a system is susceptible to, and unable to cope with, the adverse effects of climate change, including associated climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Other terms describe how ecosystem processes that are impacted by climate change will affect vegetation. In general, *stressors* are any physical, chemical, or biological entity that can induce an adverse ecosystem response. Stressors can arise from physical and biological alterations of natural disturbances, increased unmanaged demand for ecosystem services (such as recreation), alterations of the surrounding landscape, chemical alterations in regional air quality, or from a legacy of past management actions (Joyce et al. 2008).

Management

Climate change *adaptation* is an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which hopefully moderates harm or exploits beneficial opportunities (Spittlehouse and Stewart 2004). Adaptation is often referred to as preparedness, and is based on scientifically supported strategic and tactical activities that support sustainable resource management. Adaptation addresses specific aspects of the sensitivity of resources to an altered climate. An *adaptation tactic* is a specific action described in management and planning documents that supports

adaptation strategies and is implemented on the ground (e.g., reducing stem density and surface fuels in a dry mixed conifer forest, or increasing culvert size on roads along a stream that is expected to have higher flood volumes) approaches (Joyce et al. 2008; Millar et al. 2007a; West et al. 2009). *Assisted migration* is deliberately helping plant species colonize new habitats when driven out of their historical habitats due to rapid environmental change, especially climate change.

In an ideal sense, *ecological restoration* is defined as the practice of reestablishing historical plant and animal communities in a given area and the renewal of ecosystem and cultural functions necessary to maintain these communities now and into the future (Egan and Howell 2001). However, this ideal may be impossible to manage because: (1) little is known about historic conditions; (2) many key species may already be lost; (3) some efforts may be prohibitively expensive; and most importantly, (4) future climates will create novel ecosystems. As a result, The Society for Ecological Restoration has opted for a definition that states that ecological restoration is “the process of renewing and maintaining ecosystem health”.

The U.S. Forest Service manual (FSM) direction contained in FSM 2020 includes objectives and a policy for restoration. The objectives of the Forest Service ecosystem restoration policy are to:

1. *Restore and maintain ecosystems* that have been damaged, degraded, or destroyed by reestablishing the composition, structure, pattern, and ecological processes.
2. *Manage for resilient ecosystems* that have a greater capacity to withstand stressors, absorb and recover from disturbances, and reorganize and renew themselves, especially under changing and uncertain environmental conditions.
3. *Achieve long-term ecological sustainability* and provide a broad range of ecosystem services to society.

The Forest Service emphasizes ecosystem restoration across all National Forest System lands with the goal of attaining resilient ecosystems. All strategic plans, including the Forest Service Strategic Plan, land and resource management plans, and area plans, must include goals and objectives to sustain the resilience and adaptive capacity of aquatic and terrestrial ecosystems by reestablishing, maintaining, or

modifying their composition, structure, function, and connectivity. The goals and objectives must be established within this framework as defined by laws, Indian treaties and Tribal values and desires, and regulations. The goals and objectives also must consider public values and desires, social concerns, economic sustainability, the historical range of variability, ecological integrity, current and likely future ecological capabilities, a range of climate and other environmental change projections, the best available scientific information, and technical and economic feasibility to achieve desired conditions for National Forest System lands. A primary element of an integrated approach is to identify and eliminate or reduce stressors that degrade or impair the ecosystem. Restoration activities should also take into account social and ecological influences at multiple scales and incorporate the concept of a dynamic system and ecological trajectory. Some ecosystems may have been altered to such an extent that reestablishing components of the historical range of variability may not be ecologically or economically possible. Therefore, goals and activities should focus on restoring the underlying processes that create functioning ecosystems.

Functional restoration, an alternative concept used in the Forest Service, is defined as the “restoration of abiotic and biotic processes in degraded ecosystems”. Functional restoration focuses on the underlying processes that may be degraded, regardless of the structural condition of the ecosystem. As contrasted with ecological restoration, that tends to seek a historical reference condition, functional restoration focuses on the dynamic processes that drive structural and compositional patterns. Functional restoration aims to restore functions and improve structures with a long-term goal of restoring interactions between function and structure. It may be, however, that a functionally-restored system will look quite different than the historical reference condition in terms of structure and composition, and these disparities cannot be easily corrected because some threshold of degradation has been crossed or the environmental drivers, such as climate, that influenced structural and (especially) compositional development have changed.

Scales of Assessment

This chapter uses three scales to assess the impacts of climate change on forest vegetation: species, vegetation types, and resource concerns. We selected these scales and their elements to ensure flexibility

when considering the complex ecological concerns across the NR study area. Not only did this structure facilitate consistent and comprehensive assessments for the major management concerns identified in this chapter, but it also allows for the addition of new elements that may be identified in the future.

Species

At the finest level of assessment, we address climate change effects at the species or species group level. We allowed for the use of species groups by aggregating species by genera, guilds, plant functional types, or lifeforms. In this chapter we had only one species group – all cottonwood species (*Populus tricarpa*, *P. angustifolia*, *P. deltoides*). We selected the species scale to allow new species or species groups easily at later dates. This scale was meant to address regional concerns about important individual species or species groups that might be adversely impacted by climate change. Obviously, all tree species cannot be addressed, and so the list of species and species groups included here represent only those species that are identified by the government agencies in the NR as critical for addressing both management and climate change concerns.

Vegetation types

The vegetation type assessment scale addresses climate change concerns at a coarse vegetation community type level so that future evaluations can be spatially described using a map or geographic information system layer. Five forest vegetation types were assessed in this report to summarize potential climate change impacts, including dry ponderosa pine (*Pinus ponderosa*)/Douglas-fir (*Pseudotsuga menziesii*) forests, western larch (*Larix occidentalis*) mixed mesic forests, mixed mesic western white pine (*Pinus monticola*), western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), grand fir (*Abies grandis*) forests, lodgepole pine (*Pinus contorta*) mixed subalpine forests, and whitebark pine (*Pinus albicaulis*) mixed upper subalpine forests. These types are shown in both an existing vegetation map (fig. 6.1) and a potential vegetation map (fig. 6.2). Both maps and resultant categories were derived from LANDFIRE data (Rollins 2009), which covered the entire NR study area. Many of the estimated effects of climate change were based on evaluations of MC2 model simulations (see MC2 section), and figure 6.3 portrays the MC2 vegetation types used to generate the model results in appendix 6A of this

report. The potential vegetation type map and MC2 map can be used to estimate species assemblages in the absence of disturbance.

Resource Concerns

There are a number of resource concerns related to forest vegetation that were also addressed in this report. First, we addressed the impact of climate change and vegetation response on *landscape heterogeneity*, defined as the diversity in landscape structure or patch characteristics. We assumed that landscapes with high heterogeneity are more resilient to disturbance (Ahlqvist and Shortridge 2010; Oliver et al. 2010; Turner 1987). The second resource concern is *timber production*, as represented by timber volume. We attempted to address impacts of climate change on timber production solely via vegetation response, not from disturbance. Lastly, we describe climate impacts on *carbon reserves* across the NR area. NR resource specialists selected these resource concerns.

Geographic Stratification

The NR assessment area was stratified into five geographic sub-areas (fig. 6.1). The *west side* area includes northwestern Montana and northern and central Idaho. The *central area* includes west-central Montana and all lands west of the continental divide to the west side and north to Canada. The *east side* area includes the Rocky Mountain Front and southwestern Montana. The *grasslands* area includes all lands east of the *east side* boundary to the eastern border of the Northern Region. Lastly, the GYA includes all lands that have been officially designated as part of this high profile area, including Yellowstone National Park, Grand Teton National Park, the southern end of the Gallatin National Forest and the Beaverhead Deerlodge National Forest, the western side of the Custer National Forest and parts of the Shoshone, Bridger-Teton, Caribou, and Targhee National Forests.

The main purpose of dividing the assessment area into five geographic sub-areas was to refine climate change projections, impacts, and adaptation options to a specific part of the NR study area. The five sub-areas shown in figure 6.1 were included for all authors to standardize the spatial scales of their sections, but some authors of this chapter chose to evaluate climate change impacts at the national forest or finer

scale. As a result, this chapter does not include formal sections for each geographical area. Instead, the authors tuned their material to the sub-areas if the data and information allowed.

Uncertainty

Uncertainty is an expression of the degree to which something is unknown. Uncertainty can result from a lack of information or from a disagreement about what is known or even knowable. Uncertainty can also result from known and unknown errors. It may have many types of sources, from quantifiable errors in data to ambiguously-defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures, such as a range of values, or by qualitative statements, such as assessment of the judgment of a team of experts. Uncertainty is quite different from variability; variability is the actual range of a value or ecosystem variable.

All the climate models (Global Circulation Models or GCMs) that predict rapidly warming climates have a high degree of uncertainty (IPCC 2007). While there is little debate that atmospheric CO₂ is increasing and that this increase will cause major changes in climate (IPCC 2007), there is a great deal of uncertainty about the magnitude and rate of climate change (Roe and Baker 2007; Stainforth et al. 2005). This uncertainty will almost undoubtedly increase as climate projections are made at finer resolutions, for different geographical areas, and for longer time periods (Knutti and Sedlacek 2013). The range of possible projections of future climate from GCMs (anywhere from a 2.88 – 14.4 °F increase in global average annual temperature) is much greater than the variability of climate over the past two or three centuries (Stainforth et al. 2005), and the variability across GCMs is greater than the variability in each model's climate projections. Since it is impossible to know whether society will respond to climate change by employing technological innovations to minimize CO₂ emissions or to mitigate its effects, most GCMs also simulate a suite of scenarios that capture a range of possible strategies to deal with climate change, introducing yet another source of uncertainty. Moreover, it is the high variability of climate extremes, not the gradual change of average climate, that will drive most ecosystem responses to the climate-mitigated disturbance and plant dynamics, and these rare, extreme events are the most difficult to predict (Easterling et al. 2000).

Yet another source of uncertainty in attempting to predict ecosystem change is introduced when we try to predict how the Earth's vegetation and ecosystems will respond to highly uncertain climate change (Araujo et al. 2005). Mechanistic ecological simulation of climate, vegetation, and disturbance dynamics across landscapes is still in its infancy (Keane and Finney 2003; Sklar and Costanza 1991; Walker 1994). Many current ecosystem simulation models are missing the important direct interactions of disturbance, hydrology, and land use with climate that will surely dictate effects on plant distributions (Notaro et al. 2007). Little is known about the interactions among climate, vegetation, and disturbance, and interactions among different disturbance regimes (fire and beetles, for example) could create novel landscape behaviors. It is also difficult to determine how the critical plant and animal life cycle processes of reproduction, growth, and mortality will respond to changing climate (Gworek et al. 2007; Ibanez et al. 2007; Keane et al. 2001; Lambrecht et al. 2007). These modeling uncertainties greatly increase as projections are made further into the future and at finer spatial scales (Xu et al. 2009).

Managers must account for these uncertainties when using the information in this report in any land management plan or analysis. Sometimes there is less uncertainty in implementing conventional restoration designs than in designing restoration or treatment plans that attempt to account for climate change impacts. For some areas or resources, such as the restoration of western larch ecosystems, addressing climate change in management plans may require only minor changes to current management practices, while in other situations, major changes to current treatment designs may be needed, such as in ponderosa pine ecosystems. All climate effects will be manifest in different ways on different landscapes, and as a result, there is no magic "one-size-fits-all" prescription that can be adopted everywhere. The decision to modify management actions to include climate change effects must always include an assessment of the uncertainty of that modification and most importantly, local conditions.

Climate Change Assessment Techniques

Anticipating ongoing rapid climate change, ecologists are attempting to project the effects of those changes on myriad ecosystem processes across various scales (Clark et al. 2001; Joyce et al. 2014; Schumacher et al. 2006). Using traditional ecological field methods to explore climate change response

may be difficult because of the complex interactions between ecological processes, disturbance, and climate at multiple temporal and spatial scales (McKenzie et al. 2014). It would simply be too costly and time-intensive to sample at the large spatial scales and long timespans need to quantify vegetation response (Keane and Finney 2003).

In general, there are four techniques to assess and project the effects of climate change on vegetation and any other resource concern. The first is *expert opinion*, and it involves having experts in the fields of climate change, ecology, and vegetation dynamics qualitatively assess what will happen to vegetation under various climate change scenarios. The majority of papers about climate change impacts on vegetation used in this report were written by experts who have evaluated future climate projections and used their valuable experience to deduce how vegetation will respond to different climates. Information from these papers was included in this report, but expert opinions were only used when there was no other information from the other assessment techniques.

The second technique involves *field assessment* where extensive field sampling or remote sensing projects monitor vegetation change as the climate warms. Field sampling involves establishing plots in networks across the landscape, detecting change between plot measurements, and correlating these changes to climate data. Van Mantgem and Stephenson (2007), for example, related high tree mortalities to climate change using a network of monitoring plots. Demography studies track individuals over time, rather than use periodic plot-level inventories, to fully understand the role of climate relative to other risk factors like competition, variation in physiology and function, and vulnerability to insects and pathogens. Such demography data sets are rare (Iverson and McKenzie 2013), but one study has tracked more than 27,000 individuals of 40 species for about a decade to address interactions over an area of the southeastern U.S. (Clark et al. 2011). The only demographic dataset available for the NR assessment area is the Forest Inventory and Analysis database, but this extensive dataset has yet to be summarized to describe vegetation shifts due to climate change in the NR, although it has been elsewhere (McNulty et al. 1994). While field assessment techniques are the most reliable and most useful, they are often intractable

(see previous paragraphs) because of the large areas and long time periods needed to properly sample vegetation at the appropriate scales to detect changes as a result of climate.

The third method involves the use of statistical analysis to create empirical models that project climate change response. Most of the studies that project the habitat, range, or occupational shifts of NR tree species from climate warming use species distribution models (SDMs) to project future geographical ranges (Hansen and Phillips 2015; Iverson and Prasad 2002; Warwell et al. 2007). SDMs, also called bioclimatic envelope models, niche models, and species envelope models, are developed by linking current climate with the current distribution of a species of interest by means of advanced statistical modeling (Guisan and Zimmermann 2000; Watling et al. 2012). Then, using the statistical model, a future species distribution is computed using projected future climate data as inputs rather than the past climate. However, SDMs are inherently flawed for projecting future species distributions in that they relate past species occurrence to climate, resulting in predictions of potential species habitat, not species distribution (Iverson and McKenzie 2013). The projected potential habitat is only reflective of the species' distribution today and does not relate climate to historical distributions. One of the biggest limitations to this approach is that many studies have now found that most species distributions are NOT in equilibrium with climate, thereby causing SDMs to miss those areas conducive for the species but where the species is currently absent (type II error). Moritz and Agudo (2013), for example, found many species in the fossil record existed over a wider range of climates than is recorded today.

Another limitation of empirical models is that the critical ecological processes, such as pollination, cone production, seed dispersal, seed germination, seedling establishment, tree growth, mycorrhizae influences, competitive interactions, disturbance, mutualists, and mortality, as well as the many disturbance processes, are not represented in SDMs, and these are the main processes that control species abundance and presence (Iverson and McKenzie 2013; Watling et al. 2012). Dullinger et al. (2012), for example, found that range shifts predicted by SDMs retracted by over 40 percent when seed dispersal was included in the prediction process. Girardin et al. (2008) found that process models were much better at projecting climate change effects on tree growth because they accounted for changes in soil moisture and

growing season. Moreover, the climates used to develop SDMs represent a very small slice of time (50 – 100 years) relative to the long time periods that existing trees, such as the long-lived whitebark pine (>1000 years of age), have survived on the landscape today, and so SDMs cannot capture the climate for all stages of today's tree's life cycle. Most mature trees used to evaluate species occurrence in statistical models may have lived for hundreds to thousands of years and continued to survive despite major changes in climate. Along those same lines, one of the major problems of SDM modeling is that there is no sense of how long it will take for a species to be eliminated from one site and effectively populate a new site, and because migration is a slow process, the timing of SDM model results are often incompatible with management time frames. In addition, SDMs assume that the current distribution of the species is a consequence of climate alone, yet we know that fire exclusion, exotic diseases, and management actions have also impacted species occurrence (Gustafson 2013; Iverson and McKenzie 2013). Therefore, it is difficult to have any confidence in SDM projections for fine scale applications; they are informative, but not prognostic, especially on short time scales of decades and half-centuries required by land management. This is especially true when addressing the high uncertainty of the GCM derived climate used by the SDMs.

The last and perhaps the most effective technique uses simulation modeling to assess climate-mediated vegetation responses (Gustafson 2013; Iverson and McKenzie 2013; McKenzie et al. 2014). Here, future projections of climate are input into simple to complex ecological models to simulate the climate change effects (Baker 1989; He et al. 2008; Keane et al. 2004; Merriam et al. 1992; Perry and Millington 2008). A variety of existing models simulate ecological change at broad (global, regional) and fine (point, ecosystem, stand) scales (Bugmann 2001; Cramer et al. 2001). However, landscape scale (38.6 to 386 square miles) models are perhaps the most critical for predicting effects of climate change because this is a key scale at which most ecosystem processes and linkages are manifest and the scale at which most management decisions are made (Cushman et al. 2007; Littell et al. 2011; McKenzie et al. 2014). Finer-scale stand models cannot incorporate important exogenous disturbance regimes because of their limited spatial extent, and coarse-scale dynamic global vegetation models (DGVMs) are unable to

simulate important plant-, species- and canopy-level competition and disturbance effects, such as successional shifts, community dynamics, and differential disturbance effects among species (McKenzie et al. 2014).

To realistically model species composition changes, a mechanistic, process-driven simulation approach might be preferable to emphasize those physical drivers of vegetation dynamics that are directly related to climate (Gustafson 2013). However, mechanistic model design is often overly complex and therefore presently intractable because of (1) overly detailed parameterization of species life histories and physiologies for all species, (2) high complexity of many interacting disturbance factors, and (3) necessary high-resolution modeling over large areas (Lawler et al. 2006). Dynamic global vegetation models, such as the MC2 model used in this report (next section), operate at scales from regional (hundreds of miles) to global (degrees of latitude and longitude). While DGVMs project climate change across large domains, these models aggregate species into life forms or plant functional types (PFTs), using structural or functional attributes, which may be useless to local managers (Bachelet et al. 2003; Bonan 2008; Neilson et al. 2005). Most of these models project shifts to more drought-tolerant and disturbance-tolerant species or PFTs for future climates. This general shift in vegetation may be offset by physiological changes induced by CO₂ fertilization, as suggested by a DGVM (MC1) that links water-use efficiency to CO₂-simulated expansion of forests into areas where the climate is currently too dry (Bachelet et al. 2003). This particular issue deserves further study to resolve the extent and duration of such mitigating effects of CO₂; these effects could change substantially depending on the outcome of climate change projections.

To be effective at realistically predicting climate change effects, ecosystem models must simulate disturbances, vegetation, and climate, and also their interactions across multiple scales (Purves and Pacala 2008). Yet few models simulate ecosystem processes with the mechanistic detail needed to realistically represent important interactions between landscape processes, vegetation dynamics, disturbance regimes, and climate (Keane et al. 2015; Riggs et al. 2015). Direct interactions between climate and vegetation, for example, may be more realistically represented by simulating daily carbon (photosynthesis, respiration),

water (evapotranspiration), and nutrient (nitrogen, phosphorous) dynamics at the plant level than by simulating vegetation development annually using state-and-transition modeling approaches (Keane et al. [in press]). A fully mechanistic approach, however, may be difficult for both conceptual and computational reasons, and some simulated processes may always require a stochastic or empirical approach (Falk et al. 2007; McKenzie et al. 2014).

We used output from the DGVM MC2 to standardize our evaluation of change and vegetation responses for the NR. Output from this model is presented in appendix 6A, and this output was used by all authors in developing the material on future climate effects on vegetation and in the vulnerability assessment. We did not use MC2 simulated species projections in the following sections.

MC2 model

MC2 is a new implementation of the MC1 DGVM, which was created to assess the impacts of global climate change on ecosystem structure and function at a wide range of spatial scales from landscape to global (Bachelet et al. 2001; Peterman et al. 2014). MC2 is short for "MC1 version 2." MC1 was produced by combining physiologically-based biogeographic rules, originally defined in the Mapped Atmosphere-Plant-Soil System (MAPSS) model (Neilson 1995), with biogeochemical processes packaged in a modified version of CENTURY (Parton et al. 1987) and a new fire disturbance model, MCFIRE (Lenihan et al. 1998; Lenihan et al. 2003). The three linked modules simulate biogeography (lifeform interpreter and vegetation classifier), biogeochemistry, and fire. The main functions of the biogeographic module are to (1) predict lifeforms, that is, the composition of deciduous-evergreen tree and C3-C4 grass lifeform mixtures; and (2) classify those lifeforms and their associated biomass into different vegetation classes using a climatologic rule base. The biogeochemical module simulates monthly carbon (C) and nutrient dynamics for a given ecosystem. Aboveground and belowground processes are modeled in detail and include plant production, soil organic matter decomposition, and water and nutrient cycling. Parameterization of this module is based on the lifeform composition of the ecosystems, which is updated annually by the biogeographic module. The fire module simulates the occurrence, behavior, and effects of severe fire. Allometric equations, keyed to the lifeform composition supplied by the

biogeographic module, are used to convert aboveground biomass to fuel classes. Fire effects, specifically plant mortality and live and dead biomass consumption, are estimated as a function of simulated fire behavior (fire spread and fire line intensity) and vegetation structure. Fire effects feed back to the biogeochemical module to adjust levels of various carbon and nutrient pools to alter vegetation structure (e.g., leaf area index levels and woody versus grass-dominated vegetation).

The MC2 DGVM model simulations were generated by Tim Sheehan (Conservation Biology Institute). Inputs to the MC2 model include soil (depth, texture and bulk density), annual average atmospheric CO₂ concentration, and monthly average climate variables (monthly precipitation, mean vapor pressure, and means of daily maximum and minimum temperatures). Historical climate data (1895-2008) were obtained from the PRISM group (Daly et al. 2008) and were upscaled to 30-arc-second resolution (~0.23 square mile). Soils data were derived from STAGSGO (SCS 1991) by Kern (1995, 2000) and were scaled to the resolution of the climate data. Future climate projections were available from various GCMs, and we chose the MIROC 3.2 medres (Hasumi and Emori 2004) based on its relatively high overall ranking according to Mote and Salathé (2010). GCM future projections were downscaled to 0.23 mi² using the delta or anomaly method (Fowler et al. 2007). Anomalies between future and mean monthly historical (1971-2000) values were calculated to project estimates for each climate variable and each future month across the study area. We evaluated model output based on two IPCC Special Report on Emissions Scenarios greenhouse gas emission scenarios (Nakićenović et al. 2000) - A1B and A2. Future projections based on the most recent generation of emissions scenarios, the Representative Concentration Pathways, were not available across the entire NR area, but the two generations of models are relatively similar in their estimates of global temperature change and spatial patterns temperature and precipitation change (Knutti and Sedláček 2013).

To evaluate potential climate impacts on vegetation assemblages and disturbance regimes and the interaction with land management, we evaluated a suite of vegetation-related and fire occurrence variables output by the MC2 model under historical (1971-2000) conditions and future projections for mid-century and end-of-century. Specifically, we compared past vegetation distributions across the NR

with fire suppression and without, and made similar comparisons for two future years, 2050 and 2100, under both the A1B and the A2 emissions scenario (appendix 6A). Aboveground processes were examined comparing the amount of carbon in live and dead biomass for three time periods (historical, 2030-2050, 2080-2100) and with/without fire suppression (appendix 6A). Potential evapotranspiration was also evaluated to compare possible changes in aridity (over similar time spans and land management measures). Finally, projected changes in fire disturbance were examined comparing estimated fire rotation and the percent of study area burned by time period and suppression management (appendix 6A).

FOREST VEGETATION RESPONSES TO CLIMATE

In general, many scientists feel that the impacts of climate change on forest vegetation will be primarily driven by vegetation responses to shifts in disturbance regimes, and then secondarily, through direct effects of vegetation with climate through shifts regeneration, growth, and mortality processes at both individual plant and community scales (Dale et al. 2001; Flannigan et al. 2009; Temperli et al. 2013). And most of the expected climate changes are reduced precipitation and increase temperatures (see chapter 3) resulting in reduce water available to trees and understory plants. These effects will be highly variable across time, from year to year and from day to day, and across space, as the footprint of the new climate becomes manifest at fine to coarse scales. Trees will respond to projected reduced water availability, higher temperatures, and changes in growing season in diverse manners, but since trees cannot pick up their roots and move, any changes in vegetation composition and structure will be the result of changes in both a plant's life cycle processes and its responses to disturbance. This section discusses some general responses that trees and forested vegetation might have to projected climates.

Individual Plant

The impacts of climate on forest vegetation can occur as both direct and indirect effects. Direct effects are the immediate and long-term impacts of increased temperature and decreasing water availability on vegetation life cycle processes, as discussed at length throughout this document. Indirect effects, such as changes to fire, insect, and disease regimes, however, may be more important and longlasting than direct effects.

In short, there are several important modes of response of plants to changing climates (Joyce and Birdsey 2000). The first is changes in *productivity*; plant productivity may increase in the future because of increasing temperatures, longer growing seasons, more variable precipitation, and CO₂ fertilization (Aston 2010; Joyce 1995). Increases and decreases in productivity are related to changes in cone crops, tree vigor, and tree defenses. The window of successful seedling *establishment* will change (Ibanez et al. 2007); increasing drought and high temperatures may narrow the time for effective regeneration in low elevation NR forests and widen the window in high elevation forests. Climate may directly cause tree *mortality* due to temperature or moisture stress on trees; there have been increases in tree mortality around the world from drought and increasing temperatures (Allen et al. 2010; Williams et al. 2010). This of course is related to productivity, but not entirely. Extreme climate events, such as late growing season frosts and high winds causing blowdowns, may increase because of the predicted increases in climate variability (Notaro 2008), and these events may cause *catastrophic mortality* events (Joyce et al. 2014). There will also be disruptions in *phenology* as climates change; many plants may experience major damage or mortality as phenological cues and events are mistimed with new climates (e.g., flowering occurring during dry portions of the growing season) (Cayan et al. 2001). Another related mode is the *genetic* limitation of the species or tree to respond to climate change (Hamrick 2004); specialists may become maladapted to new climates (St. Clair and Howe 2007). Lastly, plants can respond to climate-mediated changes in *disturbance* in myriad ways (Aitken et al. 2008). This section only deals with those causal mechanisms that drive direct climate responses; the indirect climate-mediated disturbances responses are detailed in a later section.

Direct impacts of temperature on plant growth may increase both photosynthesis and respiration (Waring and Running 1998). Plant photosynthesis rates increase with temperature up to an optimum and then decline thereafter, with the optimum being species-dependent. If projected temperatures exceed the photosynthetic optimums for NR tree species, such as those in the lower elevation NR forests, then plant growth might suffer. However, there may be many portions of the NR where temperature increases probably will not exceed optimums, and there may be photosynthetic gains, such as in montane and

subalpine areas. This, of course, depends on whether sufficient water is available to support increased photosynthesis. Respiration also increases with temperature, thus photosynthetic gains may be lost through growth and maintenance respiration. Respiration occurs even when stomata are closed, so high temperatures coupled with low water availability may result in high respiratory losses with few photosynthetic gains (Ryan et al. 1995).

Increased atmospheric CO₂ levels may also directly modify ecophysiological growth processes. Oxygen and carbon dioxide compete for active Rubisco (primary enzyme used in photosynthesis) sites. Higher atmospheric CO₂ concentrations may increase internal leaf CO₂ concentrations, thereby ensuring CO₂ reaches most of the Rubisco sites, resulting in photosynthetic increases of 2 to 250 percent depending on site and species (Ehleringer and Cerling 1995). Conifers may also experience increased water use efficiency (WUE) in future water-limited environments, and increased WUE may compensate for decreases in water availability and increase growth rates in water-rich environments (Waring and Running 1998). WUE is the ratio of water used for plant metabolism (photosynthesis and respiration) to the water lost to transpiration. With higher CO₂ concentrations in the atmosphere, the plant would obtain more CO₂ during the time the stomata are open, resulting in less transpiration losses. Leaf biomass is usually the first to increase as plants attempt to optimize photosynthesis by growing more photosynthetically active tissue (i.e., more leaf area). However, increases in leaf area index are often transitory and greatly dependent on available nitrogen and water variability. Interestingly, increases in leaf area might also result in greater rainfall interception, higher snow collection, greater canopy evaporation, and shadier forest floors that might heighten forest soil aridity. It is also postulated that elevated CO₂ levels will change root to shoot ratios, with more aboveground biomass and fewer roots due to higher photosynthesis and WUE (Chmura et al. 2011). Increased atmospheric CO₂ levels and increasing temperatures can also interact to increase growth. Photosynthesis has temperature optima that are different among tree species and warmer temperatures might be closer to the new temperature optima, especially during the cooler early growing season, perhaps resulting in faster growth.

Another major direct effect of warming temperatures is longer growing seasons (Cayan et al. 2001; McKenzie et al. 2008); that is, increases in temperatures often lengthen growing seasons for forest plants. There are concerns that future climates are projected to be highly variable, and the coupling of highly variable daily weather with highly variable growing seasons may increase the chances that plants will be more susceptible to adverse weather during fragile phenological stages (Hanninen 1995). Warm conditions in the early spring, for example, might stimulate bud burst and early growth, only to have these expanding tissues frozen by subsequent frost events. Plant phenological cues may be disrupted or triggered inappropriately because of high weather variability, and while this variability might result in minor damage for mature individuals, it may be fatal for seedlings. This may be especially true in localized frost pockets and narrow valleys that accumulate cold air, resulting in frequent frost during the early growing season. Warmer temperatures may reduce and perhaps eliminate growing season frosts in mountain valleys, thereby allowing more frost-susceptible species, such as ponderosa pine and western larch, to exist in traditional lodgepole pine, subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*) habitats. Chmura et al. (2011) note that increased temperatures may result in decreased winter chilling that could result in delayed bud burst, reduce flowering, and seed germination. Winter dormancy prevents trees from growth flushes during warm winter periods, and future climates may trigger changes in winter dormancy and subject trees to high mortality during those cold snaps after the winter warming.

Snowpack dynamics are also directly influenced by changes in temperature and precipitation and declining snowpacks are expected under future climates (Mote et al. 2005). Since most of the water used by NR trees usually comes from snowmelt (Waring and Running 1998), the amount and duration of snowpack have the potential to influence regeneration and growth patterns of forest communities throughout the NR. Warming temperatures may cause earlier snowmelt, leading to an earlier start of the growing season. However, earlier snowmelt could also result in longer periods of low soil water during the remaining part of the growing season, effectively shortening the growing season. Earlier snowmelt may also result in greater competition for water across the plants and species that comprise the complex

plant communities of the NR. Plants with roots in the topmost layers of the soil might be able to more effectively capture the rainfall that used to occur as snowfall. This may favor grasses and some forbs over shrubs and trees (Daly et al. 2000). The lower snowpack may allow longer growing seasons in those subalpine and upper subalpine communities where cold and snowpack duration govern tree regeneration and growth; production and regeneration will likely increase with decreasing snowpacks, especially in those high mountain environments where water is rarely limiting.

An indirect effect of climate change will be the shift in distribution of microsites that facilitate tree regeneration (Jones 2013). While effects of climate change at coarser scales mostly relate to tree growth and mortality, changes to microsite conditions will likely govern tree regeneration (Petrie et al. 2016). Microsites suitable for tree regeneration must be addressed in a spatial and temporal context; suitable conditions for tree establishment may be suitable all year on small microsites of up to 1.2 square-yards, for example, while larger microsites may only be conducive for regeneration during the spring. Researchers in Washington State found that even with major changes in climate, there probably will be ample microsites that are suitable for regeneration of trees (Little et al. 1994). In the NR, however, projected climate changes will probably result in smaller and more ephemeral microsites for regeneration, and it could be that the size, distribution, and duration of suitable microsites will vary more each year and most regeneration will only occur during “wave” years (i.e., years with favorable weather conditions) where plentiful suitable microsites are widely available for long periods of time (see next section).

Climate change can also indirectly impact vegetation by altering mycorrhizae dynamics (Amaranthus et al. 1999). Nearly all NR conifers depend on mycorrhizae for enhanced water use and nutrient absorption. Even whitebark pine, a species that lives in areas with the highest precipitation in the NR, enjoys a mutualistic relationship with several species of fungi (Mohatt et al. 2008). Many trees, particularly those in the seedling and sapling stages, need mycorrhizae to survive, especially in areas of periodically severe water shortage (Walker et al. 1995). The migration of NR tree species to more favorable sites in future climates may be entirely governed by the ability of the mycorrhizae to also populate these areas to allow or facilitate tree species establishment (Lankau et al. 2015). Allison and

Treseder (2008) found warming increased fungal interactions, but drying caused significant decreases. Without viable populations of mycorrhizae, tree species movement might be significantly slowed or stopped. New microsite conditions created by predicted future climates may be inhospitable to mycorrhizae, but so little is known about how these fungi shift with climate that it is difficult to evaluate how they will respond to climate change (Fitter et al. 2000). However, mycorrhizae responses to climate change after increased fire may be more important; fire may reduce the fungi in some areas. This may be especially true if the large, severe fires projected for the future actually occur (Stephens et al. 2014). Severe fires may kill all trees in a large burn, thereby eliminating the host for the mycorrhizae, and perhaps eventually the mycorrhizae itself. Establishment of trees into these burned areas can be delayed for long periods, decades or even centuries, as both mycorrhizae and trees revegetate the area together (Schowalter et al. 1997).

Perhaps the most important future indirect ecological concern is the role of today's forest conditions and how they affect the ability of tree species to respond to future climate change. Ample research has shown that past and future human land use activities often result in ecological impacts that overwhelm any direct or indirect climate change effects (Moritz and Agudo 2013). Nearly a hundred years of fire suppression activities have resulted in increased tree regeneration and denser forest canopies, coupled with increases in duff, litter, and downed, dead woody fuel (Arno 1998; Ferry et al. 1995; Keane et al. 2002). Trees in these dense forests are in greater competition for the little water that is available for growth, along with light and nutrients. As a result, trees in many fire-excluded stands are stressed, making them highly susceptible to mortality from secondary stressors, such as insect and disease outbreaks (Anderegg et al. 2012; Wikars and Schimmel 2001), drought (Allen et al. 2010), and fire (Hood et al. 2007). Increased tree densities may also foster increases in severities of subsequent disturbances, resulting in more individuals dying and creating larger patches of mortality.

Another ecological concern closely related to fire exclusion is the current climate-mediated decline in forest communities that have recently become established as a result of fire exclusion. Some forests in the NR, including the limber pine (*Pinus flexilis*) communities along the Rocky Mountain Front, became

established during the fire exclusion era but may now be declining in some portions of the NR because of increased drought. Other NR forests, such as ponderosa pine, now have atypical forest compositions and structures due to the century of fire exclusion, and these now denser forests are stressed from both overcrowding and climate change (Millar et al. 2007b). Had fires been allowed to burn, there would probably be significantly less mortality, either from climate change or disturbance, as compare to what we are experiencing today, and the mortality levels probably would not be projected to be as high in the future (Holsinger et al. 2014). Moreover, there are areas in the NR where trees have encroached into dry grasslands (Arno and Gruell 1986), montane meadows, and subalpine forb fields (Butler 1986). Now, due to increased temperatures and decreased water availability, some of these recently established trees are now dying. Examples include the limber pine expansion along the Rocky Mountain front (Taylor and Sturdevant 1998), Douglas-fir encroachment into dry prairie (Arno and Gruell 1986), and subalpine fir into GYA forb fields (Bigler et al. 2005). There is concern as to whether climate change represents a threat to these modern forest types that were probably rare in the historical record. Does increased vulnerability in 100-year-old limber pine forests really constitute a management concern? Or is the increase in mortality expected because the forests established in wet periods of the fire exclusion era?

Many forest species in the NR may respond to direct climate warming and drying by expanding their range into new habitats. Migrating to a new site has historically been the main response of plants to climate change (Huntley 1991). Migration requires that the species have the ability to quickly occupy newly desirable sites of the future before other species get there or outcompete other species once they are there. Neilson et al. (2005) detail four basic components of migration (moving to a new site): fecundity, dispersal, establishment, and growth. To be successful in the future, a species must produce enough seeds or propagules (*fecundity*) that are easily dispersed to new sites (*dispersal*), and the seedlings that become established on these sites must be able to grow (*establishment*) so that they can also produce ample propagules that are then dispersed even further (*growth*). But, as Davis et al. (2005) note, the species also has to have the genetic capacity to migrate to the new climate and survive into maturity. Adapting *in situ* can take many forms, by reducing leaf area to minimize transpiration losses, or by surviving perturbations

in the new disturbance regimes created by climate change. Most NR tree species are long-lived and genetically plastic so that they can survive the wide fluctuations of weather in the future, but the ability to handle both deep drought and modified disturbance regimes may be the most important factor dictating future distributions of forest species (Allen et al. 2010).

It is widely thought that warming climates will result in upward shifts in the elevational distribution of plant species. For example, Lenoir et al. (2008) found that some plant species have moved upward in elevation at a rate of 31.7 yards per decade. However, it is unclear whether such elevational shifts will drive long-term changes in forest communities, or if other predominating forces will outweigh these upward trends. For example, fire plays a dominant role in most NR ecosystems, determining landscape structure and processes. Since even more extensive wildfires are expected as climates change, effects of these large events may overwhelm any shifts in distributional ranges of forest species resulting from climate warming. Also, most plants in the NR have slow migration rates, mostly because they are adapted to fire and as such rely more on regenerative organs (e.g., sprouting) than seed dispersal. Finally, implications of an upward elevational migration on forest communities need to be considered within a temporal and spatial context. That is, it may take a century or two for tree species to demonstrate significant elevational shifts due to their long life cycles, old maturation ages, highly variable weather, and low dispersal potentials. The potential for tree species to migrate may be entirely different in each of the unique mountain ranges in the NR area, depending on a host of abiotic and biotic factors (e.g., precipitation levels, invasive species) and available colonizing species.

Most projections for the response of vegetation to climate shifts are for populations of species, not for communities. Little is known about how composition and abundance of biota will change at a community level in response to climate shifts. Will new plant communities be dominated by generalist species that can exist across a wide variety of biophysical settings? Or, will future communities be similar to historical analogs where fire-adapted species dominate? Will future communities be composed of species collections that were historically rare? Answers to these questions have important implications for future land management in that there is a great deal of synergy between plants and species in historical

communities, such as interacting via root-grafting, sharing mycorrhizae, and relying on common pollinators, and future community composition may not have as many interactions. Moreover, future communities may not be as diverse because they may be dominated by a limited suite of species.

Climate change can impact important phases of the life cycle processes of plants: reproduction, regeneration, growth, and mortality. Moreover, it can impact plants at various scales from the needle to the tree to the forest, and over seconds to days to years to centuries (Eamus and Jarvis 1989). The following sections detail possible climate change effects by life cycle processes.

Reproduction

Cone and seed crops for many NR trees could be both adversely and beneficially affected by climate change (Ibanez et al. 2007; LaDeau and Clark 2001). Low elevation, xeric forests might experience fewer and smaller cone crops because of increased stand density and water stress. Cone crops might also have a lower percentage of viable seed because of increased tree stress. The infrequency of cone crops coupled with low seed numbers may result in the lack of regeneration in recently burned areas, thereby causing a shift to non-forest vegetation.

The opposite might be true in higher, colder environments where increased temperatures will increase growing season length and thereby increase potential for more cone crops with greater number of seeds. Spruce-fir communities might produce so much seed that they may overwhelm regeneration of other conifers, especially after mixed-severity fires. Subalpine pine species such as whitebark and lodgepole pine have unique cone characteristics (whitebark pine cones facilitate bird dispersal, while lodgepole pine cones may be serotinous and opened only by fire), so they may need to rely on disturbance for increased cone abundance.

An indirect result of the interaction of fire, vegetation, and climate is that as fire becomes frequent, some species, primarily trees, may be killed by fire before they reach reproductive maturity and fail to set cones. Holsinger et al. (2014), for example, found that future fires were so frequent in a western Montana watershed that lodgepole pine seedlings were killed by fire before they were reproductively mature (around 15 years). Keane et al. (1990) found that ponderosa pine forests needed occasional inter-fire

periods to be greater than 35 years to allow pine seedlings to grow above the lethal scorch height. If fire is too frequent, plants will not be able to grow to reproductive maturity or the reproductive organs might always be scorched by fire.

Climate warming and increased variability will also affect the phenology of cone crops, but impacts may be minimal as plants adapt to new conditions. Some predict higher frost mortality of emerging cones due to an earlier onset of the growing season coupled with high daily temperature variability and lower flowering and seed germination because chilling requirements will not be met (Chmura et al. 2011). Others suggest that frequency and abundance of cone crops will be reduced in the future because of high tree stress from drought (Ibanez et al. 2007). However, the increased productivity projected for many NR forests may overwhelm minor losses from extreme weather events over the long run.

With changing climate, some tree species might be restricted from their current range because warmer temperatures may not allow chilling requirements for the seed (Shafer et al. 2001). The chilling requirement was a major evaluation factor in determining climate change vulnerability in Devine et al. (2012). Similarly, new climates may be asynchronous with many tree species' phenology. Seed dispersal, for example, may occur at the driest or warmest times. Phenological keys may be out of sync with new climates, especially in a highly variable future, resulting in reduced flowering, growth, and reproduction. Interestingly, these phenological mis-cues may also occur in disturbance agents; highly variable weather may result in occasional deep frosts that kill beetle larvae, for example.

Regeneration

The life cycle phase where tree species are perhaps most susceptible to shift in climate is regeneration (Solomon and West 1993). Most tree species in the NR reproduce by producing seeds that fall to the ground to germinate and then grow into seedlings that then become mature trees. Microsite conditions needed for successful establishment are so demanding that seed germination and survival, especially for seeds that are wind-dispersed, is rarely successful (Anderson and Winterton 1996). The successfully germinated seed produces a fragile radicle (embryonic root) that must penetrate the litter, then duff, then soil to put down a root system that will eventually feed the growing aboveground tissue. This penetration

process demands moist soil conditions or the radicle and associated cotyledon (developing leaves) and hypocotyl (stem) will dry and die. To succeed in becoming a seedling, suitable moisture conditions must persist for long periods of time. Since few seeds become seedlings, many tree species often rely on high seed production to overcome mesic site conditions to ensure successful regeneration; by producing millions of seed, hopefully some will land on moist microsites suitable for establishment. For dry xeric forests, most of the successful regeneration occurs in those wet years when soils are moist for a suitable time and solar insolation does not kill developing leaves and stems. These moist years are often called “wave” years, and the pulses of regeneration that occur in these years results in even-aged patches. Projected climate change will likely decrease the frequency of these wave years, and on the driest sites, the frequency of wave years may be so low that no regeneration may occur, depending on the species. Planting on these newly dry sites may also be ineffective because of the short window of high soil moisture.

At the highest elevations, where the depth and duration of snow cover often governs tree regeneration, regeneration may be enhanced by warming. Most years are moist enough for regeneration at high elevations, but snow remains on sites too long for successful regeneration in many years. With warming temperatures, snow will likely melt earlier, giving more time for seedlings to survive and grow. Previous warm wave years in upper subalpine ecosystems are often dated using seedling and sapling tree ages. Recent observations of invasions of subalpine meadows and balds by subalpine fir, alpine larch (*Larix lyallii*), and Engelmann spruce is testimony of the high number of sequential warm years over the last decade that have facilitated high mountain regeneration (Butler 1986). Therefore, climate warming is expected to enhance regeneration at the subalpine and upper subalpine forest ecosystems.

Future climates and their high variability may also impact the ability of forest species to successfully germinate. Seed chilling requirements may not be met during mild winters, thereby reducing germination, and it could be that germination will be delayed to the driest parts of the growing season. Nitschke and Innes (2008) found that the chilling requirements were not being met for the majority of low elevation

tree species in British Columbia. Soil temperatures may be too high, causing greater mortality of both germinants and established seedlings (Rocheffort et al. 1994).

Climate change may also affect the dispersal properties of the reproductive propagules. Rodents that disperse seeds of ponderosa and western white pine, for example, may migrate or decline because of warmer, drier habitat conditions. Whitebark pine is dispersed by the Clark's Nutcracker (*Nucifraga columbiana*) that might shift habitats because of climate-mediated changes; nutcrackers usually nest in high elevation areas with ample snowpack (Tomback 1998), and these nesting habitats are predicted to decline in the future (Westerling et al. 2006). Longer and drier summers and autumns also mean that seed dispersal may take place when the ground and litter is the driest and least hospitable for seed germination and establishment (Neilson et al. 2005). Human- and ungulate-mediated seed dispersal of exotic species could also be different in future climates; warmer, drier climates might reduce human and ungulate use to lower exotic seed dispersal. Changes in landscape spatial heterogeneity may also influence mechanisms of non-wind seed dispersal by shifting potential seed sources and changing patch sizes.

Growth and Mortality

It is possible that there will be increases in productivity in some NR forests with warming climate, resulting in increased vigor and more resistance to stressors (Joyce 1995). Worldwide, Lin et al. (2010) compute increases in biomass of over 12 percent (20 percent in forests) with climate warming. However, Chmura et al. (2011) note that even with increased productivity, most forests will experience reduced growth and survival as the climate interacts with the entire tree species life cycle.

Climate can adversely impact growth and mortality in a number of ways (Bugmann and Cramer 1998; Keane et al. 2001). Projected decreases in water availability may result in shorter effective growing seasons and longer periods of continued drought in the drier NR forests (Williams et al. 2010). Longer drought might require NR conifers to close stomata longer to conserve the little water available. Some xeric conifers, such as ponderosa pine and limber pine, have excellent stomatal control and are able to remain closed for long periods of time. Other conifers, such as Douglas-fir, have poor stomatal control, and this may drive leaf water potentials to extremely low values that might result in intercellular

cavitation, tissue damage, and perhaps plant mortality (Sala et al. 2005). The projected increased temperatures will increase both maintenance and growth respiration, especially during the periods when stomata are closed, and this will require additional photosynthetic gains to counterbalance respiration losses, thus demanding even more water in a drier future. If photosynthetic production cannot exceed respiration demands, then the plant becomes stressed, thereby increasing the probability of mortality and susceptibility to insects and disease.

In the most mesic and montane ecosystems, it is likely that a warming climate will enhance growth and decrease mortality. Wu et al. (2011) found increases in plant growth for many forest and rangeland ecosystems with warming worldwide. Earlier growing seasons with ample moisture, such as that predicted for mesic montane NR forests, will likely result in increased productivity and greater growth. Although this increased biomass could result in additional foliar material to increase canopy bulk density and therefore result in higher crown fire potential, it could also result in higher growth rates for timber production and forage. This will be especially true in the higher mountain environments where cold temperatures, not moisture, limit tree growth. Longer, warmer growing seasons might result in higher productivities and greater biomass. The increased biomass will also increase competitive interactions between species, thereby favoring the more shade-tolerant individuals in the absence of disturbance. However, increased biomass could foster more intense fires, and maybe greater insect and disease outbreaks, such that the more disturbance-tolerant species might ultimately inherit the landscape.

Genetics Concerns

It is widely accepted that climate limits species distributions. Climate is also a major environmental factor affecting plant phenotypes and a critical agent of natural selection, molding among-population genetic variation. Plant adaptations to local environments have often developed a clinal or continuous response to abiotic and biotic factors such as temperature, frost-free periods, precipitation, fire, insects, and disease. More recently, a wider appreciation of ecotypic or a discontinuous response to environmental gradients is being recognized based on different soil or edaphic properties. The combination of clinal and

ecotypic environmental gradients across the landscape enhances or limits plant survival and long-term persistence.

A plant's hardiness is determined by its genetic background. Ecological genetics or genecology is a field of study investigating a species genetic architecture, phenotypic plasticity and adaptive capacity in the context of interactions among and between plant populations and environmental gradients. Ecological genetics and common garden studies are employed to study individual species. Well-designed common garden studies provide information on a species' adaptive strategy (e.g., generalist, intermediate, or specialist; table 6.1) (Rehfeldt 1994). Processes that shape a species' genetic architecture include natural selection, migration, genetic drift, and its mating system. Thus, the ability of plant populations to respond to climate change is influenced by the underlying patterns of genetic variation.

Molecular markers can reveal significant genetic diversity and divergence among populations associated with variation among populations (table 6.1). Past historical events shaping divergence among populations can be shaped by fire, volcanic activity (e.g., range shifts east of the Cascades indicated ponderosa pine was replaced with lodgepole pine, and later repopulated by ponderosa pine after the Pleistocene [Hansen 1942, 1947, 1949]), glaciation (Hamrick 2004), seed dispersal agents (whitebark pine, limber pine, and ponderosa pine) (Lorenz and Sullivan 2009), and pollinator history. Plants that are insect-pollinated or rely on animal-dispersed seed are more vulnerable to climate change because of the requirement for interaction with another organism.

Genetic diversity imparts a species' ability to adapt to changing environments, colonize new areas, occupy new ecological niches, and produce substantial and robust progeny that persist in the long term (Ledig and Kitzmiller 1992). The entire species does not adapt to environmental change over time, but populations within a species do. Genetic diversity is important to species ability to colonize new areas and occupy new ecological niches (USDA 2006). Species and populations of plants most vulnerable to climate change are rare species, genetic specialists, species with limited phenotypic plasticity, species or populations with low genetic variation, populations with low dispersal or colonization potential, populations at the trailing edge of climate change, populations at the upper elevational limit of their

distribution, and populations threatened by habitat loss, fire, disease or insects (Spittlehouse and Stewart 2003; St. Clair and Howe 2011). The underlying assumption regarding forest and rangeland species is as climate continues to change, populations will become poorly adapted to their local climates, whereby poorly-adapted populations will become stressed. A species ability to respond to environmental change is closely tied to its adaptive strategy and the mechanisms that shape its genetic structure, thus this assumption may be false. Some species such as Douglas-fir, juniper (*Juniperus* spp.) and sagebrush (*Artemisia* spp.) may show range expansion in the future (Hansen and Phillips 2015).

Historical gene flow (seed and pollen movement) creates patterns of genetic differentiation that may allow some populations to be more predisposed to respond to climate change than others. Fragmentation is a critical issue for plant populations because isolation and a relatively few number of individuals can promote inbreeding and loss of genetic diversity (Broadhurst et al. 2008; Potter et al. 2015). Information from this field also informs research and management of each species' adaptive capacity and vulnerability to climate change (i.e., its direction and magnitude). Gene flow from adjacent populations that are more typical of future climates have the ability to increase the rate of adaptation by introducing genetic variation that is pre-adapted to warmer or drier climates (Aitken et al. 2008). A practical application of this field of study facilitates evaluating options for responding to environmental gradients and climate change, for example choice of the appropriate population or seed source to increase the likelihood of attaining a desired reforestation, restoration or revegetation outcome.

The majority of species may not be able to adapt quickly enough to keep pace with projected migration rates of 328 to 3280 ft y⁻¹ with climate change (Davis 1989; Malcolm et al. 2002). Davis and Shaw (2001) and Davis et al. (2005) suggest plant adaptation may be a more important factor in response to climate change due to the slow rates of plant migration impeded by population fragmentation as a result of land use patterns. Where Hamrick et al. (1992) and Hamrick (2004) suggest that long-lived species with high levels of genetic variation are well-positioned for climate change, Etterson and Shaw (2001), Jump and Peñuelas (2005), and Parmesan et al. (2006) argue the ability of forest trees to adapt or

migrate and follow climatic shifts may be *restricted* by their long life spans, long generation intervals and long juvenile phases.

Long-lived or perennial species often maintain high levels of genetic variation and gene flow, which facilitates their ability to evolve in response to changing climates (Hamrick 2004; Hamrick et al. 1992). Whitebark pine is an example of a long-lived species with high levels of genetic variation (Mahalovich and Hipkins 2011) and extensive gene flow (Richardson et al. 2002) attributed both to long distance seed caching by Clark's Nutcracker and an outcrossed mating system involving wind pollination (Richardson et al. 2002). Since plant populations are genetically adapted to local climates, the climatic tolerance of individual populations is often considerably narrower than the tolerance of the entire species.

Existing knowledge of the adaptation of NR plant species is well documented for conifers (Rehfeldt 1994) but incomplete or lacking for other native plants. A species does not necessarily have *one* adaptive strategy, though most do. Differences in adaptive strategy can be characterized by varietal differences (e.g., *P. ponderosa* var. *ponderosa* or Rocky Mountain ponderosa pine [*P. ponderosa* var. *scopulorum*]), changes in elevation and geography. For example, *P. ponderosa* var. *ponderosa* is characterized as having an intermediate adaptive strategy; however, at high elevations (>5,000 ft), ponderosa pine has a specialist adaptive strategy. Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) is characterized as having a specialist adaptive strategy (i.e., its genetic variation is organized into numerous local populations, finely tuned to site-specific gradients); however, at higher elevations east of the Continental Divide, Douglas-fir has a generalist adaptive strategy (i.e., its genetic variation is organized into one or a few populations capable of surviving, growing and reproducing over a broad range of environments) (Rehfeldt 1989). Species possessing a generalist adaptive strategy are proposed to fair better than their intermediate and specialist counterparts with respect to climate change.

Other native plants' (e.g., shrubs, forbs, grasses, and sedges) patterns of adaptive variation are more complex, being both clinal and ecotypic, involve multiple life forms (e.g., annual, biennials, and perennials) and different ploidy levels (multiple copies of DNA, 4X, 6X, 8X, etc.) where 2X is the base level where one copy of DNA is inherited on both the maternal and paternal sides. Grasses are

hypothesized to be largely generalists and less vulnerable to climate change; however, ecotypic variation can overlay the generalist adaptive strategy. Forbs are largely insect-pollinated and coupled with longer growing seasons and changes in phenology and are more vulnerable to climate change.

Soil Responses

Each soil in the Northern Rockies has an inherent ability to produce vegetation based on climate, parent material, topography, soil biology and soil development (Armson 1977). Soil supports production of vegetation through interactions of nutrient cycling, soil hydrology, soil biology, physical support, and filtering (or buffering) (Attiwill and Leeper 1987). Amount of soil organic matter (quality and quantity), moisture (season and amount), temperature, and acidity may all be affected by climate change and ultimately affect functional properties of soils and perhaps productivity (Bonan 2008).

Climate change affects the growth, mortality, and decomposition of vegetation, which in turn impact soil biology (Waring and Running 1998). Warmer temperatures, increased CO₂, and longer growing season contribute to higher vegetative growth. Warmer temperatures, increased drought, and greater susceptibility to insects and disease may lead to increased mortality. Although higher temperatures will increase decomposition rates, the moisture required for decomposition may increase or decrease, leading to variable changes in decomposition rates (Davidson and Janssens 2006). Decomposition will increase with a combination of warmer temperature and higher moisture, whereas decomposition will decrease if summer droughts extend later (Rustad et al. 2000). Increased fire frequency and would generally reduce soil organic matter across large landscapes (Dooley and Treseder 2012).

Higher air temperatures will directly increase soil temperature. Increased vegetative cover would provide dense shade, thus decreasing soil temperature, whereas decreased vegetative cover would result in more heating at the soil surface. Dry soil, which is expected to be more common during future drought, would have wider temperature fluctuations than wet soil, which is buffered by the high heat capacity of water. In addition, if snow cover is lower but extreme cold periods continue to occur, soils will experience lower minimum temperatures (Davidson and Janssens 2006).

The vulnerability of soils to future climate change is summarized in table 6.2. Effects will differ greatly, depending on local soil characteristics, the magnitude and trend of climate change, and vegetation response.

Stressors – Biotic and Abiotic Disturbances

A warming climate will rarely be the direct agent of change for the NR tree species and communities. Most of the changes in vegetation will likely be a result of responses to disturbance or some combination of other stressors to climate change (Keane et al. [in press]). Climate change has marginally to severely altered disturbance regimes in the western U.S. (Liu et al. 2011). As we consider past climate variability and then add the projections in temperature and precipitation, there may be significant changes occurring across NR forests because of a changing water balance and the role of disturbances such as wildfires, insects and diseases. Whether it is invasive species (e.g., white pine blister rust), drought, uncharacteristic wildfires, elevated native insects and disease levels, loss of historically fire-adapted tree species, unusually high forest densities compared to historical conditions, or some other combination of disturbance agents that serve to stress trees and forest ecosystems, recent research suggests that climate change will likely further exacerbate those stressors and “stress complexes” (Iverson and McKenzie 2013). The following sections present a short summary on four major classes of stressors important in the NR. More detailed summaries of disturbance responses and their interactions to climate change are presented in chapter 8 of this report.

Wildland Fire

Wildland fire is pervasive throughout NR forest ecosystems and was historically the dominant landscape disturbance in the region (Baker 2009; Barrows et al. 1977; Wellner 1970). Fire exclusion since the 1920s has disrupted annual occurrence, spatial extent, and cumulative area burned by wildfires, resulting in increased surface fuel loads, tree densities, and ladder fuels, especially in low-elevation, dry conifer forests. Since climate change impacts to fire regimes are overlaid on a century of ecological changes to forest vegetation and fuels, observed differences between current fire patterns and historical ones are a product of management legacies as well as anthropogenic changes to climate.

Wildland fire regimes, defined by fire frequency, annual area burned, severity and pattern, are greatly influenced by variability in landscape environmental conditions including vegetation distribution, climate, weather, and topography (McKenzie et al. 2011). Climate and fuels are the two most important factors controlling patterns of fire within forest ecosystems. Climate controls the frequency of weather conditions that promote fire, whereas the amount and arrangement of fuels influences fire intensity and spread. These wildland fuels - the live and dead biomass that burn in fires - lose moisture and become flammable in the region's typically warm and dry summers, during which there are ample sources of ignition from lightning strikes and humans. Therefore, the active fire season (period conducive to active burning) is in the summer, typically from late June through October, with shorter seasons at higher elevation sites where snowpack can persist well into July. Regionally, widespread fire years are correlated with drought (Heyerdahl et al. 2008). At landscape scales, topography can influence the spatial pattern of fire spread; for example, in dissected mountainous areas, topographic features (e.g., barren slopes) can form barriers to fire spread (Grissino-Mayer et al. 2004), but where drainages are aligned with prevailing winds, topography can facilitate the spread of large fires (Sharples 2009).

Compositions and structures of forests in the NR are strongly determined by fire history. In general, fire regimes vary along environmental gradients, with fire frequency decreasing and fire severity increasing with elevation. For example, at the lowest and driest elevations where forests are dominated by ponderosa pine, frequent surface fires historically consumed litter and dead wood and killed seedlings and smaller trees. Adaptive traits such as thick bark allowed mature ponderosa pines to survive many repeated fires over time and tree densities were kept low. As mentioned above, fire exclusion since the 1920s has increased surface fuel loads, tree densities, and ladder fuels, especially in low-elevation, dry conifer forests (Schoennagel et al. 2004). As a result, fires here may be larger and more intense, and may cause higher rates of tree mortality, than historical fire. In middle and higher elevation forests, however, where fires were historically infrequent because of relatively cold, wet conditions, fire exclusion has not affected the fire regimes (Romme and Despain 1989; Schoennagel et al. 2004). However, earlier onset of snow melt, predicted to occur with changing regional climate, will reduce fuel moistures during fire season,

making middle to high elevation forested systems flammable for longer periods of time (Miller et al. 2009). As these forested systems are not fuel-limited, fire occurrence and extents are likely to increase in the future (Littell et al. 2009, 2010; Westerling et al. 2006).

Insect Outbreaks

Regional insect activity and outbreaks, climate drivers, and potential climate change impacts to insect activity are also highly correlated with climate and will dictate future forest composition and structure. The mountain pine beetle (*Dendroctonus ponderosae*) is an integral component of forest ecosystem processes because of its role in stand thinning and redistribution of resources and nutrients important for tree regeneration. It is also recognized as an aggressive and economically important forest insect responsible for tree mortality across large areas (Logan et al. 2003). Both bark beetle populations and their host trees are being influenced by changing climate. Many bark beetle life history traits that influence population success are temperature-dependent (Bentz and Jönsson 2015), and warming temperatures associated with climate change have directly influenced bark beetle-caused tree mortality in some areas of western North America (Safranyik et al. 2010; Weed et al. [in press]). Host tree distribution across the NR, and tree vigor that influences susceptibility to bark beetle attack (Chapman et al. 2012; Hart et al. 2013), will also be influenced as climate continues to change. Future bark beetle-caused tree mortality will therefore depend not only on the spatial distribution of live host trees and heterogeneity of future landscapes, as described in this chapter, but also on the ability of beetle populations and their associates to adapt to changing conditions when existing phenotypic plasticity is surpassed.

Pathogens

Forest diseases are found in all forest ecosystems of the NR. They are one of three major disturbance groups that affect ecosystem development and change, yet impacts of forest diseases on various resources and services in the region are difficult to estimate. The major groups of forest diseases in the NR that impact ecosystems and ecosystem services are fungi and rusts (fungi that infects needles and causes damage and mortality, the most important being white-pine blister rust), dwarf mistletoes (*Arceuthobium*) (a group of parasitic seed plants that are widespread across the region and which mainly cause reduced

tree growth and productivity), root diseases (a major cause of growth loss and mortality), needle casts and blights (diseases that cause crown thinning and loss of lower branches), and abiotic diseases (damage to trees resulting from impacts of adverse environmental factors on tree physiology or structure).

Effects of climate changes on forest diseases are difficult to predict. Climate change can alter pathogens through direct effects on the development and survival of the pathogen, physiological changes in tree defenses, or indirect effects on the abundance of natural enemies, mutualists and competitors (Ayres and Lombardero 2000). These dynamics are not well-captured by GCMs, because pathogens' ecology and impacts are based on local site and environmental conditions. Epidemics also depend on local conditions for spread and infection to occur. Although models usually generate mean climatic conditions, it is often the extremes that have the greatest influence on pest conditions (Hepting 1963), and these are also not well represented by GCMs. However, modeling efforts to date suggest that among the major NR diseases, root disease is projected to cause the highest basal area loss as a percent of total basal area in the NR. Projected losses from root diseases ranged from zero percent on most national forests east of the Continental Divide to 15 – 19 percent on west-side forests (Krist et al. 2014). Klopfenstein et al. (2009) used a subset of GCMs to predict how the geographic distribution of the climate envelope for Armillaria root rot (*Armillaria solidipes*, formerly *A. ostoyae*) and Douglas-fir could change in the interior northwestern U.S. Their analysis suggests that Douglas-fir will have a considerably smaller geographic space that matches its current climate envelope and that this space will shift, while *A. solidipes* will experience only minor changes. They suggest that areas where Douglas-fir is maladapted could increase, which could increase its susceptibility to Armillaria root rot. Climate-mediated changes to forest tree diseases will be dictated by disease and host responses to new climates, and their interactions (Sturrock et al. 2010), and the interactions between biotic diseases, abiotic stressors, and host status will be drive future pathogen outbreaks. Predicted increases in temperature and drought will probably serve to increase pathogen populations in the future (Chakraborty et al. 2008). The roles of pathogens as important disturbance agents will likely increase in the future because they are able to migrate to new environments at a faster rate than trees.

4244 *Drought*

4245 Soil type and depth, aspect, and elevation all contribute to effective moisture availability for tree
4246 establishment and growth, producing patterns of forests in the NR study area. Additionally, the impact of
4247 stand condition on overall water balance and the effect of site and soil conditions on moisture availability
4248 are important to consider. The Montana Natural Resources Conservation Service (NRCS) and the Natural
4249 Resource Information System of the Montana State Library have mapped the relative effective annual
4250 precipitation (REAP) for the State of Montana (<http://nr.is.mt.gov/nrcs/reap/index.asp>). REAP is an
4251 indicator of the amount of moisture available at a location, taking into account precipitation, slope and
4252 aspect, and soil properties. For example, two sites that receive the same amount of precipitation may have
4253 different effective precipitation due to unique soil and landform factors at each site. Depending upon the
4254 geographic location within Montana and degree of slope, the actual precipitation for southerly aspects
4255 may be adjusted downward while northerly aspects may be adjusted upward.

4256 Future climate change models indicate that the NR will have longer, drier summers and warmer
4257 conditions. Pioneer (seral) species such as ponderosa pine have the unique ability to establish on bare soil
4258 surfaces where high surface temperatures (>149 °F) exclude other species. One of the adaptations of these
4259 seral species are deep rooting characteristics that allow the tree to find an adequate water supply and
4260 avoid extensive competition with shallow- and fibrous-rooted grasses and forbs. As the shade from these
4261 species limits sun-loving grasses and forbs, shade tolerant tree species establish and grow, and these
4262 species usually have a shallower rooting characteristic that allows them to gather soil water from the
4263 nutrient-rich soil surface. The overall rooting structure in essence becomes much more competitive as
4264 succession progresses. In addition, the overall leaf surface area that develops over time on a given site
4265 increases. Grass/forb and shrublands usually develop a maximum total leaf area of about 3.23 ft² per 1.08
4266 ft² of soil surface area. Forests can develop leaf areas in excess of 6.46 ft² per 1.08 ft² of soil surface area.
4267 With increasing leaf area comes increased water transpiration that can deplete the soil water storage
4268 capacity needed to keep trees hydrated throughout the summer. The additional canopy interception of rain
4269 and snow in dense forests, which directly evaporates back into the atmosphere, further compounds this

effect, reducing soil water recharge. The end result is a water-stressed forest that not only becomes more susceptible to insects and disease, but also more prone to supporting severe wildfires because live fuel moisture is relatively low.

CLIMATE CHANGE ASSESSMENTS

This section contains the information that was used to assess vulnerability for all tree species, vegetation types, and resources of concern. There are four subsections for each item (e.g., tree species) to detail the (1) ecology, (2) disturbance interactions, (3) current and historical conditions, and most importantly (4) potential climate change responses. The first subsection presents important ecological information needed to understand how a species, type or concern might respond to future changes in climates, such as its drought and shade tolerance. The disturbance interactions subsection contains information on those agents that impact that species, type, or concern, and important projections of how those disturbance agents might change in the future. Historical and current conditions are included as a subsection, because any climate change response is greatly dependent on current status and past actions. Lastly, the anticipated climate change responses for the species, types, and concerns are included in perhaps the most important subsection. This material was ultimately the basis for any evaluation of vulnerability or development of potential adaptation actions.

Most of the material in this section was taken from published literature, but there are also substantial amounts of anecdotal and observational information that was included for context. However, due to imperfect knowledge across the evaluated entities and the high uncertainty in climate predictions and ecosystem responses, we admit that many of our projected climate change responses and resultant vulnerability assessments are based on our own professional experiences. Moreover, some climate change response material may appear uneven across species, types, and concerns because some species, types, or concerns do not have the detailed information of others; more information is available for timber tree species than non-timber species, for example.

Tree Species

Most of the background information used in this section was synthesized from three primary sources. The Bollenbacher (2012) report presents characteristics of the major tree species of the NR, adapted from the autecological synthesis developed by Minore (1979). The commonly used silviculture reference edited by Burns and Honkala (1990) was used throughout, and the climate change report compiled by Devine et al. (2012) for the Pacific Northwest was also used for genetics and autecological information. Table 6.3 provides a general summary of important ecological and genetic characteristics by tree species that will be important under future climate change. In this section, we attempted to integrate the genetic, morphological, ecological, and disturbance response characteristics summarized in Table 6.3 to predict how a tree species would respond under future climate warming. We also integrated any material available in the literature to aid and support our predictions.

The climate change responses subsections were synthesized from information in the literature and the MC2 modeling results (appendix 6A) to evaluate the effects of climate change on important species, vegetation types, and resource concerns. These subsections are the foundation material to support our vulnerability assessments and the adaptation strategies and tactics. Many of these climate change responses are based on the species characteristics and current ecosystem condition presented in this section.

The most astonishing finding in this section is that the literature is inconsistent on the response of tree species to future climate change. Results from SDM modeling are often, but not always, different from most other sources that include gap modeling, mechanistic ecosystem simulation, and field data summaries. As a result, we put a lesser emphasis on the SDM results in our vulnerability assessment evaluations in appendix 6B. Another finding is that the amount of climate change really matters. Most climate change studies predict few species changes after moderate warming (e.g., the B1, B2, A1B, RCP4.5 scenarios), but major species shifts under the most extreme emission scenarios (e.g., the A1 and RCP8.5 scenarios). Third, the time frame used in the climate change study is also important. Management time frames of 10 to 50 years are not long enough to effectively evaluate changes in fire, beetles, and tree growth. Ecosystem response to disturbance takes time, often two to five times the disturbance return

interval. Lastly, the GCMs used to simulate and quantify climate change are incredibly important in understanding climate change study results and subsequent ecosystem responses. Some GCMs predict minor warming for the NR, while others predict major changes.

Based on a thorough review of the literature, we feel that there are basically three modes of response to climate change for the major tree species of the NR: modification, contraction, and expansion. First, the species could increase or decrease in productivity *in situ* within its current range due to increasing temperatures and adequate precipitation (*acclimatization*); for example, the majority of information seem to support that most lands in NR will increase in productivity (Aston 2010). Next, the species could die in those parts of its range where conditions will change enough to become inhospitable to that species (Allen et al. 2010) (*contraction*). Lastly, the species could migrate to areas that are more conducive for establishment and growth (Johnstone and Chapin 2003) (*expansion*). Any species can have multiple modes of response to climate change, and most species will respond to future climates via all three modes.

Application of these three modes to determine future species dynamics demands a thorough integration of variability and scale. For example, the ebb and flow of species migration demands a relatively long temporal scope to properly evaluate species range shifts (Prentice et al. 1991). A tree species could become established in a “new” environment made suitable by climate change, such as subalpine tree expansion into snow glades, but the great variability in climate may result in one year of drought or high snow that kills all established seedlings. Conversely, one year of drought could kill many individuals in the grassland-woodland ecotone, but several wet years in a row might facilitate reestablishment of tree species into the high mortality zone. Also, the rate of climate change shifts will be governed by disturbance, not competition, so disturbance adaptations will be more important than climatic niches. Management actions, such as fire exclusion, may facilitate species expansion into areas that will eventually burn, causing extensive mortality.

All of the climate change response evaluations in this chapter have a high level of uncertainty; they are essentially best guesses from a wide variety of resource specialists. The information in the following

section may provide a starting place, a possible prioritization, or assistance in addressing climate change in forest plans, but it is in no way accurate enough to provide valid predictions of what will happen in the future.

Limber Pine (Pinus flexilis)

Autecology

Limber pine is a shade intolerant, early seral to pioneer species in the NR (Steele 1990). Its seeds are dispersed by rodents, but more importantly, by a bird (Clark's Nutcracker) that will cache limber pine seed anywhere there is microsite pattern that they use for finding the seed (Lanner 1980; Lanner and Vander Wall 1980). Limber pine has difficulty in competing with other encroaching species on more productive mesic sites and is often succeeded by Douglas-fir and subalpine fir. There is often little to no reproduction once tree densities are below 25 trees per hectare, mostly because of the lack of an effective pollination cloud, and those seeds that are produced have increased likelihood of inbreeding. Moreover, a minimum of 25 cone-bearing trees per 2.47 acres is needed for dispersal by the Clark's Nutcracker (McKinney et al. 2009). This tree species is quite slow growing but long-lived, and some of the oldest trees in the NR are limber pine.

Limber pine is a puzzling species in the ecosystem land management context. It is a tree species that occupies xeric sites across a wide range of elevations (2600 to 8900 ft elevation) in the NR that are often marginal for timber production (Jackson et al. 2010). Historically, it was often found on the margins between grasslands and forest ecosystems at the lower timberline on fire refugia (Steele 1990). Since limber pine is easily killed by fire, the species was mostly found in fire-protected cove sites that experienced rare fires of low severity, such as rocky outcrops, barren areas, and moist north slopes (Steele 1990). In these lower timberline areas, limber pine is often associated with Douglas-fir, Rocky Mountain ponderosa pine, and quaking aspen (*Populus tremuloides*). On upland montane sites, it can be often found on limestone substrates and droughty soils, but in these areas it is associated with many other NR conifers, especially lodgepole pine, subalpine fir, and Engelmann spruce (Steele 1990; Langor 2007).

Limber pine seedlings are poor competitors with grass, but do well on rocky substrates and in shrub environments.

Limber pine is quite tolerant of drought and can become established and grow in some of the most arid environments in the NR (Steele 1990) (table 6.3). It is associated with both ectomycorrhizae and arbuscular mycorrhizae that facilitate its ability to exist in extremely dry environments. Seedlings are very drought tolerant but have a low tolerance for competition, especially from herbaceous plants.

Genetically, limber pine has high outcrossing rates with average genetic diversity and average population differentiation (Devine et al. 2012). The fundamental and realized niche for limber pine is very broad in the NR, indicating that this species has a generalist adaptive strategy with wide phenotypic plasticity.

Disturbance Interactions

As mentioned previously, limber pine's thin bark and low foliage make the species highly susceptible to damage from wildland fire. Limber pine is also highly susceptible to white-pine blister rust, and many communities are currently experiencing high mortality when the disease infects trees in a new region (Smith et al. 2013). Limber pine also facilitates the expansion of currant into traditional grasslands (Baumeister and Callaway 2006), thus increasing rust infections and mortality.

Other insects and pathogens are also impacting limber pine, but at a much reduced severity. Some have detected mortality from mountain pine beetle in parts of the species range (Jackson et al. 2010). Others have noted that limber pine stands on mesic sites may have severe dwarf mistletoe infections that could result in mortality levels similar to those observed from white-pine blister rust. Porcupine (*Erethizon dorsatum*) damage is also quite prevalent east of the Continental Divide.

Historical and Current Conditions

With fire exclusion, limber pine has expanded its range from fire-protected cove sites into areas where it was historically restricted by frequent fires (Arno and Gruell 1983; Brown and Schoettle 2008). As a result of the diminished fire activity and active nutcracker caching, limber pine has expanded into grass and shrub rangelands, and this expansion has also allowed other species to inhabit historical non-

forest areas (Jackson et al. 2010). It appears that limber pine can facilitate the establishment of other forest species, especially Douglas-fir, in rangeland settings (Baumeister and Callaway 2006). As a result, NR limber pine is currently occupying areas that were traditionally grasslands, and it is difficult to determine if this is inside or outside the range of variability of this ecosystem.

Ironically, the newly established limber pine forests throughout the NR are experiencing dramatic declines due to white-pine blister rust, mountain pine beetles, and red belt (Jackson et al. 2010; Langor 2007; Taylor and Sturdevant 1998). Increasing fires are also burning some of these stands that have become established after 1910. There is some white-pine blister rust resistance in the species, but it is low, perhaps lower than 1 in 100 individuals.

Climate Change Responses

Some anticipate that warming temperatures on the east side of the NR, along with increasing but more variable precipitation, especially during the growing season, and waning snowpack will result in increased growth in many limber pine communities (Aston 2010). Increases in vigor are usually accompanied by larger cone crops, higher seed viability, greater number of seeds per cone, wider seed dispersal, and greater resistance to disease. Increased seed dispersal includes both denser caching by birds and mammals, and probably more distant caching by the Clark's Nutcracker. Increases in vigor might also extend to limber pine's competitors, so there could be increased competition from wind-dispersed conifers, especially on the more mesic portions of limber pine's range.

Warm temperatures, even with increased precipitation, could also result in drier conditions, especially for seed germination and seedling growth. Even if there are more seeds cached by mammals and birds, the subsequent establishment of seedlings from the unclaimed caches might be low because of longer drought seasons and hotter ground temperatures. Any seed dispersal to new areas, especially non-forested stands, might have limited limber regeneration success because of the lack of ectomycorrhizal associations and increased competition from grasses and dense shrubs (Coop and Schoettle 2009).

Disturbance interactions with warming climates will likely be important to future limber pine dynamics. Increasing fire frequency and intensities may burn more limber pine stands, causing higher

mortality (Coop and Schoettle 2009). Increased fire may stem the encroachment of limber pine into grasslands in areas where grazing is low. Warmer, drier conditions may also reduce blister rust infection by disrupting the blister rust cycle, especially during the late summer when *Ribes* spp. to pine infection occurs, and there may be fewer “wave years” where temperature and humidity are optimal for pine infection by white-pine blister rust. Where precipitation is projected to increase, such as the eastern portions of the NR, there may be higher blister rust and dwarf mistletoe infections, and this may cause higher limber pine mortality. Continued fire exclusion could enhance currant facilitation under mature limber pines and result in even greater white-pine blister rust mortality. Warmer temperatures also favor expansion of alternate host species such as currant, lousewort (*Pedicularis*) and Indian paintbrush (*Castilleja*) (Keane et al. [in press]).

Limber pine has an intermediate genetic adaptive strategy under changing climates largely driven by timing of pollen cloud dispersal (elevational effect) and bird dispersal (Feldman et al. 1999). The species is highly adapted to populating the increasing burned areas projected for the future because of mammal and corvid-mediated dispersal (Lanner and Vander Wall 1980). If future fires are larger and more severe, there may be less competition from other competing conifers, especially in the eastern NR along the timber-grassland ecotone. Limber pine has moderate genetic variation (capacity) in blister rust resistance, but major gene resistance to blister rust has not been identified in several studies of interior populations. There is probably little to no opportunity to hybridize with western white pine due to non-overlapping species distributions, and it will probably not hybridize with whitebark pine because the two species only overlap on limestone substrates. There is a high risk of loss of disjunct and isolated populations due to genetic drift, ineffective pollen cloud, and substrate availability.

Given all available information, limber pine responses to future climates may be minor and governed mostly by wildland fire and white-pine blister rust. If fires increase, limber pine forests, some of which are already declining from rust, will see some major declines, especially in those places where they have encroached as a result of fire exclusion. Given its minor role in the NR prior to European settlement, we feel that this species is at most moderately vulnerable to climate change based on its high tolerance to

drought and ability to populate severe environments, but high susceptibility to the introduced white-pine blister rust and fire damage may put this species in peril.

Ponderosa Pine (Pinus ponderosa)

Autecology

Ponderosa pine shows distinct geographic variation over its range. The ponderosa variety (*P. ponderosa* var. *ponderosa*) ranges from the Fraser River drainage of southern British Columbia south through Washington, Oregon and into northern California (Oliver and Ryker 1990). In the NR, it extends from the Canadian border to the central part of Montana on the west side of the Continental Divide. Rocky Mountain ponderosa pine extends east of the Continental Divide to North and South Dakota and south into Wyoming and further. Within the wide range of both ponderosa pine variants, it is absent from several areas, including a large portion of southwestern Montana. This may be due to the lack of rainfall in the summer months, which prevents establishment except at higher elevations; however, it is also limited by the shorter growing season at these elevations.

In most of western Montana and Idaho, the upper elevational limit of the ponderosa variety is around 1500 m, depending on latitude (Pfister et al. 1977). Moisture is the factor most often limiting growth, especially in the summer. Seasonal rainfall deficiency is evident from July and August precipitation (Fowells and Kirk 1945; Tarrant 1968). The distribution of ponderosa pine on drier sites is closely related to supplies of available soil moisture, which is closely related to soil textures and depth. Low temperatures, however, may dictate the success of ponderosa pine regeneration; seedlings of the species are highly susceptible to frost damage and the occurrence of frosts often excludes the pine from low valley settings, especially in frost pockets and cold air drainages (Shearer and Schimdt 1970).

Ponderosa pine is a shade-intolerant, drought-adapted species of the low elevation, dry forests of the NR (Minore 1979) (table 6.3). It can be a climax species at the lower elevational limits of NR coniferous forests, or a seral species in the higher elevation mesic forests, especially the Pacific variety. In dry climax forests, there is generally a mosaic of small even-aged groups. As a seral species, it is often associated with Douglas-fir, lodgepole pine, grand fir, and in the northwest NR, western larch. Ponderosa

pine is mostly intolerant of shade, but it is generally more tolerant than western larch and less tolerant than grand fir and western white pine. While it reaches its greatest site indexes on the mesic grand fir, western redcedar, and western hemlock sites (Cooper et al. 1991), it is rapidly replaced by a suite of more shade tolerant competitors.

Ponderosa pine is a “drought avoider” meaning it tolerates dry soil conditions by efficiently closing stomata to avoid water loss and xylem cavitation and stay alive during deep droughts (Sala et al. 2005) (table 6.3). This allows the species to tolerate intense drought better than its associates, specifically Douglas-fir, because it is a “drought tolerator” and able to obtain water at lower moisture conditions. Drought tolerators attempt to draw ground water at such low soil water potentials that they might experience extreme xylem cavitation that may cause eventual death. Ponderosa pine has been associated with several species of ectomycorrhizae, giving it a high capacity to survive in dry environments.

Cone crop periodicity varies greatly with ponderosa pine; observations indicate it is a poor seeder west of the Continental Divide and a fair seeder east of the Divide. Throughout the NR, natural regeneration is sporadic; it is best when there is a heavy seed crop followed by favorable weather during the next growing season (Heidmann 1983; Shearer and Schmidt 1970). Potter et al. (2015) performed molecular work that indicates that Rocky Mountain ponderosa pine is one of the most inbred conifers in the NR, and its vulnerability could be further compromised with limited gene flow between populations. With cone crop periodicity or masting events that only occur every 7-10 years, there appears to be increasing natural regeneration problems on the east side. Soil texture, plant competition, and seedbed conditions have the greatest effect on seedling survival. Moisture stress reduces seed germination and limits seedling survival and growth. Competing vegetation deters seedling. As mentioned, young seedlings (<36 days old) are susceptible to cold night temperatures and deep frosts, and occasionally the pine trees suffer winter desiccation in drying winds. Older seedlings (>110 days) can often withstand higher temperatures than Douglas-fir, grand fir and Engelmann spruce, making it likely they will be more successful under future climates.

Ponderosa pine has a moderate potential for outcrossing with a high outcrossing rate. It has average genetic variation, but is weakly differentiated geographically. While it has a strong population differentiation, it may be considered to be intermediate in adaptive strategy because both individuals and populations may be suited to diverse environments. There are steep clines in elevation, but gentle clines in latitude and longitude. There is high genetic variation between east- and west-side ponderosa pine in growth, survival, needle length, season pattern of root growth, and ability to germinate under moisture stress (Oliver and Ryker 1990).

Disturbance Interactions

Fires have a profound effect on ponderosa pine where competing tree species are considerably less fire tolerant; this allows ponderosa pine to maintain dominance over large areas (Arno 1988; Steele et al. 1986). Fires historically allowed ponderosa pine to maintain its dominance across most of the low elevation savannas by killing competitors. Ponderosa pine has a great capacity to survive fire, better than nearly all of its competitors (Ryan and Reinhardt 1988).

There are around 108 species of insects that attack west-side ponderosa pine and over 59 species that attack east-side ponderosa pine. The most damaging of the tree-killing insects are several species of *Dendroctonus* Erichson, 1836 (Oliver and Ryker 1990). Among bark beetles, *Ips* species are second in destructiveness only to *Dendroctonus*. *Ips* are present naturally in all stands, where they usually breed in slash. Dwarf mistletoe is ponderosa pine's most widespread disease but is rarely fatal in the NR. Western pine shoot borer (*Eucosma sonomana*) is also a concern in the future.

Historical and Current Conditions

Ponderosa pine forests have been experiencing a severe decline due to the combination of logging and fire exclusion. Large pine trees in the open pine savannas were harvested from nearly all but the most remote, inaccessible, or protected areas in the NR. Wildland fires have been excluded from remaining pine forests, causing advanced succession that was most rapid in the mesic habitat types (Arno 1988; Gruell et al. 1982). This has resulted in dense forests with overstories of stressed pines and dense understories of its shade-tolerant competitors, most commonly Douglas-fir. There are often buildups of

duff and litter, and an atypical accumulation of downed dead woody fuels on the soil surface. The dense crowns, coupled with high surface fuel loadings, ensure that when these forests are burned by wildfires, the damage from the fire will be severe with high tree mortality, deep soil heating, high fuel consumption, and abundant smoke (Keane et al. 2002).

Climate Change Responses

We expect ponderosa pine in the NR to handle increasing temperatures and deeper, longer droughts with only moderate difficulty. Its ability as a “drought avoider” to close stomata when soil water potential is low make it one of the few forest species, besides juniper, that maintains its presence in many low elevation settings (Stout and Sala 2003). Morales et al. (2015) projected an 11 percent increase in range of ponderosa pine in the western U.S., and Nitschke and Innes (2008), using a gap modeling approach, projected the replacement of dry Douglas-fir dominated communities of British Columbia with ponderosa pine. Hansen et al. (2001) projected an expansion of ponderosa pine across the western U.S. and specifically in the Pacific Northwest, when most other tree species ranges were retracting in area. Rocky mountain ponderosa pine is more intermediate in adaptive strategy than the *ponderosa* variety and therefore has a high phenotypic plasticity and is better adapted to drought (table 6.3).

However, declining precipitation and variable spatial and temporal rainfall patterns may caused declines in ponderosa pine regeneration and range contractions, except in the eastern portion of the northern region where precipitation is expected to increase. Crimmins et al. (2011) estimated that ponderosa pine environments may rise over 700 m in elevation by 2050 in its range. Similarly, Gray and Hamann (2013) estimated ponderosa pine might move over 500 km northward and almost 300 m higher in elevation by 2050 in the NR. However, Franklin et al. (1991) projected future ponderosa pine forests will cover about a third of its current range in landscapes of the eastern Cascades, and Bell et al. (2014) projected losses of over 60 percent of its range by 2090.

Increases in mountain pine beetle outbreaks, advancing competition resulting from fire exclusion, western pine shoot borer occurrence, and increases in fire severity and intensity will dictate the future of ponderosa pine in the NR. If fires are too frequent, established regeneration will never grow above the

lethal scorch height, and mature individuals will not become established. Increasing fire severity and occurrence could also eliminate many of NR relict ponderosa pine trees that provide the critical seed sources for populating future burns.

Douglas-Fir (Pseudotsuga menziesii)

Autecology

Douglas-fir has been a major component of forests of western North American since the mid-Pleistocene era (Hermann and Lavender 1990). Only Rocky Mountain Douglas-fir (var *glauca*) is found in the NR. Its range extends from central British Columbia through the Rocky Mountains into central Mexico. The range is fairly continuous in northern Idaho, western Montana, and northwestern Wyoming, with several outlying areas in eastern-central Montana and Wyoming. In the NR, Douglas-fir grows in areas with maritime influence and mild climate in all seasons except a dry period in July and August. In the central Rocky Mountains, the winters are long and severe, summers are hot and in some parts very dry. West of the Continental Divide in the NR, the rainfall may be evenly divided between winter and summer. The altitudinal distribution of Douglas-fir increases from north to south, due to the effect of climate on the distribution. The limiting factors are temperature in the northern part of the range and moisture to the south. Thus, Douglas-fir prefers southerly slopes in the northern part of its range, and northerly exposures in the southern part of its range (Pfister et al. 1977).

Douglas-fir in the NR grows in pure stands on dry, cold sites, both in an even- and uneven-aged condition (Hermann and Lavender 1990). On other sites, the associated species are dependent on the climate, and by proxy, elevation and region. Montane, low elevation, mesic Douglas-fir is often associated with western larch, western white pine, grand fir, western redcedar, and western hemlock, while on low elevation, xeric sites, Douglas-fir is associated with ponderosa pine, juniper, and quaking aspen. At upper elevational limits, the species is often found with lodgepole pine, subalpine fir, and Engelmann spruce. It is rarely found at the highest elevations associated with mountain hemlock (*Tsuga mertensiana*), whitebark pine, and alpine larch. Most of the NR Douglas-fir forests are found on droughty sites, and the species is often associated with ponderosa pine; Douglas-fir is often the primary climax

species whenever it is found with ponderosa pine (Keane 1985; Ryker and Losensky 1983; Steele and Geier-Hayers 1989). Again, proportion of other species growing with Douglas-fir varies widely depending on aspect, elevation, soil type and past history, particularly fire history, of the area.

Regeneration is most successful where Douglas-fir is seral, especially in the area of strong maritime influence in northern Idaho and western Montana, where it is associated with more montane species (e.g., grand fir, western redcedar, and western larch). Regeneration is poor where it has attained climax status in the cool, dry habitats (Ryker and Losensky 1983). Seedling growth the first year is relatively slow, limited generally by moisture, which triggers initiation of dormancy in midsummer. Competing vegetation may promote the establishment of a variety of seedlings by reducing temperature stress, but may inhibit seedlings growth by competing strongly for moisture; this is most pronounced in the southern portion of the range. In the Rocky Mountains, it is a seral species in moist habitats and climax in the warmer, drier areas of its range.

In the interior portion of its NR range, Douglas-fir ranks intermediate in shade tolerance, being more tolerant than western larch, ponderosa pine, lodgepole pine, and aspen (Table 6.3). Old growth Douglas-fir shows a wide range of age classes, indicating it established over long periods after major fires. It is gradually replaced by more tolerant western hemlock, western redcedar and true fir on mesic montane sites. Douglas-fir tolerates drought better than nearly all of its competitors except for ponderosa pine. The species is a drought “tolerator” in that it keeps stomata open to extract soil water at extremely low soil water potentials, thereby subjecting it to potential xylem cavitation and potential death (Sala et al. 2005; Stout and Sala 2003).

The species exhibits a great deal of genetic differentiation, which is strongly associated with geographic or topographic features (Rehfeldt 1978). The pattern of genetic variation in growth and phenological traits among clines (ecotypes or forms of species that exhibit gradual phenotypic and genetic differences over a geographical area as a result of environmental heterogeneity) have been observed along north-south, east-west and elevational transects. There is evidence of low genetic variation within local regions. For example, in southern Oregon, seed collected on the more xeric southern aspects grew slower,

set bud earlier, and had larger roots compared to seedlings grown from north-facing slopes. Seedlings from seed sources on southerly aspects have adaptive characteristics for a shorter growing season and drier soils and may survive under drought stress better than seedlings from north-aspect seed sources.

Disturbance Interactions

Douglas-fir has a great capacity to survive fire because of its thick corky bark and its deep main roots. The species' capacity to form adventitious roots is another adaptation that has enabled Douglas-fir to survive fire. However, young Douglas-fir have thin bark and low height to live crown, greatly increasing mortality from fire (Ryan and Reinhardt 1988). Ponderosa pine and western larch have better ability to survive fire across all life stages, so on sites with frequent fires where Douglas-fir is associated with other species, its cover is usually kept low by fire (Agee 1991). However, on cold, dry sites where the species is the indicated climax, frequent fire may create Douglas-fir savannas, especially east of the Continental Divide and the high valleys of southwestern Montana.

Douglas-fir is subject to serious damage from a variety of agents that may increase under future climates (Hermann and Lavender 1990). Western spruce budworm (*Choristoneura occidentalis*) and Douglas-fir tussock moth (*Orgyia pseudotsugata*) are the most important insects affecting Douglas-fir. Both insects attack trees of all ages at periodic intervals throughout the range of interior Douglas-fir, often resulting in severe defoliation of stands. Many Douglas-fir stands in the central NR are currently devastated by budworm and beetle. The Douglas-fir beetle (*Dendroctonus pseudotsugae*) is a destructive insect pest in old-growth stands of coastal and interior Douglas-fir. Armillaria and annosus (*Heterobasidion annosum*) root diseases may intensify in infection and widen in distribution to cause high tree mortality. Annosus root disease is particularly lethal in Douglas-fir (Hagle 2003). Of the many heart rot fungi (more than 300) attacking Douglas-fir, the most damaging and widespread is red ring rot (*Porodaedalea pini*, Murrill 1905). Knots and scars resulting from fire, lightning, and falling trees are the main paths of infection. Losses from this heart rot far exceed those from any other decay. Other important heart rot fungi in the NR are brown trunk rot (*Fomitopsis officinalis*), *Fomitopsis cajanderi*, and *Phaeolus schweinitzii*.

Historical and Current Conditions

Historical frequent wildland fires kept Douglas-fir from becoming established on those dry sites where it was associated with ponderosa pine (frequent fires favored ponderosa pine establishment). It often became established after long inter-fire periods, such as during the Little Ice Age, and easily attained dominance if fire frequency was decreased. However, in the more montane portions of the species NR range, Douglas-fir was often one of the major dominants, as it was a major competitor under historical mixed-severity fire regimes (Arno et al. 2000).

Today, however, cumulative effects of the fire exclusion era coupled with logging have allowed Douglas-fir to become the dominant species across its range, especially where it successional replaced the historically-dominant ponderosa pine forests (Arno and Gruell 1983; Arno et al. 2000; Gruell et al. 1982). As a result, we have seen an expansion of Douglas-fir into areas where fire was frequent historically, but also a densification of the forests where it is associated with more mesic species. This has created large, contiguous areas where canopy fuels have increased and become denser, and surface fuels that have been converted from grass and shrubs to heavy downed, dead woody fuels (Keane et al. 2002). This predisposes many Douglas-fir forests to severe future fires. Moreover, these dense stand conditions have contributed to decreased vigor that predisposes the species to western spruce budworm and Douglas-fir beetle outbreaks. Many Douglas-fir forests of southwestern and central Montana are currently experiencing high budworm and beetle mortality.

Climate Change Responses

Several studies suggest that Douglas-fir will respond positively with future changes in climate. Morales et al. (2015) projected a seven percent increase in the range of the species in the western U.S. by 2060. Soulé and Knapp (2013) found almost doubled radial growth in Douglas-fir in the western portions of the NR in the latter half of the 20th century, but they attributed some of this increase to other factors such as CO₂ fertilization. Rose and Burton (2009), using SDMs, projected that Douglas-fir forests in British Columbia will nearly triple by 2080, while Franklin et al. (1991) project no net loss of Douglas-fir

habitat in the future in the Pacific Northwest. Using a gap model, Cumming and Burton (1996) also found little change in the Douglas-fir zone in the future in British Columbia.

However, it is likely that myriad factors will contribute to decline of Douglas-fir forests in some parts of the NR in the future. Recent Northern Region seedling survival survey results from 2014 show significant increases in Douglas-fir three-year seedling mortality (approximately 50 percent) due to increasing drought, high temperatures, and severe conditions, presumably related to climate change. In addition, Kemp (2015) found that natural postfire regeneration of Douglas-fir on sites that burned in 2000 and 2007 varied across gradients in elevation, aspect, and burn severity, and findings indicated that Douglas-fir regeneration was significantly reduced with increased heat loading (incoming solar radiation derived from site latitude, aspect, and slope); specifically, the probability of successful Douglas-fir regeneration was lower at lower elevation sites and on sites with higher heat load (steep, southwest aspects). Likewise, Douglas-fir abundance was lower on sites at lower elevations and with higher heat loads.

On dry lower elevation southerly aspects in the southern NR, ponderosa pine will likely cope with moisture deficits better than Douglas-fir because it does not have the high potential for xylem cavitation (Stout and Sala 2003). In addition, Douglas-fir might not have the genetic potential to rapidly migrate to more conducive sites (Aitken et al. 2008). More importantly, there are a suite of insects and diseases that are increasing in NR Douglas-fir forests that are creating heavy mortality, especially in southwestern NR areas. The spruce budworm is killing many Douglas-fir stands in southwestern Montana, while the Douglas-fir bark beetle is attacking stands in other parts of the NR. Nitschke and Innes (2008) predict major losses of Douglas-fir from parts of British Columbia because of hot, dry conditions, while Shafer et al. (2001) predict major transitions in Douglas-fir in most of the US Pacific Northwest, and raise some major concerns that the climate might be too warm to meet the chilling requirements of Douglas-fir seed. Using SDM approaches, Gray and Hamann (2013) projected that Douglas-fir will migrate over 400 km north and 170 m upwards in elevation by 2050, and Bell et al. (2014) projected major losses of over 40 percent of its range in the NR by 2090.

Increases in wildland fires, coupled with adverse effects of the fire exclusion era in NR forests, could also present some problems for Douglas-fir. Increasing fire danger in Douglas-fir stands with high canopy and surface fuels may promote wildland fires that kill the majority of Douglas-fir, even the most mature individuals. If fires increase in the future, regardless of fire suppression efforts, they may be so frequent that Douglas-fir seedlings cannot become established and become mature trees.

Douglas-fir might be one of the NR tree species most limited in range expansion because of its limited genetic diversity and structure (St. Clair and Howe 2007). The species has a specialist genetic adaptive strategy at low to mid elevations and a more generalist strategy at higher elevations. With warming temperatures and a possible decrease in summer moisture conditions, Rocky Mountain Douglas-fir may contract from the driest portions of its range. Current natural regeneration failures may be exacerbated by reduced seed sources owing to large wildfires and hot and dry microclimate conditions, especially on southerly exposures at lower elevations. On moist sites (mixed mesic forest), there may be increases in root disease mortality because of increasing moisture stress.

Western Larch (Larix occidentalis)

Autecology

Western larch grows in the Upper Columbia River Basin of northwestern Montana, and in north and west central Idaho (Schmidt and Shearer 1990). It grows in the relatively moist-cool climatic zone. Limiting factors to western larch are low temperatures at the upper elevations, and lack of moisture at the lower extremes (Habeck 1990). Western larch grows on a wide variety of soils; most soils suitable for growth are deep and well drained. It is commonly found on valley bottoms, benches, and northeast-facing mountain slopes (Schmidt et al. 1976).

Western larch is adapted to extreme environmental heterogeneity, from maritime climates in the west and northwest to more continental climates, as westerly air masses move across the Bitterroot and Cabinet Mountains (Rehfeldt 1982). At comparable elevations, the frost-free period in western Montana is 30 days shorter than in northern Idaho, and thus populations from western Montana are better adapted genetically to short frost-free growing seasons as compared to similar elevations in northern Idaho (Rehfeldt 1995b).

Moreover, as elevation increases and frost-free periods decrease, growth potential decreases. Early fall cold snaps are a major temperature factor affecting seedling and sapling survival, before resting buds have had an opportunity to fully lignify (Rehfeldt 1995a). Drought is another major climatic factor affecting mid- to late-season survival. (Schmidt 1995). It is most likely to affect seedlings under heavy shade because of the heavy moisture use by the overstory and other competing vegetation. Zhang and Marshall (1994) and Zhang et al. (1994) characterize western larch as having low water-use efficiency, as compared to other conifers in the NR. Plants that have low water-use efficiency tend to be larger in stature and produce more biomass, which may be trait-limiting in future warmer and more arid or variable-precipitation climates. The lower water-use efficiency of western larch may explain its absence on xeric sites (Gower et al. 1995).

Cone and seed production in western larch is most prolific at ages older than 30 to 50 years, with seed crops occurring every 14 years in Idaho and every 10 years Montana (Owens 2008). Good cone crops may occur in successive years if conditions are favorable (Owens and Molder 1979). Spring frosts often reduce pollen, cone and seed production in western larch, leading to sporadic seed years. Cone production is higher in stands that have larger crowns, such as stands that have been thinned (Shearer 1976). Cooler, wetter springs favor foliar diseases such as larch needle cast (*Meria larisis*); successive years of infection lead to reductions in available cone crops. Cone maturation follows elevation gradients, where cones at lower elevations are generally mature in mid-August and seed dispersal occurs into September. As such, seed may be available for dispersal during the fire season.

Seed germinates best on seedbeds exposed by burning or mechanical scarification (Antos and Shearer 1980; Beaufait et al. 1977; Schmidt 1969; Shearer 1976). Western larch seedlings survive poorly on undisturbed litter, humus, sod or heavy root competition; seedlings germinated on duff do not often survive (Beaufait et al. 1977). High solar irradiation is the most important physical factor affecting seedling survival (Shearer 1976). South and west exposures are generally too severe for western larch seedlings to establish, particularly in drier sites at the lower elevational limits of its range. In the mid- and northern portion of its ranges, western larch grows well on all exposures. Young seedlings grow fast on

desirable sites. Only lodgepole pine is similar to western larch in seedling growth; Douglas-fir grows about half the rate, and spruce and subalpine fir about one quarter the rate of western larch. Site productivity has the most effect on height growth on western larch sites.

Western larch is a long-lived early seral species. It is a fast-growing species with tall, open crowns making the species easily able to out-grow all of its competitors on the more mesic sites (Milner 1992). It is also the most shade-intolerant conifer in the NR (Minore 1979) (table 6.3); it can tolerate partial shading only in the seedling stage. Western larch is replaced through succession by all other conifers except for ponderosa pine. Western larch is moderately drought tolerant and can survive seasonal drought, but performs poorly when droughts last more than one or two years. Douglas-fir is the most common associate, but others include ponderosa pine on lower drier sites, western hemlock, western redcedar, and western white pine on moist sites, and Engelmann spruce, subalpine fir, lodgepole pine and mountain hemlock on cool, moist subalpine sites (Schmidt and Shearer 1990). It has been associated with mycorrhizal fungi in many portions of the NR (Harvey et al. 1978).

Western larch has average genetic diversity with a weak population differentiation. Its low levels of differentiation indicate that it is more a generalist than specialist. The species has a moderate outcrossing rate, and the patterns of genetic variation are mostly dominated by latitude and longitude. Populations need to be separated by 1640 ft in elevation before genetic differentiation is expected.

Disturbance Interactions

Wildland fire is essential to the maintenance of western larch populations. Western larch depends on the open-canopy, high light environments, and mineral soil seedbeds created by fire for successful, widespread regeneration (Schmidt et al. 1976). Western larch has unique characteristics that allow it to survive intense fire, including the thickest bark (Ryan and Reinhardt 1988), high crowns with high moisture contents, deep roots and epicormic branch production (Fiedler and Lloyd 1995; Harrington 2012; Schmidt et al. 1976; Schmidt and Shearer 1995). Western larch is one of the few NR tree species that has adapted to survive mixed to stand-replacement fires (Hopkins et al. 2013; Marcoux et al. 2015). Tall surviving western larch can produce copious seeds that are wind-dispersed across large burns to land

on mineral soil seedbeds and ensure continued western larch domination (Stoehr 2000). However, if serotinous mature lodgepole pine trees occur with western larch, regeneration may be dominated by both species (e.g., Hopkins et al. 2013). Since western larch grows quicker and taller, it often outcompetes lodgepole pine to attain dominance (Pfister et al. 1977).

Western dwarf mistletoe (*Arceuthobium campylopodum*) is perhaps the most damaging disease-causing parasite of western larch (Schmidt and Shearer 1990). It can infect seedlings as young as three to seven years old and continue throughout the life of the tree. In addition to killing treetops, reducing seed viability, creating conditions suitable for entry of other diseases and insects, and causing burls, brashness, and some mortality, it decreases height and diameter growth. Three other important diseases are found in western larch: needlecast caused by *Hypodermella laricis*, brown trunk rot, and red ring rot. The exotic larch casebearer (*Coleophora laricella*) and native western spruce budworm are currently the two most serious insect pests of western larch (Schmidt and Fellin 1973). However, neither of these agents causes substantial mortality. Western larch is susceptible to defoliation as a result of the recent western spruce budworm outbreak (DeNitto et al. 2013). Larch needle cast results in substantial needle damage in cooler, moister springs. Episodic outbreaks of larch casebearer and western spruce budworm can also cause severe enough defoliation as to reduce the current year's tree growth (Schmidt et al. 1976) and disrupt cone production.

Historical and Current Condition

The more mesic montane western portions of the NR were often dominated by extensive western larch forests that had regenerated after major fires. The species dominated northwestern Montana and was the major timber species for most of the 1950's to 1970's. However, extensive logging beginning as early as 1908 on US Forest Service lands (Arno 2010) removed many of the large tall western larch that could have survived fire and cast seed across the landscape, and effective fire exclusion has removed the burned, mineral soil seedbeds where western larch can regenerate. Continued fire exclusion has served to densify the forest and increase surface fuel loads so that future fires may be more severe.

Climate Change Responses

Western larch is a species that is highly susceptible to climate warming. Most climate change studies predict major losses of western larch throughout the NR. Morales et al. (2015) used an SDM approach to project a 41 percent loss of western larch in its range in the western U.S., and Aston (2010) mentions major declines in western larch habitat in the northern Rocky Mountains. Rehfeldt and Jaquish (2010) projected major shifts in western larch in western NR, with major losses in Montana and gains in Idaho. Nitschke and Innes (2008) used gap modeling approaches to simulate major losses in western larch in most of British Columbia. Coops and Waring (2011) mention that western larch may invade many areas vacated by lodgepole pine in the future in some portions of the Pacific Northwest. In addition, considering western larch associates, competitive interactions among species may play a critical role in the current and projected distribution of tree species such as western larch (Thuiller et al. 2008). While temperature–precipitation interactions tend to set the limits where species can successfully compete, temperature alone seems primarily responsible for adaptation of populations within those limits (Rehfeldt et al. 2014).

Western larch will probably migrate to more northerly and higher areas in the NR, but not without surviving major fires. Gray and Hamann (2013) estimated western larch could migrate over 500 mi northward and over 1100 ft higher in elevation by 2050 in the NR. Western larch has the ability to quickly take advantage of changes in productivity of colder sites, providing these areas burn and the western larch will survive the fires to provide sufficient seed for colonization. Increasing fires may serve to return western larch to the NR landscape, but this may require significant assistance from management through planting burns with western larch before other species become established. Continued fire exclusion will probably result in major declines of western larch in the western NR, because increased competition will reduce vigor, making the trees more susceptible to damaging agents, and surface and canopy fuel buildups will be so great that many relic western larch trees will die in uncharacteristically severe fires (Arno et al. 1997; Davis 1980; Norum 1974). Keane et al. (1996) simulated major declines in the future for western larch under fire exclusion and moderate climate change, but found it increased as more fire was allowed to burn in the Glacier National Park landscape.

Western larch exhibits an intermediate adaptive strategy, and geographic clines for most adaptive traits are relatively flat (Rehfeldt 1994, 1995a). Populations from northerly latitudes and higher elevations exhibit the lowest growth potential, least tolerance to larch needle cast and the lowest survival. Using a common garden study of 143 populations, Rehfeldt (1995a) demonstrated an increase of 9 °F would produce a mean annual temperature exceeding the current ecological distribution of the species. A molecular study using allozymes indicated low levels of genetic differentiation among populations from the inland Northwest (Fins and Steeb 1986). Evolutionary bottlenecks are commonly cited as a mechanism of reduced genetic differentiation among populations, and increased differentiation within populations.

Western larch may be highly susceptible to future changes in climate primarily because of its narrow geographic and elevational distribution in the NR and its uncertain association with wildland fire. If wildland fires increase, western larch may have a distinct colonization advantage, providing fire mortality is low in those communities that have extensive fuel buildups from fire exclusion. However, if fires decrease and exclusion is continued, western larch may be outcompeted by its shade-tolerant competitors, and those seed-producing western larch that remain might be killed by severe fires created by abnormal fuel accumulations. If the NR plants western larch in those severely burned areas, the species will surely remain on the landscape in the future.

Western White Pine (Pinus monticola)

Autecology

In the interior west, western white pine grows from near Quesnal Lake, British Columbia, south through the Selkirk Mountains of eastern Washington and northern Idaho and into the Bitterroot Mountains of western Montana (Graham 1990). Isolated populations are found as far east as Glacier National Park (Loehman et al. 2011a). The climate of the interior portion of western white pine range is influenced by the Pacific Ocean, where summers are dry and the majority of the precipitation occurs in the fall and winter. Western white pine is limited by moisture at lower elevations and temperatures at upper elevations. The southern boundary is limited by a balance of precipitation and evaporation.

Western white pine grows on a diversity of soil types in the NR (Harvey et al. 2008), but it primarily grows in areas where the upper soil layers are composed of loess or loess-like material. In the NR, it generally grows between 1640 and 5906 ft elevation and where the topography is steep with v-shaped and round-bottomed valleys. It grows on a variety of slopes, but is common along moist creek bottoms, lower benches, and northerly slopes. Western white pine grows in association with a variety of species, and in the western hemlock/bride's bonnet (*Clintonia uniflora*), western redcedar/bride's bonnet, and grand fir/bride's bonnet habitat types (Cooper et al. 1991).

Western white pine seeds require 20 to 120 days of cold, moist conditions before germination occurs. Germination occurs in the spring when soil moisture is at field capacity from melting snow. Western white pine seedling establishment is favored by partial shade on severe to moderately severe sites (Graham 1990) but little to no shade on north slopes. Under full sun, germination begins earlier and ends earlier than in shaded conditions. Mineral soil surfaces are preferred over duff. Once established, western white pine grows best in full sunlight on all sites. Seedlings have low drought tolerance, and seedling mortality late in the first growing season is attributed to high surface temperatures on exposed sites, and drought in heavily shaded areas where root penetration is slow. Early root and shoot development is not rapid.

Western white pine is almost always a seral species and is classed as intermediate in shade tolerance (Minore 1979). It attains dominance in a stand only following wildfire or silvicultural systems that favor it. It is tolerant of cold when it is dormant, and similar to lodgepole pine in cold tolerance.

Genetic variation of western white pine is high, with the greatest difference being among trees within a stand. Differences occur among stands and elevational zones, but the proportion of variation is smaller than that for trees within a stand. The adaptation of western white pine to different conditions (topographic, climatic, geographic, and edaphic) is governed more by phenotypic plasticity (ability of an organism to change its phenotype in response to changes in the environment) than by selective differences. The species has a high outcrossing rate and average genetic diversity with moderate genetic

differentiation. It is a generalist species with broad climate and environmental tolerances (Devine et al. 2012).

Disturbance Interactions

Historically, western white pine forests mostly originated from wildfires, especially stand-replacement burns, but were also maintained by frequent low severity fires (Barrett et al. 1991). The species, especially when mature, is more tolerant of heat and can better survive fire than nearly all of its shade-tolerant competitors. Its relatively thick bark and moderately flammable foliage make it intermediate in fire resistance among its conifer associates (Graham 1990). Native American burning was probably the primary source of fire that created the pure stands of western white pine in northern Idaho, but lightning was also important (Graham 1990).

The most prominent agent causing the severe declines in western white pine is white-pine blister rust (Fins et al. 2002; Harvey et al. 2008). A combination of climate, extensive white-pine blister rust, abundant alternate hosts, and susceptible western white pine caused significant losses in the recent past. Selection of naturally resistant trees as seed sources and planting of rust-resistant nursery stock can reduce losses. In the absence of blister rust, western white pine is long-lived, commonly surviving to 300 to 400 years old.

The foremost root disease of western white pine is Armillaria root rot, which causes fading foliage, growth reduction, root-collar exudation of resin, dead and rotten roots, and black rhizomorphs. Annosus root disease and laminated root rot (*Phellinus sulphurascens*) also cause some mortality of individuals and groups. In periods of drought, pole blight, a physiological disorder, can occur in stands of the 40- to 100-year age class, causing yellow foliage and dead resinous areas on the trunk. Later, the top dies and, after a few years, the tree dies. The disease does not appear to be caused by a primary pathogen but results from rootlet deterioration in certain soils, restricting the uptake of water. Bark beetles are the most important insects that attack western white pine, and the most important is the mountain pine beetle, which kills groups of trees, primarily in mature forests. The mountain pine beetle often attacks trees

weakened by blister rust. Likewise, the red turpentine beetle (*Dendroctonus valens*) sometimes attacks weakened trees.

Historical and Current Conditions

Western white pine stands were once extensive across northern Idaho and parts of Montana, with large, tall pine trees dominating the montane landscapes (Harvey et al. 2008). As a result of logging, fire suppression and extensive white-pine blister rust infection, western white pine forests are nearly gone, and the species occurs only as scattered individuals in mixed conifer stands (Fins et al. 2002). This is truly an ecosystem in decline, and it may be doomed to extinction without active restoration.

Climate Change Responses

Western white pine presents a special challenge in forest management in the future. Recent studies have shown that western white pine might be the species best adapted to changes in climate change in the northwestern portions of the NR (Loehman et al. 2011a). Using SDMs, Gray and Hamann (2013) estimated western white pine could move almost 250 mi northward and 500 ft higher in elevation in the NR by 2050. Its superior growth rates, ability to survive fire, and high timber value make it a species to promote in the creation of future forests with high resilience (Baumgartner et al. 1994; Graham 1990). It has the unique ability to disperse seeds into burned areas, which will likely increase in the future, and the predicted increases in productivity in the areas where it occurs could mean that it might achieve the most significant benefits from changing climates, especially in the context of timber production. However, the species is currently ravaged by white-pine blister rust, and it has not yet developed the genetic capacity to overcome the damaging effects of this exotic disease to populate future northwestern NR landscapes (Fins et al. 2002). The species simply has not achieved a sufficient level of rust resistance to allow it to dominate future stands (Harvey et al. 2008). With white-pine blister rust and its alternate hosts (e.g., currant) predicted to also increase in the future, creating a rust-resistant population of western white pine is critical to maintaining it in the mesic grand fir/western redcedar/western hemlock habitat types (Baumgartner et al. 1994). Without a comprehensive western white pine restoration program, there is little chance that this species will play an important role in the future.

There are other issues that may govern future western white pine dynamics. While wildland fire may increase growing space, thereby providing for high regeneration potential, there may be few western white pine trees to provide the seed source needed to regenerate these large burns. Also, in some portions of the NR, the species may be highly dependent on ash cap soils (Graham 1990), which may prevent its migration to warmer sites. The species is also dependent on a unique assemblage of ectomycorrhizae whose availability in some areas might be reduced in the future; suitable substrate may not exist upslope so migration may not occur.

In summary, we feel that western white pine is highly predisposed to declines in the future due to the interacting effects of continued fire exclusion, low levels of white-pine blister rust-resistance in native populations, and rapid succession to more shade-tolerant conifer communities. While it may be a species of special interest for northwestern portions of the NR, its populations and future under changing climates is especially precarious because of white-pine blister rust. Abundance of western white pine is currently low in isolated landscapes, and thus the magnitude of any decline may be large relative to current and past populations.

Aspen (Populus tremuloides)

Autecology

Quaking aspen is the most widely distributed native tree species in North America and is abundant in the mountains of western and southwestern Montana and northern Idaho (DeByle 1985; Perala 1990). Its habitat is limited primarily to areas of water surpluses (annual precipitation exceeds evapotranspiration), and it is also limited by minimum or maximum growing season temperatures. Deterioration of aspen stands is often related to warmer summer temperatures (Perala 1983). Aspen grows on a variety of soils, but growth and development are strongly influenced by both physical and chemical properties of the soil. The best soils for aspen growth are usually well drained, loamy, and high in organic matter, calcium, magnesium, potassium, and nitrogen. Aspen has an important role in nutrient cycling because of its rapid growth and high nutrient demand. Aspen is limited by both shallow and deep water tables (>8.2 ft) because the roots need sufficient water and good aeration, especially during the growing season.

Compared to most conifer species, aspen is a short-lived, disturbance-maintained seral species (Mueggler 1985; Rogers 2002). It is shade intolerant and aggressively sprouts following any disturbance (usually fire), which kills most of the live stems, thus stimulating vegetative reproduction (i.e., suckering) (Bartos 1978). Aspen reproduces primarily by asexual root sprouting. Parent trees (genets) produce stems/trees (ramets), and this results in a clone or stand of genetically identical aspen stems (trees). Damage to parent trees alters the growth hormones (auxins and cytokinens) and stimulates a sprouting response (Perala 1990). Soil temperature is the most critical abiotic factor affecting suckering. Light is not needed for suckering but is needed for secondary growth. Eventually, most of the original root connections are severed as the ramets develop their own root systems to support nutrient uptake (Rogers et al. 2007; Shepperd and Smith 1993). This reproductive strategy allows aspen to establish quickly on disturbed sites and out-compete conifers for soil moisture, nutrients and light. In addition, the shared root system maintains overall stand vigor by allowing sharing of resources during the early stages of stand development (Mitton and Grant 1996; Romme et al. 1997).

While there are a number of different aspen classifications (Mueggler 1988; Shepperd et al. 2001), it is widely recognized that aspen occurs as both stable climax communities and as seral, disturbance-maintained communities (Mueggler 1988, 1985). Stable aspen communities occupy sites with both high soil moisture and solar radiation, which appears to preclude establishment of conifers for very long periods (or they never establish). Stable climax aspen communities do not require disturbance to maintain aspen dominance. Seral aspen seems to occur in two forms in the NR. First, there are mesic stands in northwest Montana and northern Idaho, where aspen is a common seral component, but it rarely dominates stands unless there are several consecutive burns (Campbell and Bartos 2001; Cooper et al. 1991; DeByle 1985). The second seral type occurs in the drier forested areas in the NR, such as east of the Continental Divide and southwestern Montana. In these seral types, which are created by fire and sprouting, aspen occurs as the major stand component; these stands will eventually succeed to more shade tolerant conifers (e.g., Douglas-fir, subalpine fir, and Engelmann spruce) in the absence disturbance (DeByle 1985; Mueggler 1988).

Aspen has a high genetic diversity, because it is essentially a trans-boreal broadleaf tree. It has weak genetic differentiation geographically, but strong differentiation at the population level. There is substantial phenotypic variation in the species, found both in the field and in genetic studies, as documented by varied leaf sizes, shapes, and phenologies.

Disturbance Interactions

Numerous factors other than competition will be important for quaking aspen under changing climate. Perhaps the most important factor affecting aspen regeneration and distribution is browsing by ungulates that frequently damage reproduction by browsing and by rubbing their antlers against the stems (Eisenberg et al. 2013; White et al. 1998). Elk and moose can also damage pole- and saw log-size trees by "barking" them with their incisors. Such injuries often expose individuals to secondary attack by insects or pathogens. Heavy use by overwintering ungulates can greatly reduce the number of aspen trees in localized areas. Cattle and sheep browsing is a serious problem in many areas of the NR because livestock are allowed to range through recent aspen clearcuts. Mature aspen stands adjacent to livestock concentrations (water holes, salt blocks, and isolated stands in large open areas) often have root damage, are declining, and have few if any suckers present.

Fire can kill aspen stands (Bartos 1998), but it also creates conditions conducive to aspen regeneration and suckering by eliminating shade-tolerant conifers, which compete for light and eventually overtop and shade out aspen, leading to aspen decline (Campbell and Bartos 2001; Shepperd et al. 2001). Mature aspen trees may not survive fire as well as the fire-adapted conifers of the NR, but aspen is easily the most competitive after fire because it can aggressively regenerate from suckers (Shinneman et al. 2013). It would appear that aspen could do quite well in a warmer climate with increased fire frequency, but moisture will limit its success, with varied results (Anderegg et al. 2012; Hogg and Hurdle 1995; Kulakowski et al. 2013; Worrall et al. 2013).

Following disturbance, aspen normally dominates a site for 40 to 80 years. Natural thinning from disease, aging, and succession (shading) by competing conifers eventually reduces aspen abundance (Mueggler 1985; Rogers 2002). In central Utah, Shepperd et al. (2001) found that both regenerating and

nonregenerating clones had stems of various age classes, which suggests that periodic sucker events occurred in these clones. In addition, they found that all of the non-regenerating clones had fewer roots than their regenerating neighbors, which indicates that root systems decline when clones are not periodically regenerating. Many aspen clones are known to be associated with ectomycorrhizae (Cripps and Miller 1993).

Aspen has low susceptibility to insect damage, except in urban plantings, but stem canker diseases have a significant impact on aspen ecosystems. Depending on the fungus, cankers may kill trees within a few years or persist for decades. Hypoxylon canker caused by *Hypoxylon mammatum* is probably the most serious aspen disease east of the Rockies, killing one to two percent of the aspen annually (Perala 1990). Young trees are killed by small rodents and mammals, particularly large ungulates (Eisenberg et al. 2013).

Historical and Current Conditions

Since around 1970, aspen has been in a period of general decline that is thought to be the result of wildfire exclusion, which has allowed plant succession to proceed toward conditions that ordinarily exclude aspen (Campbell and Bartos 2001; Frey et al. 2004). Recent episodes of aspen dieback have been superimposed on this general decline. Dieback can be recognized by the suddenness of the impact and by an epidemiology that begins with the death of branch tips, death of mature trees, and eventually death of entire clones (Frey et al. 2004). The dieback is suspected to be caused by drought. The condition is generally referred to as sudden aspen decline because of the suddenness of the impact.

Climate Change Response

Aspen is a species that may experience both gains and losses under future climate, depending on local site conditions, particularly soil moisture. Seral aspen communities will respond differently than stable, climax aspen communities. Aspen communities on warmer, drier sites could experience high mortality because of increasing water deficit. Ireland et al. (2014) found that drought was the major factor causing recent high mortality in southwestern aspen stands. In the boreal forests of western Canada, Hogg and Hurdle (1995) estimate that even with an 11 percent increase in precipitation, boreal forests in which

aspen is a major component will decline due to drought stress. Sudden aspen decline has been associated with severe, prolonged drought, particularly in aspen stands that are on the fringe of the species' distribution (warmer and drier sites than those typically considered optimal for aspen persistence) (Frey et al. 2004). Recent research efforts have found that extreme weather events (e.g., drought, thaw–freeze events), insect defoliation, and/or pathogens have led to aspen mortality (Brandt et al. 2003; Candau et al. 2002; Hogg et al. 2002). Marchetti et al. (2011) found that aspen mortality from various insects and disease (e.g., Cytospora canker [*Cytospora*], bronze poplar borer [*Agrilus liragus*], and aspen bark beetles *Trypophloeus populi* and *Procryphalus mucronatus*) was greater in those stands that were drought-stressed and declining due to sudden aspen death. Further exacerbating the situation is that declining stands may have little or no regeneration due to intense ungulate herbivory, and those smaller stands that persist may be smaller and fewer with increased plant stress due to increased severity of summer droughts (Rogers et al. 2013). Growth may increase because photosynthetic rates appear to increase more in aspen than other tree species as atmospheric carbon increases, but this may be offset by increased atmospheric ozone, which reduces photosynthesis and may increase susceptibility to insects and disease.

Increased fire frequency, particularly on moist sites, will likely favor aspen regeneration in the future by removing shading conifers, and younger stands (<40 years old) created by fire may be more resilient to drought. However, if future fires are severe, they may kill the shallow root systems and eliminate aspen. Increased herbivory on regenerating stands may occur as adjacent upland vegetation senesces and desiccates earlier in the growing season. Areas with mountain pine beetle-caused conifer mortality (especially in lodgepole pine) may release aspen, and it will regenerate once the conifer canopy is thinned or removed, again given sufficient soil moisture.

Grand Fir (Abies grandis)

Autecology

Grand fir is found on a wide variety of sites, including stream bottoms, and valley and mountain slopes of the northwestern U.S. and southern British Columbia (Foiles et al. 1990). Average precipitation in its range varies from 1.6 to 8.2 ft but in northern Idaho the average is from 1.6 to 4.3 ft. The average

growing season temperature is 57.2 to 66.2 °F. In the inland portion of its range, grand fir grows best on rich mineral soils of valley bottoms but also grows well on shallow exposed soils of mountain ridges if moisture is adequate (Antos 1972).

Grand fir is either a seral or climax species, depending on site moisture (Ferguson and Johnson 1996). On productive mesic sites, it grows rapidly to compete with other seral species in the overstory, but it is outcompeted by western redcedar and western hemlock. On drier sites where western redcedar and western hemlock are excluded because of drought, it is the most shade-tolerant species and can easily dominate the understory, which eventually assumes the dominant position in the climax condition. Grand fir is a major climax species in a variety of habitat types in Montana and northern Idaho, but it rarely grows in pure stands; one exception is on the Clearwater River drainage in north-central Idaho (Cooper et al. 1991; Pfister et al. 1977). In Montana and parts of Idaho, grand fir can also share dominance, even in the climax state, with subalpine fir, especially in narrow valley bottoms where subalpine fir can exert dominance in lower elevational zones (Antos 1972). In most of its range, grand fir is often associated with Douglas-fir, ponderosa pine, western larch, western white pine, and subalpine fir.

Grand fir has a high tolerance to shade but a low tolerance to drought, even though it can tolerate drought better than any of the conifers that may succeed it in the absence of disturbance (e.g., western redcedar and western hemlock). Grand fir forms associations with ectomycorrhizae and arbuscular mycorrhizae, which may allow it to outcompete some shade-tolerant conifers. It has a very low frost tolerance but can tolerate seasonally fluctuating water tables. It is monoecious and it produces large, winged seed dispersed by wind. It has average levels of genetic diversity but weak geographic differentiation. There are apparently genetic differences between the northern Idaho and western Montana populations.

Disturbance Interactions

Grand fir is susceptible to fire damage in moist creek bottoms but is more resistant on dry hillsides where roots are deeper and bark is thicker (Ryan and Reinhardt 1988). Grand fir is less resistant to fire than western larch, ponderosa pine, and Douglas-fir but more resistant than subalpine fir, western

hemlock, and Engelmann spruce. Most fires that burn grand fir sites are stand-replacement or mixed-severity, and these fires burn in fuels that generate sufficient heat to kill most grand fir trees (Arno 1980; Arno et al. 2000).

Grand fir is susceptible to heart rot and decay. Armillaria root rot and annosus root disease are common root diseases causing high tree mortality (Hagle et al. 2003). Numerous insects attack grand fir. The western spruce budworm and Douglas-fir tussock moth have caused widespread defoliation, topkill, and mortality in grand fir. The western balsam bark beetle (*Dryocoetes confusus*) and the fir engraver (*Scolytus ventralis*) are the principal bark beetles attacking grand fir (Foiles et al. 1990).

Historical and Current Conditions

Fire exclusion has increased grand fir on both dry and mesic sites, but increased tree densities have also stressed grand fir trees, contributing to increased fuel loadings, higher root rot, and greater insect damage and mortality. Historically, grand fir sites were probably dominated by western larch, western white pine, Douglas-fir, and ponderosa pine because of frequent fires, but these sites have since succeeded to the more shade-tolerant grand fir, and on the productive mesic sites, to western redcedar and western hemlock. Therefore, the condition of most grand fir stands depends on the last severe fire; if fire exclusion has caused grand fir to dominate in both the overstory and understory, then these stands are usually highly stressed because of increased root rot and insect agents. However, in earlier seral stands that have not yet experienced high grand fir regeneration, a rise in grand fir cover types is likely with continued fire exclusion.

Climate Change Responses

On xeric sites, increased drought and longer growing seasons will exacerbate grand fir stress from competition, resulting in high mortality mainly from insects and disease. Nitschke and Innes (2008), using a gap modeling approach, projected major declines in grand fir, and Coops and Waring (2011) used a mechanistic model to simulate a nearly 50 percent decrease in the range of grand fir compared to historical distributions. Franklin et al. (1991) projected that grand fir will nearly disappear from the east slope of the Cascades.

Yet, projections of increased productivity may lead to increased grand fir populations on moderate sites (Aston 2010). Urban et al. (1993) projected an expansion of grand fir forests into upland, xeric sites of the Pacific Northwest. On mesic sites where grand fir is seral to western redcedar and western hemlock, the longer growing seasons coupled with higher temperatures may increase growth rates and regeneration success, thereby increasing tree density and competition and effectively reducing grand fir components. The opposite is true on those sites where grand fir is the indicated climax; grand fir will increase in both the overstory and understory in the absence of disturbance.

Disturbance, specifically fire, could be the major factor in the rearrangement of grand fir communities across the NR landscape. Longer fire seasons and high fuel loadings from both fire exclusion and increased productivity will serve to foster large, severe fires that may reduce grand fir, especially on those sites where it is the indicated climax species (i.e., grand fir habitat types). Fire will reduce grand fir dominance at both landscape and stand scales.

In summary, while many grand fir forests are highly stressed from high tree densities, the species will probably tolerate changes in climate and remain on the landscape at levels that are closer to historical conditions rather than the high abundance observed now.

Western Redcedar (Thuja plicata)

Autecology

The inland range of western redcedar extends from the western slope of the Continental Divide in British Columbia south through the Selkirk Mountains into western Montana and northern Idaho (Minore 1990). The southern limit is Ravalli County and the eastern limit is near Lake McDonald in Glacier National Park. A few trees may exist east of the Continental Divide near St. Mary's Lake (Pfister et al. 1977). Western redcedar is abundant in many forested swamps as well as sites that are too dry for western hemlock; it has better root penetration than western hemlock (Habeck 1978). Western redcedar dominates wet ravines and poorly-drained depressions. Where there is sufficient precipitation, low temperatures limit the species range. It is not resistant to frost and can be damaged by freezing temperatures in late spring and early fall.

Western redcedar only occurs in pure stands where fire has been excluded for a long time, or where fire has been used to maintain western redcedar dominance (Barrett 1988; Barrett and Arno 1991). It is commonly associated with a wide array of tree species, specifically grand fir, western white pine, western hemlock, western larch, and ponderosa pine. Only western hemlock in the NR is more tolerant to shade than western redcedar, but western redcedar can be overtopped by Douglas-fir, grand fir, western hemlock, and western white pine (table 6.3). Its relative shade tolerance may be higher in warm than in cool areas, but western redcedar is very tolerant wherever it grows. Often present in all stages of forest succession, western redcedar can occupy pioneer, seral, and climax positions, but in the NR, most western redcedar stands are in the late seral stages; it is usually considered a climax or near climax species. It has little tolerance for drought but can exist in seasonally wet areas, especially near riparian systems (Devine et al. 2012).

Western redcedar regenerates best on disturbed mineral soil, although scorched soil is not beneficial to its regeneration. Rotten wood that is in contact with the soil is a preferred seedbed in western redcedar groves. Western redcedar also propagates by clones, and clones tend to be more abundant than young trees established by seed. Establishing seedlings survive best in partial shade, as they are not tolerant of high soil temperatures or frost. Young branches can sunscald. Roots of young seedlings grow more slowly than Douglas-fir but faster than western hemlock, and shoots have the longest growing period of any of the associated conifers.

Western redcedar has very low levels of genetic diversity, and this diversity is weakly distributed geographically and within populations. Clines are very gentle and seed zones narrow. This species cannot tolerate wide ranges of environmental conditions.

Disturbance Interactions

Relative to its associates, western redcedar is not as affected by damaging agents, but because it is long-lived, damaged trees are common (Minore 1990). Although western redcedars are somewhat wind-firm, especially on dry sites, western redcedars are often wind thrown in wetter environments. Western redcedar is less susceptible to fire damage than Engelmann spruce, western hemlock, grand fir, and

subalpine fir in the NR. Western redcedar is also less susceptible than other associated species to root pathogens. However, root disease still impacts western redcedars, and fungi eventually invade heartwood typically resistant to decay. In North America, the most important fungi attacking western redcedar are root, butt, and trunk rots, most importantly laminated root rot, honey fungus (*Armillaria mellea*), and stringy butt rot (*Perenniporia subacida*).

Historical and Current Conditions

Compared to historical distributions, there has not been a significant increase or decrease in western redcedar distribution in the NR. However, there has likely been an increase in western redcedar dominance in those stands occupying mesic western redcedar sites due to fire exclusion.

Climate Change Responses

With warmer temperatures, mesic northern Rocky Mountain ecosystems may increase in productivity (Aston 2010), and western redcedar may expand into more upland communities. Hamann and Wang (2006) projected that the western hemlock/cedar forests of British Columbia would double in range by 2050, and Urban et al. (1993), using gap modeling, simulated an expansion of western redcedar into upland western Oregon sites. Devine et al. (2012) rated western redcedar as having moderate vulnerability in the Pacific Northwest Region. With increased western redcedar productivity could come increased cone production and seed dispersal into new areas that might be more conducive for long-term seedling establishment.

Although warmer conditions in the future may benefit western redcedar, drier conditions in the future would likely result in retraction of western redcedar to the warmer, wettest NR sites; upland western redcedar stands might have high mortality from declining productivity. Woods et al. (2010) noted recent declines in western redcedar in British Colombia and attributed the decline to increased drought that decreased vigor and increased insects attacks and disease in western redcedar. Warming may also result in a loss of chilling required for western redcedar (Nitschke and Innes 2008), and western redcedar's narrow genetic potential (Devine et al. 2012) may limit its expansion into new habitats. Using SDMs, Gray and Hamann (2013) estimated western redcedar might move 400 mi northward and 1,000 ft higher in

elevation by 2050 in the Pacific Northwest. However, in some of the NR, redcedar is mostly associated with ash cap soils, so it may be that even though new climates create new habitats, the potential of non-ash soils to sustain productive western redcedar may be limited.

It is uncertain how disturbance will affect western redcedar in the future. Fire can serve to maintain western redcedar communities if it burns at low severities and kills only seedlings and saplings. However, high severity wildfires could eliminate seed sources. Continued fire exclusion may maintain current western redcedar distributions, but without proactive fuel treatments, wildfire that occurs after long periods of exclusion may burn with sufficient severity to cause extensive western redcedar mortality. Also, new warm-cold cycles may facilitate red belt and adversely affect young western redcedar, as evidenced by increased flagging during past dry seasons.

In summary, western redcedar may not be severely affected by future climate warming. The species may remain its current range, and productivity may increase in some settings.

Western Hemlock (Tsuga heterophylla)

Autecology

The inland range of western hemlock includes the west side of the Continental Divide of the Rocky Mountains in Montana and Idaho, north to Prince George, British Columbia (Packee 1990). Western hemlock thrives in mild humid climates and in environments with abundant soil moisture throughout the growing season (Hann et al. 1994). Where the growing season is relatively dry, western hemlock is confined primarily to northerly aspects, moist stream bottoms, or seepage sites. Western hemlock grows on a variety of soil types, although it is a shallow-rooted species and does not develop a taproot. Abundant roots, especially fine roots, grow near the soil surface and are easily damaged by fire.

Western hemlock is considered very shade tolerant and is perhaps the most shade tolerant tree species in the NR (table 6.3). It is a major climax or near climax species in the NR and is found with nearly all of the other conifer species, including western redcedar, grand fir, Douglas-fir, western larch, western white pine, lodgepole pine, and ponderosa pine. Seed germination and germinant survival occurs when there is adequate moisture. Western hemlock can germinate on a variety of materials and in both organic and

mineral seedbeds. Decaying logs and rotten wood are often favorable seedbeds; decayed logs have the added benefit of good nutrition. Western hemlock is highly susceptible to drought and demands abundant water throughout the growing season (Baumgartner et al. 1994). It is associated with some ectomycorrhizae. Its seedlings are highly susceptible to frost.

Western hemlock has relatively low genetic diversity and low geographic differentiation. It has a high outcrossing rate and average heterozygosity (Devine et al. 2012). Growth rate is more related to soil conditions than to genetics.

Disturbance Interactions

A variety of root and bole pathogens cause significant damage and mortality in western hemlock. It is also very susceptible to fire damage because of its shallow roots and thin bark, and it is also susceptible to wind throw owing to shallow roots. On droughty sites, top dieback is common, and entire stands of western hemlock saplings have been killed in exceptionally dry years. Western hemlock is highly susceptible to annosus root disease and Indian paint fungus (*Echinodontium tinctorium*), but seems to have a high tolerance to Armillaria root rots (Packee 1990).

Historical and Current Conditions

The current distribution of western hemlock is similar to its historical distribution. However, most stands with western hemlock have become denser and the western hemlock component has increased in both the overstory and understory. Overly dense western hemlock stands may be experiencing declines in vigor, thereby becoming more susceptible to disease, insects, and abiotic perturbations (e.g., windthrow).

Climate Change Responses

In the past, milder, western hemlock/western redcedar forests were associated with wetter conditions in the low elevation forests of the NR, but this type declined as fires and drought increased (Gavin et al. 2007). Thus, increased drought and area burned may decrease western hemlock abundance and distribution. Several studies have projected contractions in western hemlock distribution. For example, Hansen et al. (2001) simulated major contractions in western hemlock range, and Franklin et al. (1991) project that western hemlock will occupy about half its current range on the western slopes of the

Cascades. Shafer et al. (2001) noted that western hemlock may decrease in range because chilling requirements for the seeds will not be met. Using a mechanistic landscape model, Keane et al. (1996) simulated losses of western hemlock and cedar under moderate climate warming in Glacier National Park, mostly as a result of severe fires. Cumming and Burton (1996) projected minor changes in the western redcedar-western hemlock zone in British Columbia under moderate warming. Hamann and Wang (2006), on the other hand, predicted that western hemlock would increase its range by over 200 percent in British Columbia, and using gap modeling, Urban et al. (1993) simulated an expansion of western hemlock into upland western Oregon sites.

It is possible that western hemlock will maintain its current range under changing climate. It may not have the diversity in growth habit that will allow it to expand its range into the more upland sites as temperatures warm. Since the species is dependent on ash cap soils, any migration may be relegated to those wetter and warmer sites without ash cap soils.

Lodgepole Pine (Pinus contorta)

Autecology

Lodgepole pine has wide ecological amplitude, but only the inland form (var. *latifolia*) is found in the NR (Lotan and Critchfield 1990). Lodgepole pine has the widest range of environmental tolerance of any conifer in North America (Lotan and Critchfield 1990). It is relatively resistant to frost injury and can often survive in frost pockets where other species cannot (Pfister et al. 1977). In Montana, lodgepole pine does not grow on highly calcareous soils derived from dolomitic limestone (Lotan and Perry 1983). Lodgepole pine is mainly found on moist soils developed on colluviums from other types of limestone and calcareous glacial till. It grows well on gentle slopes and in basins, but it is also found on rough and rocky terrain, on steep slopes and ridges, and bare gravel (Lotan and Critchfield 1990). Compared to other associated species, lodgepole pine is intermediate in its needs for water, requiring more than Douglas-fir or ponderosa pine but less than spruce and subalpine fir in the NR.

Lodgepole pine is intolerant of shade but highly tolerant of frost and drought (table 6.3). Occasionally seedlings become established under a forest canopy, but these individuals rarely do well and remain in a

stunted form for long periods of time (decades to centuries). In the absence of fire, lodgepole pine is usually succeeded by its more tolerant associates, such as Douglas-fir in xeric environments and Engelmann spruce and subalpine fir in subalpine environments. Succession proceeds at variable rates, however, and is particularly slow in some high elevation forests (Arno et al. 1993). Lodgepole pine grows both in pure stands and in association with many conifers, primarily subalpine fir, spruce, Douglas-fir, and western larch (Steele et al. 1983). Its successional role is dependent on environmental conditions and on competition. It is seral in most mesic NR forest communities (Arno et al. 1986). However, on cool dry habitats, such as those found in the Greater Yellowstone Area and southeastern Idaho, it is dominant and tends to be persistent and form near climax communities (Despain 1983). Its ability to remain on xeric landscapes is enhanced by its association with many types of mycorrhizae.

Lodgepole pine has a great ability to regenerate due to a combination of cone serotiny, high seed viability, early rapid growth, and ability to survive a wide variety of microsite and soil conditions (Hardy et al. 2000). The serotinous cone habit, where cones only open after being heated by wildland fire, is common in the Rocky Mountains, but in general, the highest serotiny is found in the northern parts of the NR. Large quantities of stored seeds are available for regeneration after fire, and annual seed fall from non-serotinous cones helps in restocking in areas of relatively minor disturbance and maintaining lodgepole pine presence in mixed stands.

The best lodgepole germination occurs in full sunlight and on bare mineral soil or disturbed duff, with little competition. Adequate soil moisture is required for germination and survival, with the first few weeks being most critical. In southwest Montana most of the season's total germination occurs during the two weeks following snowmelt in late June when soil is saturated and temperatures most favorable. Drought is a common cause of mortality in first year seedlings. Freezing temperatures may kill seedlings, but seedlings vary in frost resistance based on seed source. Frost heaving also causes mortality. Height growth begins earlier than other associated species, except for other pines and western larch.

There is moderate genetic variation in strains of lodgepole pine, resulting in some strains growing well in cold climate and on poor sites. Lodgepole pine has an average genetic diversity but a weak

differentiation across its NR range and strong differentiation among populations. The species is a prolific seed producer and has a good cone crop at about one to three year intervals. It is wind-pollinated and its seeds are wind-dispersed.

Disturbance Interactions

Fire plays a critical role in lodgepole pine forest succession (Brown 1973; Lotan et al. 1984). Typically, many NR lodgepole pine forests were borne from stand-replacement fires, but extensive fire scars in NR lodgepole pine forests indicate the existence of a low severity, non-lethal fire regime component in lodgepole pine forests, especially in many areas east of the Continental Divide (Arno et al. 1993; Stewart and Arno 1997). Lodgepole pine appears to be able to survive low intensity fires quite well even though it has thin bark (Ryan and Reinhardt 1988). However, most NR lodgepole pine forests have a mixed severity fire regime in space and time, where all possible fire severity types are possible depending on available fuels, antecedent drought, and wind conditions (Arno et al. 2000). The end result is that lodgepole is a tree species that will be well adapted to the fires of the future. Repeated fires, however, can eliminate lodgepole pine seed sources if the fires occur before existing lodgepole has become reproductively mature (approximately 10 years) (Larson et al. 2013). In most cases, lodgepole pine natural regeneration often overwhelms a burned site with abundant seed from serotinous cones and thereby excludes other species (Lotan and Perry 1983; Nyland 1998).

The mountain pine beetle is the most significant insect pest and has played a significant role in the dynamics of lodgepole ecosystems (Roe and Amman 1970). Past research has tried to link fire, beetles, and lodgepole pine in a complex web of interactions (Brown 1973; Geiszler et al. 1980). However, recent findings have shown that fire and beetles often act independently to influence lodgepole pine dynamics (Axelson et al. 2009; Moran and Corcoran 2012; Schoennagel et al. 2012).

Historical and Current Conditions

Advancing succession due to fire exclusion is contributing to replacement of lodgepole pine with subalpine fir in many areas of the NR. Keane et al. (1994) found that upper subalpine landscapes have experienced successional advancement of subalpine communities from under eight percent of the Bob

Marshall Wilderness landscape to over 22 percent. Concurrent increases in burn areas are creating many new lodgepole stands and some may become dense thickets, but coupled with increased drought, these dense lodgepole stands may exacerbate stress from other factors, including competition, endemic insects and diseases, and wind. Warming temperatures have heightened bark beetle activity, resulting in more frequent and severe outbreaks that have devastated many mature lodgepole pine communities in the central NR (Carroll et al. 2003).

Climate Change Responses

Longer drought periods and warmer temperatures in the lower, south-facing, drier lodgepole pine subalpine environments may cause decreased tree growth and regeneration potential, perhaps resulting in a transition to more xeric trees species, such as Douglas-fir. Chhin et al. (2008) found that recent warming has decreased lodgepole pine growth rates in the foothills lodgepole pine communities of the low elevation forests in Alberta, Canada. Coops and Waring (2011) used process modeling to simulate minor declines with moderate warming in lodgepole pine in the Pacific Northwest (Oregon, Washington, and British Columbia), but major type conversions to other species with major warming. Using an SDM approach, Hamann and Wang (2006) projected a net 50 percent loss of lodgepole pine in British Columbia under severe warming. Nigh (2014) projected that lodgepole pine heights may decrease by roughly one yard in moderate future warming, but the species has the genetic capacity to mitigate this height loss, while Rehfeldt et al. (1999) found substantial decline in lodgepole pine growth and height with minor changes in climate. Chhin et al. (2008) also found decreases in lodgepole pine growth were correlated with high summertime temperatures, presumably related to summer drought. However, they also found that increases in lodgepole pine growth with high fall temperatures. Gray and Hamann (2013) estimated lodgepole pine would move over 250 miles northward and over 650 ft higher in elevation by 2050 in the NR using SDM techniques. Bell et al. (2014), using SDMs, project major losses of over 70 percent of its NR range by 2090. Given that lodgepole pine is a generalist that is capable of regenerating and growing in a wide range of environments, it is likely that the decline of lodgepole pine from drier sites will only occur under extreme warming scenarios (e.g., RCP 8.5 and A2) over longer time periods.

Another possibility is that, in the higher elevational areas of the NR subalpine, where seasonal drought is not a problem, warming climates may actually increase lodgepole pine productivity because of high precipitation (Aston 2010). Johnstone and Chapin (2003) show that lodgepole pine is not in equilibrium with current climate, and this means that the species' response to climate shifts will be difficult to predict using SDM approaches. However, they found that there are places where lodgepole pine will be positively affected by climate change. Wang et al. (2006) found major increases in lodgepole pine productivity under future climates with moderate warming, but major decreases and perhaps local extinctions under extreme warming. Romme and Turner (1991) projected increases in the lodgepole pine zone in the GYA under moderate warming.

A third possibility is that lodgepole pine will migrate into areas where it is currently excluded by harsh cold, windy conditions, such as the upper subalpine and timberline. This relocation process will likely be catalyzed by fire, especially in those areas with high serotiny. Clark et al. [in review] found that under moderate warming, lodgepole pine would remain on the GYA landscape, but it would also expand into higher elevation environments historically occupied by whitebark pine. Most studies have projected the migration of lodgepole pine into the whitebark pine zone (Hamann and Wang 2006; Romme and Turner 1991).

Lodgepole pine is well-adapted to increases in fire occurrence, depending on level of serotiny (Turner et al. 1999). Smithwick et al. (2009) simulated some positive increases in GYA lodgepole pine after fire and under climate change. However, if fire is too frequent, lodgepole may be eliminated from sites where fires reburn stands before established seedlings and saplings become reproductively mature. Clark et al. [in press] simulated major and rapid decreases in GYA lodgepole pine under high climate warming due to both inhospitable environments and too frequent fire.

In mesic subalpine sites, continued fire exclusion coupled with higher productivities will certainly heighten competitive interactions and put more lodgepole pine trees into stress, thereby increasing mortality, insect and disease vulnerability, canopy and surface fuels, and accelerating succession toward subalpine fir (Smithwick et al. 2009). Severe fires that then occur in these advanced successional

communities could revert back to lodgepole pine, providing there is not a loss of seed source. Fire exclusion, especially in areas of high serotiny, might delay the expansion of lodgepole pine.

Projected increases in climatic conditions that facilitate mountain pine outbreaks could reduce lodgepole pine populations and forest extents (Creeden et al. 2014; Gillette et al. 2014). Lodgepole pine is highly susceptible to bark beetle mortality, especially on those landscapes where fire exclusion has resulted in an abundance of mature hosts (Temperli et al. 2013). Bark beetle outbreaks will favor the more shade tolerant, non-host tree species, thereby creating dense stands that may be subject to severe crown fires after 10-20 years. If beetle-killed stands burn, lodgepole pine can occupy the burned area only if viable seed sources still remain. The varying levels of serotiny and beetle mortality will dictate future stand conditions in beetle-killed stands. Landscape heterogeneity is the only hedge against massive declines of lodgepole pine in the future (Logan and Powell 2001).

In summary, lodgepole pine is expected to both expand and contract in range, but as long as fire remains on the landscape, the species will likely maintain its presence in the NR at roughly the same proportions as during the last 100 years, albeit in different areas. The species is highly exposed to any climate changes because of its wide range and diverse growing environments, but Soulé and Knapp (2013) note that the steep clines associated with lodgepole pine seem to be driven more by density-dependent selection than by environmental selection, so this species may be well-adapted to future changes in climate. In addition, while the magnitude of climate effects will likely be great for tree growth, it may be only moderate for the species survival compared to other species, and the likelihood of these effects are highly uncertain, mainly because of the role that fire will play in the maintenance of lodgepole as a major component on future landscapes.

Whitebark Pine (Pinus albicaulis)

Autecology

Whitebark pine is an important component of high-elevation upper subalpine forests in the western U.S. and Canada (Arno and Hoff 1990). It is a keystone species because it supports unique community diversity, and it is a foundation species because of its roles in promoting community development and

stability (Tomback and Achuff 2010; Tomback et al. 2001). Since more than 90 percent of whitebark pine forests occur on public lands in the U.S. and Canada, maintaining whitebark pine communities requires a coordinated effort across federal, state, and provincial land management agencies (Keane et al. 2012).

Whitebark pine is a long-lived tree of moderate shade tolerance (Minore 1979) (Table 6.3). It is common to find mature whitebark pine trees well over 400 years of age, especially on harsh growing sites; the oldest is more than 1,275 years (Luckman et al. 1984). Well-formed, thrifty individuals often have smooth, grey bark, especially in the tree crowns, which may appear whitish in bright sunlight (Arno and Hoff 1990). Whitebark pine is slowgrowing in both height and diameter, and it rarely grows faster than most of its competitors, except on the most severe sites (Arno and Hoff 1990). In general, whitebark pine grows where summers are short and cool, most precipitation comes in the form of snow and sleet, with rain only in June through September. Whitebark pine survives strong winds, thunderstorms, and severe blizzards, and is one of the few upper subalpine species that can tolerate long periods of drought (Callaway et al. 1998).

Whitebark pine is a major component of high elevation forests throughout the upper subalpine and timberline zones in the NR (Arno and Hoff 1990). Whitebark pine forests occur in two high mountain biophysical settings. On productive upper subalpine sites, whitebark pine is the major seral species that is replaced by the more shade-tolerant subalpine fir, Engelmann spruce, and mountain hemlock, depending on geographic region (Arno 2001). These sites, referred to as “seral whitebark pine sites”, support upright, closed-canopy forests in the upper subalpine lower transition to timberline, just above or overlapping with the elevational limit of the shade-intolerant lodgepole pine (Pfister et al. 1977), and the two pine species can often share dominance. Other minor species found with whitebark pine on these sites are Douglas-fir, limber pine, and alpine larch (Keane et al. 2012). Sites where whitebark pine is the only tree species able to successfully dominate high elevation settings (called “climax whitebark pine sites”) occur in the upper subalpine forests and at treeline on relatively dry, cold slopes. Other species, such as subalpine fir, spruce, and lodgepole pine, can occur on these sites, but as scattered individuals with truncated growth forms. Whitebark pine can also occur as krummholz, elfin forests, clusters, groves, tree

islands, and timber atolls in the alpine treeline ecotone (Tomback 1989) and as a minor seral in lower subalpine sites (Cooper et al. 1991; Pfister et al. 1977).

Whitebark pine is eventually replaced, in the absence of fire, by the shade-tolerant subalpine fir, spruce, and mountain hemlock on the productive, seral whitebark pine sites (Arno and Hoff 1990). It can take 50 to 250 years for subalpine fir to replace whitebark pine in the overstory, depending on the local environment and previous fire history (Keane 2001). Whitebark pine competes with lodgepole pine during early successional stages in the lower portions of its elevational range. Lodgepole pine usually has the competitive advantage over whitebark pine when it establishes from seed after a stand-replacing disturbance event because of its fast growth, serotiny, and copious seed production.

A bird, the Clark's Nutcracker, and whitebark pine have coevolved into mutualistic relationship to ensure their continued presence on the landscape (Tomback 1982, 1983). Whitebark pine has evolved a nearly exclusive dependence on nutcrackers to disperse its large wingless seeds, and in turn, nutcrackers utilize the large whitebark pine seeds as an important food source. The key behavior that benefits the whitebark pine is the tendency of nutcrackers to bury thousands of whitebark pine seeds each year as food stores in small clusters or "seed caches" across diverse forest terrain (Keane et al. 2012). Nutcrackers retrieve these seed caches primarily in spring and summer months as an important food source for themselves and their young. However, not all seed caches may be recovered, particularly following a large cone crop. Snowmelt, spring rains, and summer showers stimulate seed germination, leading to whitebark pine regeneration. While whitebark pine depends nearly exclusively on nutcrackers, nutcrackers often harvest and cache seeds of other large-seeded pines.

Whitebark pine is a genetically diverse species because of its dependence on bird-mediated seed dispersal (Keane et al. 2012). As a result, the species is highly adapted to exist across many environments, and is only limited by competition, even at the lowest elevations. It has only six seed zones across its entire range, so it is easily able to migrate across local landscapes to rapidly take advantage of newly burned areas. Whitebark pine has weak geographic differentiation in the NR, but a moderate level of inbreeding. One concern in the future is that the breeding of rust-resistance in future whitebark pine

seedlings may compromise other important traits; Mahalovich et al. (2006) found lower cold tolerance in high rust-resistant seedlings grown in the nursery.

Disturbance Interactions

Whitebark pine fire regimes are quite complex and variable in space and time, but in general, all three types of fire severities describe whitebark pine fire dynamics: non-lethal, stand-replacing, and mixed-severity (Morgan et al. 1994b). Some whitebark pine stands may experience fire events that burn in low-intensity, non-lethal surface fires (sometimes called underburns or low-severity fires) because of sparse surface and canopy fuel loadings and unique topographical settings. However, most fires in the upper subalpine burn in mixed-severity patterns that best facilitate continued existence of whitebark pine (Keane et al. 1994).

Mountain pine beetle is by far the most damaging insect in mature stands of whitebark pine. Much of the mature whitebark pine in the NR was killed by this insect between 1909 and 1940. Epidemics evidently spread upward into the whitebark pine forest after becoming established in the lodgepole pine forests below. The GYA whitebark pine ecosystems have recently experienced one of the most severe mountain pine beetle mortality events in recorded history.

The principal disease of whitebark pine is the introduced white-pine blister rust (Schwandt 2006). Blister rust is particularly destructive where the ranges of whitebark pine and blister rust coincide with the rust's alternative host, currant. Where there is a source of inoculum from lowland forests, the spores that infect pine can be carried by wind to the trees, but cool, moist conditions are needed for infection in whitebark pine. Blister rust damage is severe and prevents tree development in many upper subalpine settings of northern Idaho and northwestern Montana. Whitebark pine has some resistance to the disease, and efforts at developing rust-resistant seed for regenerating burned and treated areas have been quite successful.

Historical and Current Conditions

Whitebark pine has been declining since the early 20th century from the combined effects of native mountain pine beetle outbreaks, contemporary fire exclusion policies, and the spread of the exotic white-

pine blister rust (Schwandt 2006; Tomback and Achuff 2010). Losses of whitebark pine in some areas of the NR exceed over 80 percent (Keane et al. 2012). Whitebark pine is listed as endangered in the province of Alberta, Canada, it is a candidate species for listing under the U.S. Endangered Species Act (U.S. Fish and Wildlife Service 2011), and it is listed as endangered in Canada under the federal Species at Risk Act. Within the last decade, major outbreaks of pine beetle and increasing damage and mortality from blister rust have resulted in cumulative whitebark pine losses that have altered high-elevation community composition and ecosystem processes in many regions of the U.S. and Canada.

Climate Change Responses

There is much confusion in the research and management communities about the fate of whitebark pine as climates slowly warm. Some maintain that projected warmer conditions will severely reduce whitebark pine habitat and push whitebark pine “off the tops of mountains” (Lenoir et al. 2008) or restrict the species to north of the Canadian border (Koteen 1999; Schrag et al. 2007; Warwell et al. 2007). This assumes that less hardy, shade-tolerant conifer species would establish in those higher elevation stands where whitebark pine currently dominates, and whitebark pine would “migrate” upslope to the limited areas above its current elevational range (Romme and Turner 1991). Bell et al. (2014), using SDMs, project minor losses (10 - 20 percent) in whitebark pine’s range in the NR by 2090. Others hold that climate-mediated changes in the disturbance regimes will serve to keep whitebark pine within its current range, albeit at lower levels (Loehman et al. 2011b). The fate of whitebark pine is uncertain because of high uncertainty in regional climate change predictions, the high genetic diversity and resilience of the species, and the localized changes in disturbance regimes and their interactions (Keane et al. [in press]).

Climate change has the potential to significantly impact whitebark pine ecosystems (Bartlein et al. 1997). Devine et al. (2012) rated whitebark pine the most vulnerable of all the PNW tree species, primarily because of restricted range and white-pine blister rust infections. However, taking a historical perspective, whitebark pine was able to persevere through many major climatic cycles in the past. Historical analogs of warmer climates in the paleoecological record indicate whitebark pine was maintained and even increased in some places under past warmer and drier climates in some parts of its

range (Whitlock and Bartlein 1993; Whitlock et al. 2003). Whitebark pine can grow within a broad upper elevation zone in the west; it just happens to grow best at high elevations where there is little competition from other tree species. For example, Arno et al. (1995) found that whitebark pine's elevational range extended over 500 ft below the current lower elevation limits of whitebark pine in the Bitterroot Mountains of Montana. Nitschke and Innes (2008) suggested that temperature alone would exclude whitebark pine from British Columbia landscapes. However, whitebark pine occupies the largest range of any five-needled pine in the U.S. and Canada, including about 18° of latitude and 21° of longitude, indicating a great deal of tolerance to different climates (Tomback and Achuff 2010), and because it is bird-dispersed, it is planted and grows in many environments and only dies from competition (Arno and Hoff 1990). Moreover, its longevity provides potential buffering against changing climates (Morris et al. 2008).

The same three responses of tree species to climatic change will occur for whitebark pine: ranges will decline, stay the same, and expand. SDM studies have projected dramatic decreases in whitebark pine habitat over the next 50 years (McDermid and Smith 2008; Warwell et al. 2007). Hamann and Wang (2006) project a 100 percent decline in whitebark pine in British Columbia with high levels of warming. These same models also predict that whitebark pine will probably transition to timberline environments that are above the current elevational range, but these transitional areas are much smaller in size than whitebark pine's traditional range, thereby resulting in a net loss of the species. Climate can adversely impact growth and mortality of whitebark pine in a number of ways (Bugmann and Cramer 1998; Keane et al. 2001). Projected decreases in water availability may result in less water being available for some droughty sites. Longer drought might cause whitebark pine to shut their stomata longer to conserve the little water available, resulting in slow growth.

However, many whitebark pine stands may have positive responses to warming climates. Anecdotal evidence shows that some whitebark pine forests are experiencing abnormally high growth and more frequent cone crops with warmer summers and longer growing seasons. These observations are consistent with some region-based scenarios using computer modeling (Loehman et al. 2011b). Recent modeling

efforts have shown that whitebark pine might be maintained on the landscape in the future, providing that projected increases in large, stand-replacement fires create large, competition-free burned areas (Clark et al. [in review]; Loehman et al. 2011b). If tree dispersal enables range shifts to occur, this will lead to a new northern distributional range of whitebark pine (Hamann and Wang 2006; McKenney et al. 2007). Moreover, whitebark pine shows promise for being maintained in the NR because of high levels of genetic diversity (Mahalovich and Hipkins 2011; Richardson et al. 2002); moderate to high heritabilities in key adaptive traits (Mahalovich [in press]); demonstrated blister rust resistance (Hoff et al. 2001; Mahalovich et al. 2006); minimal inbreeding (Bower and Aitken 2007; Mahalovich and Hipkins 2011); and generalist adaptive strategies (Mahalovich [in press]).

Future climates may enhance whitebark pine diameter and height growth and decrease mortality, especially in mesic seral whitebark pine forests. Earlier growing seasons with ample moisture, such as those projected for the upper subalpine forests, will result in increased productivity and greater growth. Longer, warmer growing seasons may also result in higher productivities and greater biomass, especially considering the high amounts of precipitation that currently fall in upper subalpine forests. The abundant moisture may enable longer high elevation tree growth, thereby increasing growing seasons. Increased biomass could result in higher growth rates for timber production and forage, especially in the widespread higher mountain areas where cold, not moisture, limits tree growth, creating potential for the inclusion of whitebark pine in the timber base. Increased biomass could also foster more intense, severe fires, and maybe insect and disease outbreaks, but more importantly, the increased biomass will probably increase cone crop abundance and frequency. However, this increased production may also heighten competitive interactions between whitebark pine and its associated species, thereby favoring the more shade-tolerant individuals in the absence of disturbance. However, if disturbances increase, the more fire-tolerant whitebark pine might inherit the landscape.

Whitebark pine cone and seed crops could be both adversely and beneficially affected by climate change. In high elevation, historically cold environments, increased temperatures may increase growing seasons and thereby increase potential for more frequent and more abundant cone crops with greater

numbers of seed. This is important because decreases in species abundance and associated cone production may be offset by climate-driven increases in cone crops. Climate warming and its variation will also affect the phenology of cone crops, but these impacts may be minimal as plants adapt to the new conditions. Some predict higher frost mortality of emerging cones due to earlier onset of the growing season, coupled with high daily temperature variability (Chmura et al. 2011), while others suggest that cone crops will be reduced in the future because of high tree stress from drought resulting in less frequent and abundant cone crops. Since whitebark pine is both drought-tolerant and cold-tolerant, many expect that changes in climate variability and timing will have low impact on species reproduction.

Perhaps the most critical whitebark pine life stage is regeneration, where most species, but especially trees, are most susceptible to shifts in climate (Solomon and West 1993). The microsite conditions needed for successful regeneration are so demanding that seed germination, especially from seeds that are wind-dispersed, is rarely successful (McCaughey and Tomback 2001). Bunn et al. (2003) emphasized the importance of accounting for microsite variability in assessing climate change response; high-elevation microsite changes, coupled with increased fire activity, could increase whitebark pine regeneration and growth as climates change. The depth and duration of snow cover often governs high elevation tree regeneration. Most years are moist enough for regeneration, but snow remains on sites for a long time, thereby limiting the number of days that a seedling can actually photosynthesize and grow. If temperatures increase, then snow might melt earlier, giving more time for seedlings to survive and grow. Warm years often result in waves of regeneration and can be dated in upper subalpine ecosystems using seedling and sapling tree ages (Little et al. 1994; Rochefort et al. 1994). Recent observations of invasions of subalpine meadows and balds by subalpine fir, alpine larch, and spruce are testimony to the high number of sequential warm years over the last decade that has facilitated high mountain regeneration. Moreover, there is often abundant precipitation in upper subalpine settings, and projections for the future indicate roughly the same amount, so seedling mortality from drought might continue to be minimal.

Many climate change studies consistently project drier conditions in the range of whitebark pine, which would result in large increases in the annual number, area burned, and severity of wildfires

(Flannigan et al. 2009; Krawchuk et al. 2009; Marlon et al. 2009). With increased fire, whitebark pine will have a unique opportunity to maintain its range or even increase in distribution in the future because it has bird-mediated seed dispersal mechanisms that can disseminate seed great distances into large, severe burns, well before wind can disperse the seeds of its competitors (Tomback 1977, 1982, 1989; Lorenz et al. 2008). Whitebark pine also has morphology that enables it to survive low- to moderate-severity fires (Ryan and Reinhardt 1988). Therefore, whitebark pine is uniquely positioned as a species that can increase under the more frequent fire regimes that result from warming climates. Also, since nutcrackers may be harvesting seeds from trees that have survived blister rust, there is some chance that seeds from unclaimed nutcracker caches may become blister rust-resistant trees. It is entirely possible that as long as wildland fire creates areas where birds will cache seeds and resultant seedlings can grow without competition, whitebark pine will continue to thrive throughout its range.

Current mountain pine beetle outbreaks are killing more whitebark pine than historical records indicate, and these outbreaks are probably a result of warmer winter temperatures that facilitate expansion of and establishment of beetle populations in the higher-elevation whitebark pine zone (Logan and Powell 2001; Logan et al. 2003). A warmer climate may also accelerate the spread of blister rust (Koteen 1999).

In summary, whitebark pine is not expected to do well under future climates, not because it is poorly-adapted to shifts in climate regimes, but rather because it is currently experiencing major declines from the exotic disease (white-pine blister rust) that preclude its immediate regeneration in future burned areas. Moreover, these declines from white-pine blister rust and mountain pine beetle have served to reduce whitebark pine populations to severely low levels, and now the nutcracker is acting more as a seed predator than a seed disperser (Keane and Parsons 2010). Climate shifts will only exacerbate this decline and complicate restoration efforts. Whitebark pine will be highly exposed to any climate changes because of its (1) confined distribution to the upper subalpine environments; (2) severely depressed populations; and (3) lack of an ability to regenerate when populations are low because of nutcracker predation. However, the species has the genetic capacity to overcome both white-pine blister rust and new climates to thrive over the next century, but only with extensive restoration efforts.

5589 *Subalpine Fir (Abies lasiocarpa)*

5590 Autecology

5591 Subalpine fir grows in the coolest and wettest forest areas of the western continental U.S. (Alexander
5592 et al. 1990). Although widely distributed, it grows within a narrow range of mean temperatures of 25° to
5593 40 °F; however, January temperatures average 5° to 25°F degrees. Compared to other subalpine species,
5594 cool summers, cold winters, and deep winter snowpack are more important than precipitation in
5595 determining where subalpine fir grows.

5596 Subalpine fir occupies the lower valleys to upper subalpine zone in the NR. In the lower valley
5597 bottoms and footslopes, it is often associated with grand fir, western larch, Douglas-fir, western redcedar,
5598 and western white pine (Pfister et al. 1977). At the mid-subalpine, it is often associated with lodgepole
5599 pine, Douglas-fir, and Engelmann spruce, while at the upper subalpine, it is associated with whitebark
5600 pine, alpine larch, mountain hemlock, and Engelmann spruce (Arno 2001). In the Rocky Mountains,
5601 subalpine fir is commonly found with Engelmann spruce, and the two together are often called spruce-fir
5602 forests (Moran-Palma and McTague 1997). The subalpine fir habitat types are probably the most common
5603 forest habitat types in the NR (Pfister et al. 1977).

5604 Subalpine fir is shade-tolerant, and is often the most shade-tolerant of all its associates, except for
5605 grand fir and mountain hemlock in isolated cases (Alexander et al. 1990; Minore 1979) (table 6.3).
5606 Although subalpine fir can grow under nearly all light conditions, seedling establishment and early
5607 survival are usually favored by partial shade (Knapp and Smith 1982). In the absence of grand fir and
5608 mountain hemlock, subalpine fir will survive under closed-forest conditions with less light than
5609 Engelmann spruce. It may not compete well with the spruces, lodgepole pine, or interior Douglas-fir in
5610 the lower subalpine when light intensity exceeds 50 percent of full shade. Subalpine fir is quite intolerant
5611 of drought, and many seedlings can be killed if droughts are overly long or deep. The species is highly
5612 tolerant of frosts and can remain alive in seasonally wet conditions. Subalpine fir is usually the climax
5613 tree species in most subalpine areas of the NR, although it sometimes shares climax status with spruce.

Subalpine fir is a prolific seeder, often having large cone crops every two or three years (Alexander et al. 1990). Its seedfall usually occurs in late autumn, over snow in most places. The species is restricted to cold, humid habitats because of its seedlings' low tolerance to high temperatures and dry conditions (Knapp and Smith 1982); newly germinated subalpine fir seedlings rarely tolerate high solar radiation, and they are susceptible to heat girdling and drought (Little 1992). Seedlings are also killed or damaged by spring frosts, competing vegetation, frost heaving, damping off, snowmold, birds, rodents, and trampling and browsing by large animals, but losses are not different than for any of the species' common associates (Alexander et al. 1990). However, the fir's abundant seedfall, coupled with cool conditions in the subalpine, often create dense mats of seedlings in stands that contain partial shade and overwhelm seedling establishment of all other species. Subalpine fir has average genetic diversity for an NR tree species and weak geographic differentiation. There are strong clinal variations in phenological and morphological characteristics.

Disturbance Interactions

Subalpine fir is highly susceptible to fire damage because of thin bark, low hanging dense foliage, and shallow roots (Ryan and Reinhardt 1988). Even the lowest-severity fire can cause high mortality in subalpine fir. Frequent fires often eliminate subalpine fir from both the overstory and understory, thereby maintaining the more fire-adapted species of lodgepole pine, whitebark pine, western larch, and western white pine (Little et al. 1994; Murray et al. 1995; Wadleigh and Jenkins 1996). Invariably, some fir trees survive even the most severe fires in refugia, thereby providing a seed source for future stands (Murray et al. 1998; Veblen et al. 1994).

In spruce-fir forests, the most important insect pests are the western spruce budworm and western balsam bark beetle. The silver fir beetle (*Pseudohylesinus sericeus*) and the fir engraver may at times be destructive, but only in local situations in the NR. Fir broom rust (*Melampsorella caryophyllacearum*) and wood rotting fungi are responsible for most disease losses, but root and butt rots may be important locally. Wood rots and broom rust weaken affected trees and predispose them to windthrow and windbreak. Decades of intense competition, coupled with a period of moderate to severe drought, often

cause extensive mortality in subalpine fir stands. These high mortality events are often attributed to a complex of disease, insects, and other agents, but the underlying cause is low vigor in existing trees from over-competition.

Historical and Current Conditions

Effects of one hundred years of fire exclusion have not yet become manifest in most subalpine fir ecosystems because of historically infrequent fire and slow successional advancement. However, abundance of subalpine fir cover types has increased in many subalpine and upper subalpine landscapes (Keane et al. 1994), and many stands that had low subalpine fir components now have fir dominating the understory and encroaching in the overstory. This densification has resulted in many stands becoming stressed from competitive interactions, resulting in increasing susceptibility to disturbances. Recent dry, droughty conditions have led to high elevation subalpine fir mortality of undetermined origin called subalpine fir “die off”, usually attributed to a complex of causal mechanisms such as drought, heightened competition, higher temperatures, and increasing diseases. Therefore, as fire is progressively kept off the subalpine landscape, the subalpine fir stands that replaced the pine communities will progressively decline in vigor and be more susceptible to fire, insects, and diseases. A concern is that if these overly dense, unhealthy stands continue to escape fire, the seed sources of the fire-adapted pines will be eliminated, and high elevation sites may be converted to grass and shrublands (Keane 2001). Another concern is that as fire is excluded from these dense subalpine fir forests, canopy and surface fuels will accumulate to such levels that, when burned, fires will be of extremely high severities (Keane 2001; Morgan et al. 1994b).

Climate Change Responses

It is challenging to predict responses of subalpine fir to future climate change. It is a species that is highly adapted to moist growing conditions, so it will likely respond poorly to increasing temperatures and drought (Alexander et al. 1990). On the other hand, it is a fierce competitor that can outcompete all subalpine tree species for shade, and it is a species that has a diverse range throughout the NR. Subalpine fir could expand its range into the timberline, become more or less productive in its current range, and

decline in productivity and occurrence in those areas that become inhospitable for the species, presumably the warmer, drier portions of its current range. Most paleo-reconstructions over the Holocene show subalpine fir dominated during periods of cold, moist conditions but declined in extent as climates warmed (Brunelle et al. 2005; Whitlock 1993, 2004). Hamann and Wang (2006) projected that future losses of subalpine fir from drought will exceed gains from range expansion, resulting in a 97 percent decrease in the species' range in British Columbia. Romme and Turner (1991) estimated major to minor losses in subalpine fir in the future in the GYA, depending on degree of warming, and Bell et al. (2014) modeled little loss of subalpine fir in the NR. Using SDM techniques, Crimmins et al. (2011) estimated that the subalpine fir/spruce zone would move upward in elevation by 300 ft by 2050. Woodward et al. (1994) speculated that subalpine fir will experience less frequent and lower cone crops in the future. However, seedling establishment may be the bottleneck for subalpine fir establishment in the future; the species needs long periods of high moisture for seeds to germinate and seedlings to thrive (Urban et al. 1993), and those years that meet these conditions may be less frequent in the future in the lower subalpine.

In those areas with abundant precipitation, longer growing seasons and reduced snowpacks may increase regenerative success of subalpine fir, especially in those subalpine areas where snow historically controlled regenerative success (Means 1990; Urban et al. 1993). These areas constitute the majority of the fir's range in the subalpine to timberline. Little and Peterson (1991) found that most fir regeneration occurred in low snow years because there were more suitable microsites. Villalba et al. (1994) found subalpine fir growth was positively correlated with increasing summertime temperature. Higher productivity in these subalpine forests may also increase cone crops, tree growth, and species densities. Denser stands may eventually result in high competitive stress, making these fir stands even more vulnerable to high mortality from insects, disease, and abiotic factors, and therefore less resilient. However, declines in whitebark pine and lodgepole pine from beetle- and rust-caused mortality may facilitate fir regeneration and growth, resulting in more fir trees and more stands dominated by subalpine fir.

Those NR areas in high elevation (timberline) settings may see an increase in subalpine fir as the heavy snow and cold conditions that precluded fir regeneration at timberline become less frequent (Cayan et al. 2001; Rochefort et al. 1994). However, the decline of whitebark pine trees that act as nurse crops to facilitate subalpine fir establishment may contribute to the inability of the fir to gain purchase in the high elevation settings. Establishment of populations at the upper subalpine and timberline may only be possible when fire is absent long enough to allow enough subalpine fir to gain reproductive maturity so that sufficient seed can be dispersed over enough years to ensure suitable environmental conditions for seedling establishment (Little and Peterson 1991; Little et al. 1994).

Increases in wildland fire would decrease subalpine fir throughout the NR, and those decreases would be much more extensive and steeper than any resulting from direct climate change effects. Frequent fires would favor nearly all of subalpine fir's associates because it is the least adapted to survive fire (Arno and Hoff 1990; Keane 2001). Little et al. (1994) found little subalpine fir regeneration over 30 years after a fire at Mt Rainier, USA, but those regeneration events that did occur happened after low snow years. Heusser (1998) found that subalpine fir increased in growth with warmer temperatures during the spring of the growth year, but growth was negatively correlated with high summer temperatures the previous years.

In summary, the future of subalpine fir will depend on both the future level of fire and the degree of climatic warming. Subalpine fir will likely be a species that shifts across the high mountain landscape, with gains in expansion balancing losses of contraction (caused directly by changes in climate). However, future increases in fire, disease, and insects may limit its abundance. Since fir is an aggressive competitor, it is expected that its gains through advanced succession in the upper subalpine will probably be balanced or exceed its losses from the drier, lower subalpine caused by fire, drought, and pathogens.

Engelmann Spruce (Picea Engelmannii)

Autecology

Engelmann spruce is widely distributed in the western U.S. and is a major component of the high elevation NR forests (Alexander and Shepperd 1990). It grows in humid climates with long, cold winters

and short, cool summers, and occupies one of the highest and coldest environments of the western U.S. The range of mean annual temperature in which this species occurs is narrow considering its wide distribution. Engelmann spruce grows best on moderately deep, well-drained, loamy sands and silts, and clay loam soils from a variety of volcanic and sedimentary materials. It also grows well on glacial and alluvial soils where the water table is accessible.

Engelmann spruce is rated tolerant in its ability to endure shade, but is less shade tolerant than its major associate, subalpine fir (Minore 1979) (table 6.3). It is more shade enduring than interior Douglas-fir, western white pine, lodgepole pine, quaking aspen, western larch, or ponderosa pine (Alexander and Shepperd 1990). The species does not tolerate drought well and it is perhaps the least adapted to drought conditions of the subalpine tree species (Alexander and Shepperd 1990). It is highly frost-tolerant and one of the few upper subalpine species that can tolerate seasonal standing water. It is associated with mycorrhizae but does not seem to be dependent on the fungi for survival. It is wind-pollinated and its seeds are wind dispersed.

In the NR, Engelmann spruce is mostly associated with subalpine fir but grows with many other tree species, including mountain hemlock, whitebark pine, western larch, Douglas-fir, quaking aspen, lodgepole pine, limber pine and western hemlock. In most upland subalpine NR sites, Engelmann spruce is a minor species associated with subalpine fir in later seral communities. It is often found in the upper subalpine as scattered individuals with the greatest height and diameter (Arno 2001). Pure Engelmann spruce communities are found in wet areas and riparian settings, and in severe frost pockets where all frost-sensitive tree species are excluded.

Spruce seeds germinate in a variety of substrates, including duff, litter, and decomposed humus, and seedlings have best initial survival on duff seedbeds, rather than on mineral soil. Engelmann spruce has low tolerance to high temperatures and drought, especially in the first five years of establishment. Due to its slow initial root penetration and sensitivity to heat in the succulent stage, drought and heat girdling kill many first-year spruce seedlings. Drought losses can continue to be significant during the first five years

of seedling development, especially during prolonged summer dry periods (Alexander and Shepperd 1990). After establishment, adequate soil moisture, cool temperatures, and shade favor survival.

Engelmann spruce is similar to subalpine fir in that it has an average genetic diversity with weak geographic differentiation. It is considered intermediate in its adaptive strategy, being neither a generalist nor a specialist. Populations show habitat specificity. Engelmann spruce has a high outcrossing rate and possesses the ability to cross with white spruce (*Picea glauca*).

Disturbance Interactions

Engelmann spruce is highly susceptible to fire injury and death, but some spruce survive severe burns because of their large size (Bigler et al. 2005; Wadleigh and Jenkins 1996). The species can survive fire better than its primary associate, subalpine fir (Ryan and Reinhardt 1988). Surviving large spruce trees can provide abundant seed in burned areas, but rarely do these seeds germinate to create forests dominated by Engelmann spruce; these spruce-dominated forests only occur in seasonally-wet habitats (Pfister et al. 1977).

Engelmann spruce is susceptible to windthrow, especially after any cutting in old-growth forests. The spruce beetle (*Dendroctonus rufipennis*) is the most serious insect pest of Engelmann spruce. It is restricted largely to mature and over-mature spruce, and epidemics have occurred throughout recorded history. The western spruce budworm also attacks Engelmann spruce.

Historical and Current Conditions

It is difficult to determine recent trends in Engelmann spruce forests across the NR because the species is rarely the dominant component in a stand. One would expect that advancing succession under a century of fire exclusion has increased spruce in the subalpine and upper subalpine. However, logging and fire has reduced spruce in lower elevation areas where it occurs in seasonally wet areas and frost pockets.

Climate Change Responses

Similar to subalpine fir, some losses of spruce are likely in the drier portions of its range, especially in those seasonal moist sites that will be mostly dry in the future. Liang et al. (2015) found that major

mortality events have occurred in Engelmann spruce over the last twenty years because of increased drought, presumably related to changing climate. Alberto et al. (2013) found that this species had a reduced growth the year following warm, dry years in the U.S. Cascades. Using SDMs, Morales et al. (2015) projected a 47 percent contraction in Engelmann spruce in the northern Rocky Mountains by 2060, and Hamann and Wang (2006) projected a 27 decrease in the range of Engelmann spruce in British Columbia by 2050. Gray and Hamann (2013) estimated Engelmann spruce would move 230 ft northward and 550 ft higher in elevation by 2050 in the NR. Using SDMs for the southwestern US, Notaro et al. (2012) projected that Engelmann spruce would disappear by 2050. Using gap modeling, Burton and Cumming (1995) project a precipitous collapse of Engelmann spruce in the mesic forests of British Columbia. Coops and Waring (2011) used mechanistic modeling to simulate a retraction in spruce range by over 50 percent.

Spruce may be the first species to become established in high elevation areas where snow precluded conifer regeneration historically, but where there now may be a seasonal wetland or subalpine wet meadow (Schauer et al. 1998). Jump and Peñuelas (2005) note that Engelmann spruce has the genetic capacity to adapt to large swings in climate *in situ* by taking advantage of shifts in microsites. Due to its great seed dispersal ability and tall stature, spruce is able to disseminate into previously unforested areas, such as glades, meadows, and balds, to expand its range. Whitlock (2000) found increased spruce regeneration during the warmest periods of the past several centuries, and Luckman et al. (1984) found Engelmann spruce growth positively correlated with increasing summertime temperature. Various SDM approaches project minor changes in the spruce-fir subalpine zone (Bell et al. 2014; Crimmins et al. 2011)

Engelmann spruce is poorly-adapted to fire, and thus major declines are expected with the projected increases in area burned. These declines, however, may be offset by increased regeneration on burned areas with mineral soil substrates. Continued fire suppression activities may maintain spruce on the landscape, but it may persist at lower abundance because of increased drought. Fire suppression may also ensure the demise of Engelmann spruce in that, when fires eventually burn, the severities may be so great that they kill all spruce seed sources. In addition, Bentz et al. (2010) note that future climates will likely

be more conducive to the spruce beetle, and Stout and Sala (2003) note that future climates may foster more spruce budworm events, leading perhaps to further declines in spruce.

In summary, while Engelmann spruce is a species that is highly-sensitive to climate, it is likely going to persist in future NR landscapes because of its superior ability to seed into new areas, especially burned areas, and its ability to remain in the high mountain landscape. Projected increases in subalpine productivity will also serve to keep spruce on the NR landscape.

Mountain Hemlock (Tsuga mertensiana)

Autecology

Mountain hemlock is usually found on cold, wet, snowy upper subalpine sites where it grows slowly and sometimes lives to be more than 800 years in age. The species appears to be limited by late snowmelt, short growing seasons, and cool summer temperatures throughout much of its range in the Pacific Northwest. Earlier snowmelt, higher summer temperatures, and lower summer precipitation in the lower portions of its range produce conditions under which growth is limited (West et al. 2009). Areas occupied by mountain hemlock generally have a cool to cold maritime climate that includes mild to cold winters, a short, warm to cool growing season, and moderate to high precipitation. The presence of mountain hemlock in the Rocky Mountains is closely correlated with the eastward penetration of moist maritime air masses (Woodward et al. 1994). Mountain hemlock occurs in mixed upper subalpine stands in the western portions of the NR, often relegated to the moist north slopes.

Mountain hemlock is considered highly tolerant of shade and other forms of competition, and it is probably more tolerant than any of its NR associates, even subalpine fir in some places (Minore 1979). Mountain hemlock is considered a minor climax species in most of its limited habitats; mountain hemlock often succeeds lodgepole pine or subalpine fir (Means 1990). The species has a low tolerance for drought but a high tolerance for frost and standing water. It is wind-pollinated, and the seeds are wind-dispersed.

Mountain hemlock has large cone crops about every three years. It reaches reproductive maturity quickly by around twenty years, and most of the seedfall occurs during the fall months. It has average genetic diversity, weak geographic differentiation, but moderate population differentiation.

5821 *Disturbance Interactions*

5822 Mountain hemlock is considered susceptible to fire because it often retains branches almost to the
5823 ground, grows in clusters, and often has shallow roots that are throughout well-developed forest floors
5824 that dry out in the summer (Dickman and Cook 1989). It has thick bark and can withstand some low
5825 intensity fire, but overall, it will often succumb to fire damage over time. Fire is a rare visitor to these
5826 mesic, cold stands, so any increase in fire frequency will reduce mountain hemlock populations.

5827 The most striking damage to mountain hemlock is probably that caused by laminated root rot. This
5828 fungus spreads from centers of infection along tree roots so that all trees are killed in circular areas that
5829 expand radially. Mountain hemlock is the most susceptible species to root rot in subalpine forests (Means
5830 1990).

5831 *Historical and Current Conditions*

5832 There have been few evaluations of mountain hemlock distributions in the NR, and thus it is difficult
5833 to gauge trends in this species over the last century. The fire exclusion era has advanced succession in
5834 those subalpine sites where mountain hemlock can be found, thereby increasing the numbers and density
5835 of the species. These dense forests are probably not currently stressed because of high productivity in
5836 these areas. Mountain hemlock has a limited range in the NR, so any significant warming and drying
5837 could drive the species to be locally extinct.

5838 *Climate Change Responses*

5839 With warming climate in western North America, existing mountain hemlock forests will probably
5840 increase in productivity, especially in the upper and lower elevational boundaries of the mountain
5841 hemlock zone (Means 1990). Near Mount Baker, Washington, ring width of mountain hemlock increased
5842 with increasing monthly temperatures in the preceding 12 months, decreasing winter precipitation, and
5843 decreasing snow depth, implying that productivity should increase with predicted temperature increases
5844 (Woodward et al. 1994). Graumlich et al. (1989) estimated that productivity increased 60 percent in the
5845 last century in four high-elevation stands in Washington, three of which contained 48 to 96 percent
5846 mountain hemlock. They related this increase most strongly to the increase in growing season temperature

during this period (about 2.7 °F). West et al. (2009) projected that mountain hemlock growth and productivity will likely increase throughout much of its range in Washington and northern Oregon, but increased summer drought stress will reduce productivity in mountain hemlock forests of southern Oregon and near the species lower elevation limit. Peters and Lovejoy (1992) estimated that if mean annual temperatures increase 4.5 °F, the mountain hemlock zone may be shifted upwards 1800 ft and decrease in area from nine to two percent in Oregon. An increase of 9.0 °F may induce an upward shift of 3700 ft, which is above all but the tallest peaks, effectively eliminating the species from the NR (Means 1990). Woodward et al. (1994) speculated the mountain hemlock will experience less frequent and lower cone crops in the warm future.

In summary, the high productivity of mountain hemlock sites in the western NR may mitigate the potential decline of mountain hemlock over the next fifty years. There will likely be local shifts of the species where it is established in droughty low elevation areas of Idaho and western Montana, but overall, the species might be somewhat stable under climate warming, and it might even increase in productivity and make range expansions into the lower timberline. The species is not highly exposed to climate changes because of its limited range in the NR and its somewhat confined niche. The magnitude of climate effects on mountain hemlock responses will be great, but mostly positive, and the likelihood of these effects have a high uncertainty, mainly because of the role that fire will play in the dynamics of mountain hemlock populations in future landscapes.

Alpine Larch (Larix lyallii)

Autecology

Alpine larch is a deciduous conifer that occupies the highest and most remote environments in the NR, growing in and near the timberline on high mountains across the inland Pacific Northwest (Arno 1990). In the Rocky Mountains, alpine larch extends from the Salmon River Mountains of central Idaho northward to Lake Louise in Banff National Park, Alberta (Arno 1990). Within this distribution, alpine larch is common in the highest areas of the Bitterroot, Anaconda-Pintler, Whitefish, and Cabinet Ranges of western Montana. It is also found in lower abundance in isolated stands atop many other ranges and

peaks in western Montana and northern Idaho (Arno and Habeck 1972). Alpine larch grows in very cold, snowy, and generally moist climates where for more than half of the year, mean temperatures are below freezing. Mean annual precipitation for most alpine larch sites is between 32 and 75 inches, the larger amount being more prevalent near the crest of the Cascades; most stands in the Montana Bitterroot Range receive 39 to 59 inches. About 75 percent of this precipitation is snow and sleet. Ridgetop alpine larch stands are exposed to violent winds; most alpine larch stands annually experience winds reaching hurricane velocity or more, especially during thunderstorms or during the passage of frontal systems.

Alpine larch is perhaps the most drought-susceptible conifer in the NR because of its reliance on subsurface water during the dry summer months (Arno 1990). It achieves its best growth in high cirque basins and near the base of talus slopes where the soils are kept moist throughout the summer by aerated seep water. It can also tolerate boggy wet meadow sites having very acidic organic soils. The species is most abundant on cool, north-facing slopes and high basins where it forms the uppermost band of forest. It also covers broad ridgetops and grows locally under relatively moist soil conditions on south-facing slopes. The NR may have a droughty period for a few weeks in late summer, but the effect is minor in most alpine larch sites; however, dry surface soils may prevent seedling establishment in certain years.

Alpine larch is the most shade-intolerant conifer growing at high elevation NR sites and is classed as very intolerant (Minore 1979) (table 6.3). Its evergreen associates attain their best development in forests below the lower limits of larch. An exception is whitebark pine, another timberline inhabitant, which is most abundant on warm exposures and microsites and thus tends to complement rather than compete with larch. Alpine larch grows mostly in pure stands but it can be found with whitebark pine, subalpine fir, and Engelmann spruce near their upper limits. Alpine larch roots extend deep into fissures in the rocky substrate. Trees are well anchored by a large taproot and large lateral roots and are very windfirm. Alpine larch is easily replaced by subalpine fir in most upper subalpine sites, but the species can act as a climax species in the lower timberline (Arno and Habeck 1972).

Alpine larch is one of the few deciduous conifers in the NR, and as a result, it has a high capacity to survive wind, ice, and desiccation damage during the winter because the needles are off the trees. The

species also has an evergreen sapling stage that allows it to quickly take advantage of the short growing season in the early summer after snowmelt (Arno and Habeck 1972). Alpine larch seedlings are frost tolerant. Mature trees produce good cone crops every fifth year, and these seeds drop in early fall. It is assumed that the species has an average genetic diversity and weak geographic differentiation, but there has been little genetic work done on this species.

Disturbance Interactions

Fire is an occasional but localized visitor in alpine larch stands, causing injury or death in most cases. Large fires are infrequent in the cool, moist, and rocky sites where alpine larch occurs, and fire spreads poorly on these sites because of light and discontinuous fuels. Unlike its thick-barked, fire-resistant relative, western larch, alpine larch has thin bark, has low resistance to surface fire, and often dies after low-intensity fires (Ryan 1998).

Powerful winds in alpine larch stands often damage crowns, in conjunction with loads of clinging ice or wet snow (Arno and Habeck 1972). Nevertheless, this tree's deciduous habit and supple limbs make it more resistant to wind damage than its associates. Death usually occurs when advanced heart rot has so weakened the bole that high winds break off the trunk. Brown trunk rot produces the only conks commonly found on living trunks (Arno 1990); this fungus is evidently the source of most heart rot. Snow avalanches and snowslides are an important source of damage in many stands, but again, this species is better adapted to survive these disturbances than its evergreen associates.

Historical and Current Conditions

This species is rarely studied, and as a result, very little is known about its population trends in the NR. Our best guess is that alpine larch populations have stayed roughly the same across most of its range in the NR over the last 100 years. There have been some losses from fire in some areas, especially the Bitterroot Mountains of Montana, but there have also been gains. Recent anecdotal observations have found that alpine larch has been increasing in ribbon forests glades and high elevation open areas where snow accumulated historically, but over the last two decades, these heavy snow areas have been clear of snow enough of the year to foster alpine larch regeneration.

5925 Climate Change Responses

5926 We feel alpine larch has a high potential to experience decreases in both productivity and abundance
5927 with climate change. On one hand, alpine larch is a shade- and drought-intolerant species, indicating that
5928 it does not do well in areas of increasing dryness and competition (Arno and Habeck 1972). Its high
5929 demand for sub-surface water during the growing season appears to be the main factor limiting its range
5930 in the NR (Arno 1990), making it highly susceptible to increasing drought in the future. Alpine larch
5931 growth is highly correlated with high snowpack, especially in April, which is usually indicative of high
5932 subalpine moisture throughout the year (Colenutt and Luckman 1991; Peterson and Peterson 1994). The
5933 lack of summertime ground water would be more likely in the southern part of alpine larch's range in the
5934 NR, specifically western Montana and central Idaho.

5935 On the other hand, alpine larch can produce copious amounts of seed that may land on upper
5936 subalpine and timberline areas that were historically covered with snow the majority of the year, but in
5937 the future may be sufficiently snow-free to allow wind-dispersed seed to germinate and grow into viable
5938 seedlings. There is ample anecdotal evidence documenting alpine larch encroachment into snowfields,
5939 glades, and ribbon forests. These seedlings could become mature trees, provided there is sufficient
5940 moisture. With higher rates of productivity in a warming climate, seedlings and trees may have greater
5941 growth and cone production. However, short-term increases in alpine larch regeneration may be offset by
5942 the high variability in drought in the upper subalpine to eventually cause declines in the larch. Another
5943 possibility is that the more shade tolerant subalpine conifers, such as spruce and subalpine fir, might
5944 become established in these new open areas and outcompete alpine larch for dominance. Along those
5945 same lines, the more drought-tolerant whitebark pine may also become established in the snow free areas
5946 and survive the anticipated long droughts.

5947 While alpine larch does not seem to have the morphological, ecophysiological, and genetic capacity
5948 to adapt to new environments, it does have the ability to genetically integrate with western larch to
5949 produce hybrids that may be more tolerant of drought and competition (Carlson et al. 1990). Moreover, its
5950 superior seed dispersal capability may allow it to become established in treeline areas made

environmentally favorable by climate change, mainly from decreasing snowpacks and higher temperatures. These areas, however, may be significantly smaller and more isolated than areas in its current range, where it will decline because of lack of water.

Alpine larch is not well-adapted to survive wildland fire (Arno 1990), and as its existing range becomes drier and fires become more probable, it is expected that more alpine larch will burn, providing there are sufficient fuels. Those upper subalpine forests that are co-dominated by whitebark pine and alpine larch are probably the most susceptible of subalpine larch habitats to increases in fire. Rocks, scree, and fuel-free areas protect many alpine larch communities, so it may be years before fire, or the more shade-tolerant competitors, invade pure alpine larch woodlands (Arno and Habeck 1972). While alpine larch does not seem to be impacted by major insects and pathogens (Arno 1990), it could be that future climates may increase the possibility that insects and diseases that were relatively minor in the past could become more significant in the future, especially in timberline environments where damaging agents were depressed by cold (Woods et al. 2010).

In summary, alpine larch is one of the most susceptible tree species in the NR to climatic shifts that result in increasing drought and fire. Its exposure to climate change will likely be high, because upper subalpine areas may experience the greatest climatic change (Luce et al. 2013). Due to its specialized habitat, alpine larch has the highest risk for major range shifts, and impacts to the species may be great if there are insufficient environments created upslope.

Green Ash (Fraxinus pennsylvanica)

Autecology

Green ash is the most widely distributed of all the American ashes (Kennedy 1990), but primarily occurs in the eastern and central U.S. In the NR, green ash is restricted to the northern Great Plains, which is the northwestern edge of its range (Girard et al. 1987; Lesica 2009). Naturally a moist bottomland or stream bank tree, it is well-adapted to climatic extremes and has been widely-planted in the Plains states and Canada. It is probably the most adaptable of all the ashes, growing naturally on a range of sites, from clay soils subject to frequent flooding and overflow, to sandy or silty soils where the amount of available

moisture may be limited. In the northern Great Plains, green ash grows best on fertile, moist, well-drained alluvial soils, primarily along river bottomlands and woody draws. It also occurs in broad upland depressions and ridges, which have subsurface water early in the growing season (Girard et al. 1987; Lesica 2003; Lesica and Marlow 2013). Natural stands of green ash are almost completely confined to bottomlands, but the species grows well when planted on moist upland soils. It lines the watercourses in the western parts of its range where rainfall is insufficient to support upland growth.

Green ash varies from intolerant to moderately shade tolerant in woody draws. It is an early seral species, colonizing alluvial soils. It regenerates from seed when exotic grass (which inhibits germination through competition for soil moisture) is absent or has low cover (Lesica 2003; Lesica and Marlow 2013). It also regenerates vegetatively through stump sprouting. Uresk and Boldt (1986) reported 90 percent sprouting success following trunk removal in an experimental study in North Dakota. Lesica (2009) found that stump sprouts can achieve full tree height in 20 years. While green ash is generally drought-tolerant, since it is at the most arid edge of its range, prolonged drought may affect regeneration success (Severson and Boldt 1974). Kennedy (1990) found that a population from the arid, northwestern part of the green ash range was more drought resistant than one from the moister central Great Plains and northeast.

Disturbance Interactions

Green ash is easily killed by fire, but stumps of most size classes of green ash sprout readily after both fire and mechanical trunk or stem removal (Lesica 2009). The species has several insect and disease agents; it is particularly susceptible to white stringy heartrot (*Perenniporia fraxinophila*), which weakens the plant and makes it more susceptible to wind or ice breakage (Lesica and Marlow 2013).

Historical and Current Conditions

Very little is known about the range expansion or contraction of green ash. However, green ash in the NR is at the northwestern (most arid) edge of its range (Lesica 2009), and there is evidence suggesting that many of the green ash communities on the western fringe of the Northern Great Plains are declining (Boldt et al. 1978; Lesica 1989, 2001).

Climate Change Responses

Green ash has a broad ecological amplitude and can survive droughty conditions, but it grows optimally on moist sites. As soil moisture declines with a warmer, drier climate, marginal sites may become less favorable for regeneration and survival of young green ash trees. With increases in fire frequency, there will likely be increased vegetative regeneration and decreased production of seedlings following fire; fire often kills green ash seed on or near the soil surface, restricting seedling recruitment to surviving seed-producing trees. Green ash may benefit from increased temperatures, because seedling and mature tree growth may increase with increasing soil temperatures. However, those green ash populations associated with moist upland microsites (e.g., northeast facing residual snow-loaded depressions) may experience severe drought stress as snowpack declines and melts sooner, and regeneration may decrease, eventually resulting in loss of those communities.

Since most mature green ash communities are somewhat resistant to wildland fire, given that the species can sprout afterward, the projected increases in fire in the future may not impact most green ash stands, especially the moist communities. Low-severity fires might promote regeneration by thinning stands and stimulating sprouting; green ash has both root crown and epicormic sprouts, and both are typical following fire events, especially in the woody draws and riparian areas of the Great Plains. High severity fires, however, may result in mortality. Browsing pressure on green ash communities will also likely increase with increased drought, as upland grasses and forbs desiccate and senesce earlier, or are replaced by invasive, less palatable species.

Cottonwood (Populus spp.)

Autecology

Black cottonwood (*Populus trichocarpa*) is the largest of the American poplars and the largest hardwood tree in western North America (Debell 1990). Narrowleaf cottonwood (*P. angustifolia*) and black cottonwood grow primarily on seasonally wet to moist open canopy sites (typically along streams and rivers) in the western portion of the NR. Plains cottonwood (*Populus deltoides*) occurs in eastern Montana and the Dakotas portion of the NR. All three species typically occupy fluvial surfaces along floodplains of streams and rivers.

Cottonwoods typically dominate riparian communities on alluvial sites at low to mid-elevations. Various riparian shrubs (e.g., willows (*Salix*), alder (*Alnus*), birch (*Betula*), dogwood (*Cornus*) and a variety of graminoids and forbs occur in the understory of cottonwood stands (Merigliano 2005). Cottonwood is very shade intolerant, and shade-tolerant conifers (e.g., Douglas-fir, Rocky Mountain juniper (*Juniperus scopulorum*), ponderosa pine, Engelmann spruce, subalpine fir) may encroach and become dominant in upland cottonwood forests (typically on river and stream terraces). The species is also drought intolerant, and requires an accessible water table (i.e., free, unbound water) during most of the growing season (Rood et al. 2003). Older cottonwood individuals become can access very deep water tables. Plains cottonwood is likely more able to extract water in the unsaturated zone once the water table has dropped below the extent of the roots (Merritt et al. 2010). The finer textured soils in the northern Great Plains hold more water, but it is harder to extract due to the finer soil texture. However, plains cottonwood appears to have adapted to extract water and will likely be more resilient to drought than the other species.

For all three species of cottonwood, high streamflows are required for successful seedling establishment; the associated scouring action and deposition of fresh alluvium creates optimal surfaces for germination. All species of cottonwood are prolific seed producers, and the windborne seeds disperse widely once the catkins have matured and seeds are released. Seeds are only viable for about two weeks, and thus timing of seed release and recession of flood flows is essential to successful germination (Malanson and Butler 1991). Black and narrowleaf cottonwood seedlings are usually established on a yearly basis, depending on flood frequency, timing and duration. Plains cottonwood establishment is less frequent and more episodic, since flows are more variable in both magnitude and frequency. Scott et al. (1997) found that approximately 72 percent of the plains cottonwoods along the Missouri River of eastern Montana established after a very large flood event (flow $>1831 \text{ yd}^3/\text{s}$ with a recurrence interval of 9.3 years). High numbers of seedlings become established in the first year after a flood, but they naturally thin out up to several years later, if they have not been scoured away by high flow events. The young

seedlings and saplings that survive are frequently injured and sometimes killed by unseasonably early or late frosts (Debell 1990).

Disturbance Interactions

Cottonwood is mildly fire-tolerant owing to its thick bark, high branches, and foliage that is too moist to burn in most years. It is considered a weak stump sprouter, but unlike aspen, cottonwood rarely regenerates from suckers (Brown 1996). Gom and Rood (1999) found that black and narrowleaf cottonwood were more successful at coppice (stump) sprouting and suckering than plains cottonwood. Cottonwood is able to survive low intensity fires in the short term, but fire injuries can lead to the introduction of diseases that weaken and perhaps kill the tree (Borman and Larson 2002).

Although several insects attack cottonwood, none has yet been reported as a pest of economic significance. Tent caterpillars (*Malacosoma*) are the most important foliar feeders that affect the NR. At least 70 fungal species cause decay in cottonwood, but only six fungi cause significant losses; two of these (brown stringy heart rot (*Spongipellis delectans*) and yellow laminated butt rot (*Pholiota populnea*) cause 92 percent of the loss. Russian olive (*Elaeagnus angustifolia*) and saltcedar (*Tamarix ramosissima*) are aggressive invasive trees that often outcompete plains cottonwood, particularly during or following drought (Shafroth et al. 2009). These species, along with invasive herbaceous species, are a threat to cottonwoods in general.

Historical and Current Conditions

Black cottonwood was common throughout the Columbia River watershed in Lewis and Clark's day, and can still be found today, but it is greatly reduced in extent.

Climate Change Responses

As the snowpack declines and melts earlier with warming temperatures, there will be reduced, attenuated river flows (loss of extreme high and low flows), along with a possible shift in timing of peakflows to earlier in the season, before cottonwood seed is viable for germination. These shifts in timing, magnitude and variability may result in both decreased germination and establishment of young cottonwoods (Whited et al. 2007). There will also likely be increased human demands for water in the

future, which will likely result in creation of additional diversions and reservoir expansions. Any alteration of hydrologic flow regime (i.e., timing, magnitude and duration) will affect both floodplain interaction and available water to cottonwoods, which in turn may reduce recruitment and establishment of seedlings (Auble and Scott 1998; Beschta and Ripple 2005). Decreased streamflows and floodplain interactions may result in a conversion of streamside vegetation from cottonwood to upland species, along with reduced growth and regeneration (recruitment) and increased mortality of cottonwood (Beschta and Ripple 2005). Upland conifers (e.g., Engelmann spruce, lodgepole pine, and Douglas-fir) typically establish once the stream and local water table have dropped, and they can shade out the remaining cottonwoods. In addition to competition from upland conifers, there may also be increased browsing pressure on cottonwoods, which will further contribute to declines in cottonwood regeneration and recruitment.

Plains cottonwood may be more persistent under changing climate because of greater plant available soil water in the unsaturated zone (as a result of finer textured soils) in its habitat. Black and narrowleaf cottonwood typically occur in coarser substrate, which will become much drier as flows are lower and recede earlier than in the past, or are attenuated due to diversions. Seedling and sapling mortality may increase in these species. Plains cottonwood regeneration occurs with episodic flooding, whereas black and narrowleaf cottonwood regenerate with 1-3 year bankfull flow return intervals (typically an annual recruitment cycle); therefore, plains cottonwood will likely be more adapted to irregular flows that may occur with climate change. Black and narrowleaf cottonwood will likely be at greater risk to changing climate because of soil water characteristics in their habitats and their narrow amplitude in terms of germination and flood events on specific fluvial surfaces.

Vegetation Types

Vegetation types are broad species assemblages that are used to identify the geographic distribution of vegetation in the NR. Vegetation types are different than species in that species can be a major to minor component in a vegetation type, but vegetation types can be composed of a number of species. Here we describe generally the likely response of forest vegetation types in the NR to climate change.

This section is less detailed than the species section (above), because we assumed that individual species for each vegetation type could be referenced above.

Dry Ponderosa Pine/Douglas-Fir Forests

Ecology

Dry ponderosa pine and Douglas-fir forests are the driest forests in the NR. These forests are relatively rare in northern Idaho, more common in western Montana, and prominent in central and eastern Montana where moisture is most limited. They are often found at the foothills of mountain ranges in the NR, but also in extensive flatlands bordering perennial grasslands and shrublands. Historically, frequent fires often maintained pure to mixed ponderosa pine woodlands and savannas in areas currently occupied by this type. However, fire exclusion has led to increased tree density and abundance of Douglas-fir, making these forests susceptible to uncharacteristically severe fire.

Disturbance Interactions

These forests recover from disturbance by slowly transitioning from fire-tolerant pioneer species to less fire-tolerant and shade-tolerant “climax” species over time. This successional process can occur over 200 to 1000 years. Ponderosa pine is often able to colonize the hot dry surface conditions of a disturbed site. Over time, as it matures, it provides a shaded environment where less heat-tolerant Douglas-fir can establish. In a frequent low-severity fire regime, the thick-barked ponderosa pine survives fire, while the thinner-barked Douglas-fir and ponderosa pine seedlings do not. If frequent fires are sustained, the ponderosa pine forest can develop into large patches of open grown old-growth, intermixed with relatively small openings that can persist for centuries. During a cool wet climatic period, or through fire suppression, Douglas-fir or denser ponderosa pine can become established. The increased biomass and structural heterogeneity of these denser forests allow fires to develop into active crown fires that return the site back to the initial stand establishment phase. If fires re-burn these areas, forest establishment may be limited because of loss of seed source, limited soil moisture, and high surface temperature.

Historical and Current Conditions

A century of fire exclusion, coupled with extensive logging and grazing, has changed these open dry woodlands to closed, dense forests that are often dominated by Douglas-fir.

Climate Change Responses

This vegetation type may be reduced in some areas of its current range under changing climate because of dry, hot conditions. However, this type may expand into the mixed mesic forest type (next section), especially on south slopes, as drought increases. This forest type will probably be the most dynamic in the future, with many of the current areas of this type seeing losses in Douglas-fir, balanced by gains in ponderosa pine. Dry Douglas-fir communities that are currently too cool to support ponderosa pine may support more ponderosa pine with warming climate. Fire exclusion in this type has resulted in forest densification and accumulation of surface fuels that will likely support high-severity fires in the next century (Keane et al. 2002).

Western Larch Mixed Mesic Forests

Ecology

Western larch mixed conifer forests, found in northern Idaho and northwestern Montana, evolved under a mixture of moist air masses from the west and cold air masses from Canada, resulting in a patchy forest condition with a mixture of western larch, ponderosa pine, lodgepole pine, Douglas-fir and spruce subalpine forests. Western larch is most prominent on cooler, moist topographic positions (Touzel 2013), and thus, the influence of a warming climate may change the potential distribution of western larch to the more northerly aspects with soils most capable of retaining needed moisture during the growing season (Rehfeldt and Jaquish 2010).

Disturbance Interactions

These forests evolved under a mixed-severity fire regime, which produced a diverse pattern of shade intolerant western larch, ponderosa pine, lodgepole pine and Douglas-fir. High-severity fire was more common on moist and cool sites, and produced very large burn patches, often with legacy western larch (Marcoux et al. 2015). Under fire exclusion, many of these forests have become denser, putting them at risk from high-severity fire (Arno 2010; Harrington 2012; Hopkins et al. 2013).

Historical and Current Conditions

In the past, wildland fire maintained extensive stands of western larch across Montana and Idaho. Due to its great value as a timber species, many older western larch stands were harvested across much of the NR, and these forests were often planted back to western larch after extensive site treatments. With fire exclusion, succession advanced and western larch was replaced with mixed stands of lodgepole pine, Douglas-fir, and grand fir.

Climate Change Responses

The western larch mixed conifer forests of northern Idaho and northwestern Montana are a forest type that has been changing and will likely continue to change. Fire exclusion, coupled with climate change, will likely continue to reduce western larch and increase the more shade-tolerant Douglas-fir, grand fir, and subalpine fir in some areas. Continued fire exclusion will result in further accumulation of surface and canopy fuels, and coupled with hotter and drier conditions with climate change, put these forests at risk of high-severity fire, which may result in high mortality of the seed-bearing western larch and ponderosa pine.

There are some attributes of this cover type that may serve to make it more resilient in the future. Western larch is not susceptible to the wide range of insects and diseases common to its associated tree species, and it has the best ability to survive fire of all its tree associates. As such, it makes an excellent candidate to feature in management to increase resilience. Overall, however, western larch mixed mesic forests are one of our most vulnerable forests to climate change impacts, mainly because past land management has made natural western larch forests susceptible to the damaging effects of uncharacteristically high-severity wildfires. Management of these forest types to create stand and landscape conditions within the historical range of variability will likely increase resilience to climate change.

Mixed Mesic Western White Pine, Cedar, Hemlock, Grand Fir Forests

Ecology

The moist forests within the NR range from 500 to 1750 ft and occasionally occur at 1900 ft (Jain and Graham 2005). These forests are influenced by a maritime climate with wet winters and dry summers. Precipitation ranges from 20 to 91 inches and predominantly occurs from November to May. A defining characteristic of these forests is a layer of fine-textured ash (up to 24 inches thick) that caps the residual soils. In addition, these forests are characterized by complex topography, including dissected slopes and varying degrees of slope angle, all of which influence soil development and ash cap depth. Disturbance is also a main component of these forests that contributes to creating vegetative mosaics. Thus, the combination of disturbance, topography, moisture and temperature regimes, parent material, soil weathering, and ash cap depth results in productive and complex vegetation in terms of composition and structure. For example, eight to nine and sometimes ten different tree species can occupy a given square yard of this forest type (Jain and Graham 2005).

The primary nine tree species that grow together in this wet forest type, outside of riparian areas, are ponderosa pine, western larch, Douglas-fir, grand fir, western white pine, western redcedar, western hemlock, lodgepole pine, and Engelmann spruce. The niche that these species occupies varies by habitats. For example, western redcedar is a mid-seral species in western hemlock types but is late-seral on western redcedar riparian and upland habitat types. The genetic adaptive capacity and autecological characteristics of individual trees species and their tolerances for light, moisture, temperature, and disturbance is also highly variable among the different tree species in this forest type (Minore 1979). Some species are more adapted to regenerating in shade (western hemlock and western redcedar), while other species can regenerate in a wide range of conditions (western white pine). Some have a stronger competitive capacity than other species when growing together (western larch cannot compete with western hemlock). Some are drought tolerant (ponderosa pine, western larch, and western white pine), et al. are drought intolerant (western hemlock).

Disturbance Interactions

Natural disturbances (snow, ice, insects, disease, and fire), when combined, create heterogeneity in patch sizes, forest structures, and composition in this forest type. Ice and snow create small gaps and

openings, reducing forest densities and altering species composition. Native insects (e.g., bark beetles) and diseases (e.g., Armillaria root rot and dwarf mistletoes) infect and kill the very old or stressed individuals, and tend to diversify vegetation communities (Hessburg et al. 1994). A mixed-severity fire regime also plays a role in creating a mosaic of forest compositions and structures. Historically, non-lethal surface fires occurred at relatively frequent intervals (every 15 to 25 years) in a quarter of the area of this forest type. Lethal crown fires burned about a quarter of the area at intervals of 20 to 150 years, occasionally extending to 300 years. A mixed-severity fire regime characterized the rest of the moist forests, with return intervals of 20 to 150 years. Fires typically started burning in July and were usually out by early September (Hann et al. 1997).

Historical and Current Conditions

In addition to white-pine blister rust and salvage that removed most of the western white pine, harvesting removed the early-seral, shade-intolerant species (e.g., ponderosa pine and western larch) that were resistant to fire and other disturbances. Partial canopy removal and minimal soil surface disturbance in these harvests were ideal for Douglas-fir and grand fir, which regenerated aggressively, rather than the shade-intolerant pines and larch species. Fire exclusion also prevented the creation of canopy openings and receptive seedbeds for the regeneration of pine and larch. Similar to the dry forests, high canopies (>55 yds) of western white pine, western larch, and ponderosa pine and other early- and mid-seral species are currently absent. In their place, the present forest structure and composition (grand fir and Douglas-fir) favor the compression of nutrients, microbial processes, and root activity toward the soil surface (Harvey et al. 2008). When wildfires occur, surface organic layers can be consumed, decreasing the nutrition and microbial processes important for sustaining these forests. In general, the lack of the early-seral species and historical structures most likely have altered the disturbance regimes that sustained these forests.

Climate Change Responses

Habitat types are not static but reflect the operational environment that supports a particular set of plant species. As the moist forests experience climate change, the competition among species and how

these forests evolve will be particularly dynamic. Thus, any discussion concerning climate change and an individual tree species that grows in moist mixed conifer (and dry mixed conifer) must be placed within the context of species cohorts, an individual tree species adaptive capacity, the interaction of disturbance, and how environmental niches change over time and space. For example, if future moisture regimes no longer support the current distribution of western hemlock, the remaining species that thrive on the upland western redcedar habitat types will likely become dominant (Graham 1990). How disturbance changes (intensity, extent, and return interval) with a warming climate can also influence the subsequent effects on particular tree species. In a drier climate, western redcedar may become the late-seral species in what we consider to be western hemlock habitat types.

Lodgepole Pine Mixed Subalpine Forests

Ecology

Lodgepole pine forests straddling and occurring east of the Continental Divide are associated with the cold continental air mass that influenced their development. The higher elevations combined with the relatively dry cold climate associated with this type exclude many of the warm and moisture-dependent tree species found on the west side of the Continental Divide. Aspen, which is often associated with moisture seeps, swales, and other moist sites within this type, is released from conifer suppression by fire. Disturbance is needed to maintain aspen in this type and to keep seral lodgepole pine communities from becoming dense with subalpine fir.

Disturbance interactions. Lodgepole pine mixed subalpine forests in the NR evolved with both high-severity and mixed-severity fire regimes. Mixed-severity fire regimes were common in central Montana on flatter slope positions and produced a diverse pattern of various-sized patches of different ages and tree sizes. Stand-replacing fire return intervals were 100 to 500 years (Fischer and Clayton 1983). However, stands reaching 60 to 80 years of age often experienced severe mortality from mountain pine beetle, creating snags and down fuel (Jenkins et al. 2008).

Historical and Current Conditions

This forest type was probably the most extensive in the NR, with vast subalpine areas dominated by even- and multi-aged stands of lodgepole pine, mixed with aspen, created by mixed-severity fire. There have likely been increases in subalpine fir as a result of fire exclusion, but more importantly, most of this type is currently dominated by large, mature lodgepole pine. Landscapes of these mature forests have fostered the large mountain pine beetle outbreak observed in many parts of the NR (central and GYA).

Climate Change Responses

This type will probably see expansion and contraction, but provided that fire is not excluded from these areas, it will likely not change substantially under changing climate.

Whitebark Pine Mixed Upper Subalpine Forests

Ecology

Perhaps the most threatened forest type, whitebark pine mixed upper subalpine forests are associated with high elevations, and the distribution of this type is primarily influenced by the cold continental air masses in Montana and higher elevations in northern Idaho. In this type, whitebark pine is found with subalpine fir, Engelmann spruce, and mountain hemlock, and subalpine larch in the area west of the Continental Divide. This type occurs on approximately 5 million acres in the NR, primarily on the higher ridges and mountaintops. At the lower elevations within the range of this type, whitebark pine typically serves as a minor early seral species in mixed conifer stands. At the uppermost elevations, whitebark pine can serve as a major climax species.

Disturbance Interactions

Whitebark pine and its associates developed under both a stand-replacing fire regime on steep north slopes, and under a mixed-severity fire regime on other aspects and flatter slope positions. Various sized patches are common within the range, with density depending on moisture availability. The future could bring more intense fire that could further threaten whitebark pine distribution.

There have been three outbreaks of mountain pine beetle in the northern Rockies over the last 100 years. The first one in the 1920s-30s killed significant areas of whitebark pine (Tomback et al. 2001).

Snags from this outbreak can still be seen today. There was another major outbreak in the early 1980s, but the largest outbreak started in the mid-2000s and has continued, especially in the GYA.

Historical and Current Conditions

Over 14 percent of the NR could have consisted of whitebark pine forests, with late-seral mixed fir-spruce patches mixed throughout, prior to 1910. However, with extensive white-pine blister rust epidemics and mountain pine beetle outbreaks over the last several decades, the upper subalpine landscape has slowly shifted from whitebark pine to more spruce and fir and non-forest vegetation in some places (Tomback et al. 2001).

Climate Change Responses

There may be substantial change in the upper subalpine forests over the next century. However, that change will likely be driven by whitebark pine mortality from the exotic white-pine blister rust rather than climate change, and the changes will primarily be in forest composition and structure rather than distribution. Over the last forty years, whitebark pine has become a minor component of this forest type in many parts of the western NR because of white-pine blister rust, allowing subalpine fir to become dominant in both the overstory and understory. While the GYA has yet to see massive die-offs from white-pine blister rust, it has not escaped recent mountain pine beetle outbreaks, and the whitebark pine mortality rates in cone-bearing trees from these outbreaks exceed 50 percent in most areas. Recent fires in the upper subalpine have served to reset the successional clock to the earliest seral stages of shrub and herbaceous communities, but whitebark pine regeneration levels are low in these burns because of low population levels (Leirfallom et al. [in press]). It appears that the nutcracker is eating most of the seeds from the few remaining whitebark pine trees and not enough of their seed caches go unclaimed to germinate and grow into trees (Keane and Parsons 2010). This has served to keep recently burned areas in the shrub/herb stage for long periods, which may allow time for other wind-dispersed tree species to populate the burn. Thus, whitebark pine may continue to decline in this type, and species dominance will likely shift to subalpine fir, Engelmann spruce, and lodgepole pine.

It is likely that most of the range shifts of this forest type will be in wilderness areas, since about 50 percent of this type is found in wilderness (Keane 2000). Many NR wilderness areas have lands that are above the elevations at which this type occurs, so there are potential areas for this type expand. Wildland fire will be the catalyst for any range shifts in this forest type. Continued fire exclusion may seem appropriate for whitebark pine types, but it is contra-indicated in many situations; most whitebark pine will eventually succumb to white-pine blister rust, and thus suppressing fire does not necessarily protect it. Fire is needed to create conditions in which whitebark pine can become established and grow to maturity. If fires are suppressed and no rust-resistant trees are planted, then whitebark pine will likely remain a minor component of this forest type. However, if wildland fires occur and burned areas are planted with rust-resistant trees, then whitebark pine may become more abundant in the high-elevation settings of the NR. Therefore, land management will likely be more critical than climate in dictating the future composition and extent of this forest type.

Resource Concerns

Landscape Heterogeneity

Background

Historically, most Northern Rockies landscapes were shaped by disturbance regimes interacting with vegetation and climate creating shifting mosaics of diverse vegetation assemblages. Wildfire was the primary sculptor of historical landscape composition and structure, especially at lower elevations (including ignitions by Native Americans and lightning), with other disturbances (mountain pine beetle outbreaks, root rot pockets, windthrow) woven into the patchwork of forestlands. Forest patterns were constantly shifting over time and space at rates governed by interactions among vegetation, disturbance, and climate, resulting in different patch sizes, shapes, and distributions. Therefore, understanding the variability and scale of disturbance and succession is critical to quantifying historical landscape heterogeneity, which in turn affects biological diversity and ecosystem resilience.

High landscape heterogeneity creates diverse biological structure and composition that are considered more resilient and resistant to disturbances (Bannerman 1997; Cohn et al. 2015; Haire and McGarigal

2010; Turner 1987). For example, the effects of mountain pine beetle outbreaks are less severe in landscapes with diverse age structures of host tree species (Schoettle and Snieszko 2007). Heterogeneous landscapes also promote population stability (Oliver et al. 2010), because fluctuations in plant and animal population are less when landscape structure is diverse (Turner et al. 1993). Heterogeneous landscapes may also have more corridors, buffers, and refugia for wildlife and plant migration.

During the past 100 years, land management practices have altered the temporal and spatial characteristics of Northern Rockies landscapes. Timber management has modified patch shape and structure at lower elevation, and fire exclusion has changed patch size and diversity. Fire exclusion has in many cases created landscapes with large contiguous patches of old, dense stands with high surface and canopy fuel accumulations (Keane et al. 2002), although some areas with frequent disturbance (e.g., frequently burned ponderosa pine forest) are also homogeneous compared to pre-settlement montane forests (Romme 2005). Since we have directly or indirectly managed for late-seral conditions, some Northern Rockies landscapes are highly susceptible to insects and disease, owing to low tree vigor from intense competition, and have an abundance of live and dead fuels that will contribute to the severity of future wildfires.

Climate Change Responses

Many current Northern Rockies landscapes have less ability to buffer potential climate change effects because of widespread forest densification with shade tolerant species, although some landscapes, especially in subalpine forests, still have structures and compositions similar to those observed in the historical record. Recent wildfires, restoration activities, and timber harvest have helped return some heterogeneity, especially in wilderness areas and national parks. However, most Northern Rockies landscapes are outside their historical range and variability (HRV) in landscape structure, making it challenging to implement effective climate change adaptation.

Landscape heterogeneity may increase if climate-mediated changes in disturbance regimes increase (Funk and Saunders 2014). During the past 20 years, wildfire area burned and mountain pine beetle outbreaks have both increased, replacing late-seral forests with younger age and size classes and thereby

increasing heterogeneity. Continued increases in wildfire and other disturbances are projected in a warmer climate (Bentz et al. 2010; Marlon et al. 2009), so projected declines in biodiversity (e.g., Botkin et al. 2007) could be balanced by gains in landscape heterogeneity (Kappelle et al. 1999).

Continued fire exclusion in a warmer climate may promote late-seral forests that would be stressed from competition and drought (van Mantgem and Stephenson 2007). Wildfires that will eventually burn these landscapes may become large and burn more severely, thereby creating large patches of homogeneous post-burn conditions (Flannigan et al. 2005, 2009). These fires may also create semi-permanent shrublands and grasslands in areas that have become too dry for conifer establishment or where seed sources are eliminated (Fulé et al. 2004). However, some have found a high degree of heterogeneity in severity and vegetation conditions following large fires (Collins and Stephens 2010; Keane et al. 2008). Although the size, shape, and distribution of forest management treatments are a concern for landscape heterogeneity, the effects of management on landscape properties may be overwhelmed by other disturbances.

Is there an appropriate level of heterogeneity for Northern Rockies landscapes? How can management facilitate landscape heterogeneity and minimize adverse climate change effects? Mechanistic ecosystem models can be used to simulate landscape structure and composition in the future and for understanding effects of management actions (Keane 2013), but cannot generate heterogeneity metrics as design criteria for ecosystems. Using the HRV of landscape characteristics is a more straightforward and useful approach (Keane 2013; Morgan et al. 1994a; Nonaka and Spies 2005) (box 6.1). The HRV of landscape metrics may not represent future conditions (Millar 1997; Millar and Woolfenden 1999), but does provide an estimate of landscape conditions under which ecosystems have developed over the last thousand years, conditions that produced functional, heterogeneous ecosystems (Landres et al. 1999). It is preferable to first use HRV as a reference for landscape heterogeneity (Keane et al. 2015), then ecological models can be parameterized for historical conditions and used to generate a set of useful landscape metrics (Keane 2012).

Timber Production

6387 Background

6388 The area managed for timber production as one of the objectives for management is approximately
6389 8,600 out of 34,000 square miles of forested lands throughout the Northern Region of the U.S. Forest
6390 Service. This area includes approximately 2,600 square miles in northern Idaho, 3,800 square miles in
6391 western Montana, 1,400 square miles in central and eastern Montana, and 460 square miles in the Greater
6392 Yellowstone portion of the Northern Region.

6393 During the 1970's and 1980's, an average of 98 square miles were harvested each year, which
6394 amounted to about 1,900 square miles that had some type of harvest treatment implemented to meet
6395 various management objectives including timber production. During the time period from 1990 through
6396 2014, an average of 39 square miles were harvested each year, which amounted to about 970 square
6397 miles. Recent harvest during 2014 of 32 square miles may be more typical of current and near term future
6398 harvest levels.

6399 The species composition of timber harvests has fluctuated during the past 45 years, as harvest has
6400 often followed some disturbance agent such as mountain pine beetle in western white pine and lodgepole
6401 pine, spruce beetle in Engelmann spruce, white-pine blister rust in western white pine, root disease in
6402 Douglas-fir and grand fir, Douglas-fir beetle and spruce budworm in Douglas-fir, and wildfire in a variety
6403 of species types. The current percentage of total hectares in each of the major species composition groups
6404 within the approximately 8,687 square miles of lands suitable for timber production across the Northern
6405 Region is 6 percent ponderosa pine, 13 percent dry Douglas-fir, 27 percent lodgepole pine, 6 percent
6406 western larch, 12 percent mixed subalpine fir and Engelmann spruce, and 35 percent mixed western white
6407 pine, grand fir, western hemlock, moist site Douglas-fir and western redcedar forests.

6408 Many of the current timber harvests in mixed mesic types of northern Idaho and western Montana are
6409 removing grand fir, Douglas-fir and western hemlock, and replanting western white pine, western larch
6410 and ponderosa pine. Other harvests involve removal of lodgepole pine and replanting of western larch.
6411 Thinning in ponderosa pine and dry Douglas-fir forests is also common. Within the eastern Montana and

the GYA, harvesting is concentrated on mountain pine beetle-susceptible or dead lodgepole pine and ponderosa pine, and thinning in ponderosa pine and dry forest Douglas-fir forests is also common.

Climate Change Responses

With increasing temperatures and the potential for increases in forest productivity (Aston 2010; Joyce 1995) and biomass accumulation (Lin et al. 2010) will probably come increases in timber production for most NR forests (Garcia-Gonzalo et al. 2007). Since the majority of NR forested lands are in the mesic montane, subalpine, and upper subalpine, the productivity increases are projected to be substantial. The increase in biomass might result in higher basal areas, greater timber value, and increased regeneration (Sohnngen et al. 2001). However, these mesic temperate forests might also become denser, which may result in decreased vigor that may offset gains in productivity from climate alone. Depressed vigor might also increase susceptibility to insects and disease, and since insect and disease outbreaks are projected to increase in severity and frequency, there may be some major timber losses from forest pathogen and insect mortality (Joyce et al. 2008). There will also be an increase in potential mortality from wildland fire with increased fuel, drier conditions, and longer fire seasons, and this might facilitate even more timber losses. Future timber harvests from mature timberland might be a race against losses from increased insects, disease, and fire. The greatest climate change impacts on commercial forestry may come from changes in the disturbance regimes rather than changes in productivity (Kirilenko and Sedjo 2007).

There are other considerations in addressing how timber resources in the NR will change with warming climates. First, the majority of roads on NR lands are in drier, lower elevation forests where productivity may decline and more trees are projected to die from drought. Fewer roads are in the subalpine and upper subalpine where productivities and associated timber values are likely to increase, resulting in limited ability to transport timber to markets. Creation of new roads is expensive, risky, and environmentally damaging. These higher lands are distant from timber markets and sawmills, and are also more topographically complex and steep, thereby limiting the potential for mechanized timber removal while also increasing harvesting costs. These higher elevation lands are also where most of the threatened

and endangered plant and animal species are found, especially grizzly bear (*Ursus arctos*), Canada lynx (*Lynx canadensis*), and wolverine (*Gulo gulo*), making it more difficult to implement timber harvest projects in these sensitive areas. If increases in insects, diseases, and fire are realized, the quality of timber will probably be reduced, and the value of the timber for building material will drop dramatically (Gillette et al. 2014; Kirilenko and Sedjo 2007; Spittlehouse and Stewart 2004). Longer fire seasons will probably mean there will be less time to perform forestry tasks, such as inventory, sale layout, and cruising. This may also mean that less agency money will be spent on forestry projects, such as ecosystem restoration, fuel treatments, and timber harvest sales, and more money will be spent on fire suppression activities. As the risk of uncharacteristic fire severity due to uncharacteristically high forest density increases, there will most likely be reductions in timber production opportunities, especially in dry forest areas that may be lost and converted to grass and shrub lands (Allen et al. 2010).

Timber species will also shift in the future. Increases in temperature and soil moisture deficits may result in shifts of desirable timber species, such as western larch, to species compositions that are susceptible to root disease, such as Douglas-fir and grand fir. Any increases in production at mid and higher elevations from warming temperatures could be offset by losses from root disease because of continued fire exclusion. Land management efforts that create late-seral, shade-tolerant communities, namely fire exclusion and some fuel treatments, will increase the risk that any standing timber will be affected by damaging agents before it can be harvested.

Many new forest practices, harvesting techniques, and markets are being proposed to offset carbon emissions from fossil fuels with carbon emissions from harvested biomass (Kirilenko and Sedjo 2007). Most of these new technologies will result in better utilization of timber resources and a more diverse and vibrant timber market. Biomass burning for energy, for example, could provide a market for non-commercial material removed from proposed fuel treatments. Slash piles could have value as biomass for energy. A more diverse market for wood products would surely enhance potential timber harvests in the NR, but it is essential that any proposed cutting activity be done in an ecological context, especially in this time of rapidly changing climates. Proposed harvesting activities must address a wide diversity of

issues, such as landscape character, species mix, successional dynamics, and fuels, to ensure these activities are effective and to minimize the long-term environmental impact.

It is essential that ecological principles be used to design harvest treatments of the future to ensure the creation of resistant, resilient forests that can withstand major impacts of climate change. Designing fuel treatments without considering ecosystem restoration concerns, for example, might create forests that are highly susceptible to insects and disease or fire. Favoring shade-tolerant, fire-susceptible species over fire-tolerant, sun-loving, early-seral trees species is ecologically inconsistent and will likely create landscapes that are intolerant of future climate change.

One proposed management alternative, carbon sequestration (see next section), might be cause for concern. The main assumption of most carbon sequestration options is to maximize biomass to sequester carbon from the atmosphere and put it into timber products to offset fossil fuel burning. The problem is that this approach must recognize the role of disturbance to be effective in the long term. Many studies have shown that the most resilient forests are ones with sub-optimal carbon sequestration.

Again, the major issue related to climate change and timber production in the near term is loss from disturbance. The anticipated increases in drought, severe large wildfires, root disease, other diseases such as white-pine blister rust, and insect damage such as that from large-scale bark beetle outbreaks, need to be addressed throughout the NR. Tactics to increase landscape heterogeneity overall, and reduce forest density in the dry forest types will be key climate change responses in the near term. Additionally, in the short and long term, adjusting species composition and distribution will be very important to sustaining long-term timber production.

Carbon Sequestration

Background

North American forests are considered important carbon sinks and currently offset about 13 percent of annual continental fossil fuel emissions (Pacala et al. 2007). Size and persistence of forest carbon sinks depends on land use and land management and environmental factors such as vegetation composition, structure, and distribution, climate, and disturbance processes including wildfire. Carbon accumulates in

woody biomass and soils for decades to centuries until a disturbance event releases this stored carbon into the atmosphere. Although long intervals between disturbance events, such as wildfires or insect outbreaks, can allow carbon to accumulate for years to centuries, probability of disturbance increases with time (Loehman et al. 2014). Thus, disturbance-prone forests will eventually move stored carbon to the atmosphere, regardless of management strategies designed to limit or prevent disturbance events. However, unless structural or functional ecosystem shifts occur, net carbon balance in disturbance-adapted systems at steady state is zero when assessed over long time periods and at landscape scales. This is significant to management for two reasons: (1) disturbance-prone ecosystems cannot be managed to increase stored carbon over historical amounts without limiting the occurrence and magnitude of disturbance events; and (2) major shifts in vegetation composition, distribution, and structure resulting from climate change will result in different patterns of carbon storage on the landscape as compared with the historical period. Thus, it is important to develop expectations for landscape carbon storage potential in the context of projected climate change effects on both disturbance dynamics and vegetation patterns, and the relationships between them.

Vegetated landscapes play an important role in storing carbon in the form of plant and animal materials (both live and dead), aboveground and in soils. Forests store carbon in soils (approximately 45 percent of total storage), above and belowground live biomass (approximately 42 percent), deadwood (approximately 8 percent), and litter (approximately 5 percent) (Bonan 2008; Pan et al. 2011). Since forests contain large reservoirs of carbon (i.e., carbon sinks) and facilitate flows of carbon from the atmosphere to the biosphere (i.e., carbon sequestration), they are an important component of the global carbon cycle and are thought to have the potential to mitigate climate change (Ingerson 2007; Pan et al. 2011). For example, North American forests currently offset about 13 percent of annual continental fossil fuel emissions (Pacala et al. 2007). The carbon sequestration potential of Earth's forests is about 33 percent of global anthropogenic emissions from fossil fuels and land use (Denman 2007). Size and persistence of forest carbon sinks, and thus their potential to mitigate climate change, depends on both anthropogenic activities such as land use and land management, and environmental factors such as

vegetation composition, structure, and distribution, climate, and disturbance processes including wildfire (Loehman et al. 2014). Carbon typically accumulates in woody biomass and soils for decades to centuries until a disturbance event releases this stored carbon into the atmosphere (Goward et al. 2008). Disturbance is recognized as the primary mechanism that shifts ecosystems from carbon sinks to carbon sources (Baldocchi 2008), and wildfire in forested ecosystems is one of the primary disturbances that regulates patterns of carbon storage and release (Kasischke et al. 2000a,b). Forest insect outbreaks can also release carbon through decomposition of needles and other fine fuels from attacked trees (Kurz et al. 2008). The amount and rate of carbon release from a disturbance event depends on the extent and severity of the disturbance, as well as predisturbance site conditions and productivity (Bigler et al. 2005; Falk et al. 2007). In the case of both wildfires and insect outbreaks, although long intervals between events can allow carbon to accumulate for years to centuries, probability of disturbance increases with time (Clark 1989). Climate changes, in combination with other ecosystem stressors such as disturbance, may be sufficient to cause structural or functional changes in ecosystems, and thus fundamentally alter carbon dynamics of landscapes.

Climate Change Responses

As described in chapter 8, future warmer, drier conditions are likely to result in more frequent, larger wildfires, and greater annual area burned, that will serve to move carbon from biomass storage to the atmosphere. Warmer temperatures and increased drought stress are also projected to increase the area susceptible to or affected by beetle outbreaks. Regrowth of forests following disturbance may be delayed if the climatic conditions stress remaining or re-establishing species. Disturbance events in combination with additional climate-caused stressors may also result in functional transitions, such as a shift from forests to montane woodland or grassland-dominated vegetation types, which would likely result in less stored carbon. Frequent fires may also maintain open woodlands and savannas that might sequester less carbon than forests, but these carbon pools may be more stable and resilient to climate shifts.

Strategies that aim to manage carbon resources should consider the following:

1. Is the system disturbance-prone? If so, is it reasonable to expect the system to accumulate carbon over historical (steady-state) levels, especially given future climatic conditions that may increase the frequency, severity, and magnitude of disturbance events?

2. What are appropriate temporal and spatial scales over which to measure carbon storage? For example, in forests with multi-century disturbance cycles, it may take hundreds of years for forests to attain pre-disturbance levels of carbon, but this does not mean that they have become carbon sources at the appropriate, ecological scale of measurement?

3. Can potential future disturbance events be managed? For example, will it be possible to suppress or exclude wildfires from the system in the future, and at what economic or ecological costs?

4. Can additional stressors (e.g., drought stress, invasive weeds, and other management activities) be mitigated, to help maintain existing vegetation communities?

5. How might the system change with changing climate and disturbance? For example, are future climatic conditions conducive to persistence of forests, or will conditions become too warm or dry for the current dominant species?

6. Do planned carbon accounting methods assess ecological benefits of natural disturbance processes in carbon-equivalent units so that they can be weighed against carbon losses from disturbance? For example, wildfires confer many important ecological benefits not measurable in carbon units (e.g., nutrient release and redistribution and stimulation of plant growth, increased productivity in soil systems from decomposition of burned material, initiation of vegetation succession and forest regeneration, and increased availability of resources for surviving trees) that may actually increase carbon sequestration rates.

Two complementary activities, monitoring and modeling, can improve our understanding of cross-scale ecological drivers and responses to disturbance (Loehman et al. 2014). Monitoring programs can be used to quantify long-term carbon dynamics before and after disturbance, evaluate responses of ecosystems to changes in climate, and identify shifts in ecosystem patterns and processes emergent under

changing climates. Monitoring data can also be used to provide inputs to, calibrate, and validate models. Models, in turn, can be used to simulate emergent environmental patterns, compare effects of potential treatments, identify vulnerable landscapes or ecosystem components, and bridge gaps between landscape-scale ecological processes and variables measured in small areas and over short periods of time. There is room for improvement on both fronts, as described previously in this chapter. Although it may be tempting to meet policy-driven goals of increased carbon storage via management strategies designed to exclude or limit the extent and magnitude of disturbance events (e.g., wildfires), it is important to remember that native disturbance processes confer many important ecological benefits not measurable in carbon units (e.g., nutrient release and redistribution and stimulation of plant growth, increased productivity in soil systems from decomposition of burned material, initiation of vegetation succession and forest regeneration, increased availability of resources for surviving trees). Thus, it will be important to develop accounting methods that can assess ecological benefits in carbon-equivalent units so that they can be weighed against carbon losses from disturbance.

VULNERABILITY ASSESSMENT

All items in each of the three scales of assessment were rated as to their vulnerability to climate change using the same rubric employed across all chapters in this report (Table 6.4), and the results are summarized in detail in appendix 6B. We populated a table with valuable information for the eight categories in Table 6.4 using a thorough consideration of five factors: (1) climate; (2) disturbance; (3) life history; (4) dependencies; and (5) other stressors. For climate, we considered whether the species, vegetation type, or resource concern was sensitive to changes in direct effects of climate (temperature and precipitation) or indirect effects of climate (e.g., soil moisture, snowpack, seasonality of flows, climatic water deficit, altered flow regimes, and stream temperature). For example, we asked, “Does the system inhabit a relatively narrow climatic zone or does it experience large changes in composition or structure with small climatic changes?” We also considered both direct sensitivity to climate change (e.g., ecophysiology and life history) and indirect sensitivity to climate change (e.g., ecological relationships such as competition, dispersal, and migration). Vulnerability to disturbance was assessed in reference to

whether the species, type, or concern was sensitive to major disturbances, mainly wildland fire, insect outbreaks, drought, and pathogens. Disturbances are major catalysts for vegetation change and can combine with climate stressors and non-climate stressors to create a broader stress complex with multiple interactions. Life history aspects of the species and vegetation type were considered to address the impact of a species' growth rate, susceptibility to mortality, longevity, and reproductive strategy, which may influence sensitivity to climate change. Species with long life spans may have lower vulnerability than short-lived species. We also addressed the species dependencies on other ecosystem processes or landscape elements. Riparian species, for example, are dependent on wet conditions. Lastly, non-climate stressors, such as land use, grazing, and timber harvest, and fire exclusion were integrated into our assessment.

The appendix 6B vulnerability assessment is further summarized in Table 6.5 for only the tree species included in this report. We ranked each species by the NR geographic regions (fig. 6.1) and removed those species that did not occur in those regions. We also included the rankings of two other efforts for comparison purposes. The Devine et al. (2012) report assessed vulnerability for a number of tree species in the Pacific Northwest, and the Hansen and Phillips (2015) effort assessed vulnerability for some NR tree species using SDMs. This information is presented as a means to aid land managers to integrate climate change impacts into their planning documents and analyses.

ADAPTATION STRATEGIES AND TACTICS

This chapter documents what could happen to NR forest resources under potential future climates. However, the real question facing land managers is what they should do to adapt to climate change and mitigate any adverse impacts incurred as a result of changing climate. Adaptation can be defined as initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects (IPCC 2007). Adaptation actions range from the simple, such as doing nothing or increasing the harvest rotation age, to the complex, such as implementing fuel treatments to reduce the risk of high-severity fire in ecosystems with rare plants (Spittlehouse and Stewart 2004). Most land managers have the tools, knowledge, and resources to begin to address climate change, but as

Swanston and Janowiak (2012) note, managers need to expand their thinking to consider new issues, spatial scales, timing, and prioritization of efforts. For example, managers need to account for the high variability and trend of climate in the design of alternative land management actions.

There are some fundamental principles that can serve as starting points in the development of adaptation approaches (Joyce et al. 2008; Millar et al. 2007a; West et al. 2009). First, it will be increasingly important to prioritize management actions based on both the vulnerability of resources and on the likelihood that actions to reduce vulnerability will be effective (i.e., prioritization). Next, adaptive management principles provide a decision-making framework that maintains flexibility and incorporates new knowledge and experience over time (i.e., adaptive management). Management actions that result in a wide variety of benefits under multiple scenarios but have little or no risk may be initial places to look for near-term implementation (i.e., low-hanging fruit). Where vulnerability to a particular resource is high, precautionary actions to reduce risk in the near term, even with existing uncertainty, may be extremely important (i.e., triage). It is important to remember that climate change is much more than increasing temperatures; increasing climate variability across all components of climate, such as precipitation, humidity, and radiation, will lead to equal or greater impacts that will need to be addressed (i.e., increased uncertainty). Lastly, many adaptation actions are often complementary with other land management actions, and any actions to adapt forests to future conditions may also help restore these forests to healthy conditions (i.e., multiple objectives). When designing adaptation actions, it is important to address and integrate these principles to maximize efficiency.

The concepts of resistance, resilience, and response serve as the fundamental options for managers to consider when responding to climate change using adaptation (Millar et al. 2007a; Swanston and Janowiak 2012). *Resistance options* improve the ecosystems defenses against anticipated climate change responses or directly defend the ecosystem against disturbance to maintain current conditions. Resistance actions are often effective in the short term, but it is likely that resistance options may require greater effort over the long term as the climate shifts further from historical norms. Moreover, there is a real risk that the ecosystem will undergo irreversible change because of large climatic shifts, thereby rendering all

resistance activities ineffective. *Resilience options* allow some change, but emphasize a quick return to prior conditions after a disturbance. Resilience actions are also short-term and should be used for high-value resources or areas that are buffered from climate change impacts. *Response options* intentionally accommodate change and allow ecosystems to adaptively respond to changing and new conditions. A wide range of actions exists under this option, all working to influence ways in which ecosystems adapt to future conditions.

Resistance, resilience, and response options serve as the broadest and most widely applicable level of a continuum of management responses to climate change. Along this continuum, adaptation actions become increasingly specific from options to strategies to tactics. Adaptation *strategies* describe how adaptation options could be employed, but they are still broad and general in their application across ecosystems, while *tactics* are more specific adaptation responses, and they can provide prescriptive directions on how actions can be applied on the ground.

There are many broad strategies and associated tactics that can be used to adapt to climate change impacts in the NR, and the major ones that were identified by managers and scientists in a series of workshops in the fall of 2015 are detailed in Table 6.6 and described below. Adaptation tactics for all NR species, vegetation types, and resource concerns discussed in this chapter are summarized in Table 6.7. Adaptation tactics were designed at different scales and levels of organization. Some concern NR managers at the highest levels of agency organization, while others concern ecologists, silviculturists, and resource specialists at the lower levels of organization. Some tactics concern multiple species or resources, while others are specific to just one entity. These tactics were design so that NR managers can use these recommendations to directly address climate change impacts in their planning and implementation of any action, specifically National Environmental Policy Act analysis.

As in other adaptation efforts, many tactics developed by NR managers were focused on protecting forests from severe disturbance, mainly fire (Table 6.6). For example, managers identified promoting disturbance-resilient forest structure and species as key strategies. Thinning and prescribed fire can both be used to reduce forest density and promote disturbance-resilient species. Disturbance-resilient species

can also be planted. Managers recognized the importance of promoting and planting site-adapted species, specifically western larch and western white pine on moist sites, ponderosa pine on dry sites, Douglas-fir on extremely dry sites, and lodgepole pine on harsh sites that are difficult to regenerate.

Preparing for disturbance will also be important under a changing climate. Tree regeneration after severe fire may be more limited in the future with increased drought. Promoting legacy trees of disturbance-resilient species may help to increase postfire regeneration. Managers may also want to increase seed collection and ensure that adequate nursery stock is available for post-disturbance planting.

Another theme in the adaptation strategies and tactics developed by NR managers was promoting diversity, including species diversity, genetic diversity, and landscape diversity. Increasing diversity is a “hedge your bets” strategy that reduces risk of major forest loss. Areas with low species and genetic diversity will likely be more susceptible to the stressors associated with climate change, and thus, promoting species and genetic diversity, through plantings and in thinning treatments, will likely increase forest resilience to changing climate. Promoting landscape heterogeneity, in terms of species and structure, will also likely increase resilience to wildfire, insects, and disease.

There is a lot of uncertainty associated with climate change, and managers identified several ways to increase knowledge and manage in the face of uncertainty. Implementation of an adaptive management framework can help managers deal with uncertainty and adjust management over time. In the context of climate change adaptation, adaptive management involves: definition of management goals, objectives and timeframes; analyzing vulnerabilities; determining priorities; developing adaptation strategies and tactics; implementing plans and projects; and monitoring, reviewing, and adjusting (Millar et al. 2014). Development of a consistent monitoring framework that can capture ecosystem changes with shifting climate is a key component of the adaptive management framework. For example, tracking tree species regeneration and distribution will help managers determine how species are responding to climatic changes and how to adjust management accordingly (e.g., guidelines for planting). Integration between research and management and across resource areas (e.g., forest management and wildlife) will also be key in implementation of the adaptive management framework to ensure that the best available science is

being considered in on-the-ground management and that management approaches do not conflict (e.g., what effects will particular thinning treatment have on wildlife?).

Managers also identified adaptation strategies and tactics to maintain particular species or community types of concern. For example, climate change will likely lead to increased whitebark pine mortality through increased mountain pine beetle activity, fire and white-pine blister rust. There will also likely be a loss of site conditions that support whitebark pine. To promote resilient whitebark pine communities, managers may want to focus restoration efforts on sites less likely to be affected by climate change (i.e., refugia). A variety of management strategies can be implemented to promote whitebark pine, including fire management, planting at lower elevations, and removing other dominant species (e.g., lodgepole pine, spruce and fir). Genetically selected seedlings can also be planted to promote blister rust resistance.

Finally, managers recognized that stressors associated with climate change cross boundaries, making it increasingly important that agencies coordinate and work across boundaries. Agencies can coordinate by aligning budgets and priorities for programs of work, communicating about projects adjacent to other lands, and working across boundaries to maintain roads, trails and access that will likely be more frequently impacted by fire and flood events under changing climate.

DISCUSSION

Given the high uncertainties in predicting climate, vegetation, and disturbance responses to increasing CO₂, we feel that assessing vegetation change and vulnerabilities is currently more of an educated guess based on inconsistent and contradictory studies rather than a highly confident evaluation of comprehensive scientific investigation. Many of the techniques used to predict tree species response to climate change in the literature present only one possible future out of seemingly unlimited possibilities. These predictions would change if a new climate change scenario were used; if new data were augmented with existing data; if new variables were included in the analysis; if simulation parameters were modified; or if new algorithms were included in existing models. Moreover, there are still many unknowns in ecosystem science, and if you link those unknowns to the unknowns in climate systems, these

uncertainties would certainly swamp any educated guesses that we might have. The end result is that these projections and assessments must be interpreted in the context of high uncertainty.

One important lesson that we learned while writing this chapter is that climate change is only one of the many challenges facing land managers, and some of these other challenges might be more important than mitigating climate change. We found that by successfully mitigating ecosystem impacts from past management actions, such as fire exclusion and exotics introductions, will also mitigate against climate change impacts. Restoring fire-prone ecosystems declining due to fire exclusion, for example, might successfully solve two issues – it would increase ecosystem health and create resilient forests that could thrive under future climate changes. These fire-dominated forests have already experienced great variation in past climate and clearly have broad amplitudes of resilience with respect to climate. In another example, fostering greater rust-resistance in our native five-needle pines may allow us to create those forests that are less vulnerable to changes in climate. There will be places in the NR where the primary challenge will be climate change impacts, such as drought at the lower treeline, but overall, we feel that the best approach is to integrate climate change considerations into current management actions rather than conduct management actions for the sole purpose of climate change mitigation. Ecosystem restoration, as a prime example, could be the best approach for preparing for climate change.

The main question then, is how do we restore ecosystems in the NR? Managers need reference conditions at the stand and landscape scales to prioritize, plan, design, and implement effective restoration activities. This becomes somewhat problematic when we need that reference to include the trend and variability of future climate. Considering the high uncertainty of future climate and vegetation projections, and knowing the resilience of fire-adapted species, we suggest that any conclusions about the infeasibility of ecosystem restoration under changing climate are imprudent. On one hand, it may be more prudent to wait until simulation technology has improved to include credible pattern and process interactions with realistic regional climate dynamics for the future so that we base decisions on the restoration of ecosystems on better information. But improving ecosystem models may take decades before simulations can be used to predict species and landscape response to climate change with

reasonable accuracy, and while we wait, we lose valuable populations and rust-resistant trees, and our options for restoration diminish greatly. Even with climate change, restoration activities will probably be appropriate considering the considerable genetic variation across the range of this species, which provides the foundation for adaptation (Rehfeldt et al. 1999; Bower and Aitken 2006, 2008, Mahalovich and Hipkins 2011). Therefore, we believe that the current emphasis on ecosystem restoration in the NR will lead to more resilient ecosystems for the future. Until we have realistic models and less uncertain climate change projections, we desperately need a construct to use as a reference for restoration. It may be less uncertain to use historical data to guide future management actions rather than build new references based on uncertain climate change projections. Therefore, we believe that historical ranges and variability (HRV) may provide sufficient reference conditions in the future.

We feel that the concept of HRV still has a valid place in land management, at least for the near future. Landscape models can be used to simulate fire regimes and their interaction with climate and vegetation to create HRV time series that can be used as reference conditions to assess, plan, evaluate, design, and implement ecosystem restoration treatments. HRV should only be used to guide land management; not as a target on which to evaluate success or failure. There are few measures of ecosystem health that match the scale, scope, flexibility, and robustness of HRV analysis. HRV might provide a useful, but not ideal, reference for land management over the next several decades until simulation modeling advances to a level where future models can forecast both accurate climate and climate responses by the ecosystems.

CONCLUSIONS

Climate change is one of many challenges facing land managers, and some of these other challenges might be more important than climate change. In addition, mitigating past ecosystem damage (e.g., fire exclusion and nonnative introductions) is a climate-smart practice. For example, restoring fire-prone ecosystems can both improve ecosystem function and create forests that will be resilient in a warmer climate. Fire-prone forests have already experienced variation in past climate and have broad amplitudes of resilience with respect to climate. There will be places in the NR where climate change will be the

primary challenge (e.g., drought at lower treeline), but integrating climate change considerations into current management operations is preferable to a climate-centric management strategy. Even with climate change, restoration will be appropriate considering the high genetic variation across the range of forest species, providing a foundation for adaptation (Bower and Aitken 2006, 2008; Mahalovich and Hipkins 2011; Rehfeldt et al. 1999).

Multi-resource monitoring will be critical for managing ecosystems in the future, building on existing monitoring systems but with additional elements to accommodate the effects of climate change (Janowiak et al. 2014). Although costly in terms of money and personnel, an extensive monitoring system will save money in the long run by evaluating the effectiveness of adaptation tactics and providing a means to adjust them. Without monitoring, it will be impossible to know the magnitude and trend of climate effects on vegetation, or if actions proposed in this document (see adaptation section) are useful for planning and management. Monitoring data can also be used to provide inputs to, calibrate, and validate models. Models, in turn, can be used to simulate emergent environmental patterns, compare effects of potential treatments, identify vulnerable landscapes or ecosystem components, and bridge gaps between large-scale ecological processes and variables measured in small areas and over short periods of time. Therefore, any future land management planning will be complete only if a plan for monitoring proposed actions is included.

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Chapter 7: Effects Of Climate Change On Rangeland Vegetation

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INTRODUCTION

Rangelands are dominated by grass, forb, or shrub species, but are usually not modified using agronomic improvements such as fertilization or irrigation (Lund 2007; Reeves and Mitchell 2011) as these lands would normally be considered pastures. Rangeland includes grassland, shrubland, and desert ecosystems, alpine areas, and some woodlands (box 7.1). Within the Northern Rockies, rangelands occupy more than 65 million acres (Reeves and Mitchell 2011). Ecosystem services derived from rangelands in the Northern Region include, but are not limited to, forage for millions of domestic and wild ungulates, greater sage-grouse (*Centrocercus urophasianus*) habitat, and numerous recreational opportunities (see chapter 10).

The sustainability of goods and services is threatened by land-use change, including residential development, energy development, and invasive (nonnative) plant species (see chapter 11). These threats, expressed against the backdrop of climate change, pose unique challenges for managers in the Northern Region. The effects of climate change on rangelands have received less attention than forests, but similar to forests, past and future human land-use activities may exceed climate change effects, at least in the short term (Peilke et al. 2002). Interactions between land-use change, management, and climate change are not well understood and difficult to forecast. Therefore, this analysis of potential climate change effects on rangelands does not explicitly include estimates of future land-use change or management, and instead focuses estimated regeneration success, response to disturbance (especially fire), and life history traits.

Relative to forests, rangelands usually occur in more arid environments, either due to edaphic (e.g., some montane grasslands, subalpine shrublands, and fell-fields) or climatic factors. These arid conditions

present challenges for studying the effects of climate change because some rangelands will be less resilient to changes in environmental influences such as fire regimes and periodicity of precipitation. Understanding resistance and resilience for rangelands is important for estimating possible effects of climate change. Generally speaking, resilience refers to the capacity of ecosystems to regain structure, processes, and functioning in response to disturbance (Allen et al. 2005; Holling 1973), whereas resistance describes capacity to retain these community attributes in response to disturbance (Folke et al. 2004). These concepts are especially critical when considering establishment of nonnative plants and interactions between climate change stressors (Chambers et al. 2014). In the Northern Rockies, areas receiving higher precipitation and cooler temperatures generally result in greater resources and more favorable conditions for plant growth and reproduction (Alexander et al. 1993; Dahlgren et al. 1997). These concepts are demonstrated in figure 7.1, which indicates that management for ecosystem services derived from rangelands will be relatively more effective in more mesic rangelands.

In this chapter we explore potential effects of climate change on selected rangeland habitats. The evaluation of risk was qualitatively and synthetically determined using a combination of workshop output, literature (where available) and our judgement and that of two reviewers. It is meant to represent our best guess as to the relative vulnerability of each system to estimated perturbations brought forth by expected changes in climate across the Northern Region.

VEGETATION CLASSES

The rangeland assessment focuses largely on groupings of vegetation types but also references individual species where information and data suggest inferences can be made for species. Identifying rangeland vegetation to be included in the vulnerability assessment was accomplished by first reviewing the extent of rangelands within the conterminous United States (Reeves and Mitchell 2011). The National Resources Inventory (NRI) definition (box 7.1) of rangelands was used to identify rangelands within the Northern Rockies. The list of U.S. Ecological Systems designated as rangelands that were retained for evaluation is found in table 7.1. The great complexity of rangeland vegetation combined with a paucity of climate change effects studies suggests that a grouping of individual vegetation types into classes would

be useful. The resulting grouping and the final groups to be analyzed include Northern Great Plains (mixtures of cool and warm-season species), montane shrubs, montane grasslands (referred to as “western grasslands” and dominated by cool season species), and sagebrush systems. It is important for the reader to understand that multiple vegetation types comprise each of the four broad classes of vegetation. In the case of sagebrush systems, however, four groups were identified (short sagebrushes, big sagebrushes, sprouting sagebrushes, and mountain sagebrush) which were subsequently further permuted by individual types (table 7.1).

The Northern Great Plains has a broad geographic expanse and mixture of both cool-season (C3) and warm-season (C4) species. Montane shrubs are comprised of species important for browsing by native ungulates. Montane grasslands have a unique position on the landscape, dominance of cool-season species, relative scarcity and specific types of habitats they provide in juxtaposition to forest vegetation.

Sagebrush systems (dominated by species in the genus *Artemisia*) provide critical wildlife habitat, including for the imperiled greater sage-grouse, and are a ubiquitous and iconic species in much of the western United States. In addition, sagebrush systems, especially those dominated by big sagebrushes (Wyoming big sagebrush [*Artemisia tridentata* ssp. *wyomingensis*], mountain big sagebrush [*A. tridentata* ssp. *vaseyana*], and basin big sagebrush [*A. tridentata* ssp. *tridentata*]) have been more widely studied, at least partially as a result of recent research on sage-grouse habitat. Therefore, the vulnerability of some sagebrush species is supported by a richer body of information than for other vegetation. However, this does not mean that all sagebrush types have been studied equally in the context of climate change. To reflect the disparate amount of study on climate change effects on sagebrush species, four sagebrush types were delineated for the Northern Rockies for the purposes of this study (fig. 7.2, sagebrush types):

- Big sagebrushes—Wyoming big sagebrush and Basin big sagebrush
- Low sagebrushes—low sagebrush (*A. arbuscula*) and black sagebrush (*A. nova*)
- Sprouting sagebrushes—silver sagebrush (*A. cana*) and three-tip sagebrush (*A. tripartita*)
- Mountain big sagebrush

Figure 7.2 does not represent an exact accounting of these four vegetation classes but suggests an estimated distribution where each grouping is usually found. In addition, using Ecological Systems mapped at this level it is not possible to differentiate the distribution of silver and three-tip sage as they are often disjunctively commingled with other types. As a result, only three categories are mapped but within the largest category, the big sagebrushes, and sprouters are all represented in one estimated distribution.

The Wyoming and basin big sagebrush types were aggregated for their similar life histories, stature, and areal coverage in the Northern Region, and because they represent critical habitats for many species of birds and wild and domestic ungulates. Despite having similar life history traits, basin big sagebrush occupies sites with deeper soils (often on alluvial fans). These conditions tend to increase available moisture with higher coverage by perennial bunchgrasses, suggesting these sites may be more resilient and resistant to various threats (Chambers et al. 2007). Similarly, the low sagebrushes were chosen for the unique habitats they represent (especially black sagebrush) and similar life histories. Both silver sagebrush and three-tip sagebrush can resprout after fire, making them unique in that regard among the sagebrush species, with the exception of periodic sprouting by some variants of mountain big sagebrush.

Finally, mountain big sagebrush was chosen for its (usually) distinct positioning on the landscape, in addition to being the most mesic of sagebrush communities in the Northern Rockies. Communities dominated by Wyoming big sagebrush are by far the most common and occupy the greatest area (table 7.2), whereas the low sagebrush type occupies the least. However, although basin and Wyoming sagebrush are common throughout the Northern Region, mountain big sagebrush communities occupy the greatest extent on lands managed by the Forest Service, U.S. Department of Agriculture. Although the communities dominated by the *Artemisia* species listed here were subdivided for evaluating possible effects of climate change, four species (Basin-big, Wyoming, three-tip, and silver) were grouped for mapping purposes as the “big or sprouter” category (table 7.1) since differentiating these across the landscape was impractical.

VEGETATION PRODUCTIVITY IN RESPONSE TO CLIMATE CHANGE

Although the current extent of rangeland in the Northern Rockies can be accurately described, uncertainty in the underlying global climate models (GCMs) used to estimate climate change effects (see chapter 3), and uncertainty in models of physiological response, make it difficult to confidently project the effects of climate change on rangelands. Our understanding of the potential effects of climate change can be improved if comparisons of impacts are made with other areas our understanding of the relative effects in the Northern Region can be improved.

The primary inference about climate change effects on rangeland vegetation nationally is one of increasing temperature, lower soil moisture, changing phenology, and decreasing annual production. However, projected temperatures exhibit far less variability among scenarios and GCMs than precipitation. Therefore, areas where projections suggest temperature rather than precipitation is a dominant driver may be more reliable. Figure 7.3 suggests that, relative to much of the rest of the country, the Northern Region could experience an increase in annual net primary productivity (NPP). In addition, the modeled overall increases in productivity appear to be more consistent in the Northern Rockies compared with other areas because there is less disagreement among the three emission scenarios evaluated (Nakicenovic et al. 2000; Reeves et al. 2014).

Changing climate regimes will also influence phenology in unexpected ways. For example, in tallgrass prairie (a rare type in the Northern Rockies), a 7.2 °F increase in ambient temperature caused earlier anthesis among spring blooming species and later anthesis in fall-blooming species (Sherry et al. 2007), implying that climate change will influence vegetation in complex ways (Suttle et al. 2007; Walther 2010). In addition, effects of climate change may be greater at higher elevations (Beniston et al. 1997) (fig. 7.3, panel A), a logical projection for the Northern Rockies where the primary factor limiting plant growth at high elevations is growing-season length and cold temperatures.

The modeled overall effect of projected climate change in the Northern Rockies appears to be increased growing season length and increased NPP, which may be especially pronounced at higher elevations. Removal of growth limitations could result in significant changes in vegetation at higher

elevations, such as the Greater Yellowstone Area subregion. Higher NPP may seem counterintuitive because increased temperatures suggest greater moisture stress and therefore potentially less favorable growing conditions. Indeed, if all other factors besides temperature remained constant in the future, then vegetation might experience significant reductions in productivity from increased evaporative demand and reduced soil moisture. Conversely, some high elevation areas may experience increased production with increasing temperatures (Reeves et al. 2014), especially some relatively more mesic areas supporting mountain sagebrush.

Increased atmospheric CO₂ concentrations may modify ecophysiological growth processes in rangeland vegetation. Carbon dioxide enrichment can enhance water use efficiency through reduced water lost through stomata (see chapter 6), but the response is not consistent across all vegetation. For example, in tallgrass prairie, Owensby et al. (1999) found that elevated CO₂ could increase productivity of above- and below-ground biomass, but response depended on water stress. These findings are consistent with results from Reeves et al. (2014) and suggest that desiccation effects of increased temperature can be offset to some extent by CO₂ enrichment via reduced transpirational demand (Leakey 2009; Morgan et al. 2004b, 2011; Woodward and Kelly 2008), and higher water use efficiency (Bachelet et al. 2001; Christensen et al. 2004; Morgan et al. 2008, 2011; Polley et al. 2003).

Recent experimental research on the Northern Great Plains is particularly relevant to the managers in the Grassland subregion where northern mixed grass prairie dominates. The Prairie Heating and CO₂ Enrichment (PHACE) study reported an increase of aboveground productivity by an average of 33 percent over three years (Morgan et al. 2011), which substantiates estimates of Reeves et al. (2014) of a 28 percent increase in productivity for the Northern Great Plains by 2100.

As a footnote to the discussion above, it is important to note that all models are a simplification of reality, and interpretation of model results needs to consider uncertainty, inputs, and model assumptions. Models cited here have increasing disparity as time progresses, especially in more arid regions where changing precipitation amounts and patterns may be the primary driver of change.

Management Concerns

The primary management and ecological concerns affecting rangelands in the Northern Rockies identified include uncharacteristic fire regimes, improper grazing, and invasive species. Uncharacteristic fire regimes, which are based on the historic fire regime, threaten some rangeland habitats, especially sagebrush steppe, across much of the western United States including the Northern Rockies. It is suggested, however, that the overall concern over uncharacteristic fire regimes is smaller than for other regions such as the Great Basin. On one end of the spectrum, it appears “too much” fire presently affects the landscape relative to historic fire regimes, because many sagebrush habitats now have shortened fire return intervals. It is widely documented that increasing dominance of invasive annual grasses have created a positive feedback cycle characterized by frequent fire followed by increased dominance of annual grasses that further create fuel conditions that facilitate combustion (Chambers et al. 2007). These conditions are exacerbated by wetter and warmer winters, which are projected throughout the study area in the future.

On the other end of the spectrum, fire exclusion has led to decreased fire return intervals that may be responsible for Douglas-fir (*Pseudotsuga menziesii*) encroachment into montane grasslands (Arno and Gruell 1986), and in higher elevation sagebrush habitats, especially those dominated by mountain big sagebrush (Heyerdahl et al. 2006) (fig. 7.4). Overall, the invasive species of greatest concern throughout rangelands of the Northern Region in sagebrush communities is cheatgrass (*Bromus tectorum*), although Japanese brome (*B. japonicus*) and leafy spurge are also concerns in the Northern Great Plains. Recent range expansion of cheatgrass is particularly prominent in the western half of the Northern Rockies and can be somewhat explained by genetic variation leading to increased survival and persistence in otherwise marginal habitats (Merrill et al. 2012; Ramakrishnan et al. 2006). This rapid range expansion may be enhanced by elevated atmospheric CO₂ concentrations and increased soil disturbance (Chambers et al. 2014). Improper grazing, a term referring to the mismanagement of grazing that produces detrimental effects on vegetation or soil resources, can exacerbate these conditions (see chapter 6). However, U.S. rangelands are generally not improperly grazed (Reeves and Bagget 2014; Reeves and Mitchell 2011) to the point of degradation. Although improper grazing does occur, it is not the normal condition across the

extent of rangeland rangelands in the Northern Region. Where improper grazing does occur, it can accelerate the annual grass invasion/fire cycle, especially in some sagebrush types, the Northern Great Plains, and montane grasslands.

BROAD-SCALE VULNERABILITY OF RANGELANDS TO CLIMATE CHANGE

Determining the vulnerability of rangeland vegetation is a difficult task inherently wrought with great uncertainty. Uncertainty exists in the projections of future climatic conditions as well as in expected effects of vegetation. Given the lack of studies focused on manipulated climate on vegetation performance, we are limited to past observations; some published scientific studies, and our collective best judgement. Despite the lack of focused studies on the effects of climate change on rangeland vegetation and the large uncertainty of projected climates, there are a few elements of climate change that are increasingly recognized as potential outcomes. As a result, in this section, we briefly discuss some overarching expected climatic conditions against which the estimation of likely future vegetation outcomes of each previously identified vegetation class is formulated.

Of all the estimated future climate outcomes, projected temperature increases (IPCC 2014; chapter 3) are expected to increase evaporative demand (e.g. potential evapotranspiration; Klos et al. 2014) and pose greater overall temperature stress (Polley 2013). Projected changes in precipitation patterns and increasing potential evapotranspiration could encourage more frequent and intense fires from the combined effects of early season plant growth combined with the desiccating effects of warmer, drier summers (Morgan et al. 2008). Collectively, these changes may result in considerably drier soils, particularly in the summer months when plants are phenologically active (Bradford et al. 2014; Polley et al. 2013). However, winter precipitation is projected to increase by 10 to 20 percent in the Northern Region (IPCC 2014; Shafer et al. 2014; chapter 3), which may compensate for increasing severity and frequency of droughts. In addition, rising CO₂ levels may offset water loss due to higher evaporative demand by increasing stomatal closure and water use efficiency.

Warmer winters, and decreasing snowpack may also be significant factors affecting rangeland vegetation classes discussed below. Minimum temperatures are expected to increase more than maximum

temperatures, providing longer frost-free periods. Warmer, wetter winters would favor early-season plant species and tap-rooted species that are able to access accumulated early growing season soil water (Polley et al. 2013). These conditions are projected to significantly increase annual area burned and fire intensity (Westerling et al. 2006).

Montane Grasslands

Montane grasslands are associated with mountainous portions of the Northern Rockies including the Palouse prairie and canyon grasslands of northern and central Idaho. Montane grasslands occur in intermountain valleys, foothills, and mountain slopes from low to relatively high elevation. They are dominated by cool-season (C3) grasses, along with a large number of forbs and upland sedges. Shrubs and trees may occur with low cover. Dominant species include bluebunch wheatgrass (*Pseudoroegneria spicata*), rough fescue (*Festuca campestris*), Idaho fescue (*F. idahoensis*), Sandberg bluegrass (*Poa secunda*), needle-and-thread (*Hesperostipa comata*), western wheatgrass (*Pascopyrum smithii*), prairie junegrass (*Koeleria macrantha*), western needlegrass (*Achnatherum nelsonii*), and Richardson's needlegrass (*A. richardsonii*).

Many low elevation grasslands have been converted to agricultural use or are grazed by domestic livestock. They have also been subject to extensive human use and land-use conversion. Those grasslands that remain, particularly at lower elevations, are typically highly disturbed, fragmented, and frequently occupied by many nonnative, invasive plant species. Prolonged improper livestock grazing, native ungulate herbivory, and nonnative invasive plants are the primary stressors in these grasslands (Finch 2012). Loss of topsoil can occur if vegetation cover and density decline and bareground increases. Lack of fire is also a chronic stressor because conifers from lower montane forests can become established in some areas, and increase in density and cover with fire exclusion (Arno and Gruell 1986; Heyerdahl et al. 2006). As conifer density and cover increase with fire exclusion, grass cover declines, because most grassland species are shade intolerant (Arno and Gruell 1983). Although lack of fire has been a stressor, if fires become hotter and more frequent, there is an increased risk of mortality of native species and invasion by nonnative plant species but invasive plants may not always establish and dominate a site

(Ortega et al. 2012; Pearson et al. in review) under these conditions. It is thought, however, that greater spring and winter precipitation may facilitate exotic annual grasses, particularly cheatgrass, which germinates in the winter/early spring, to establish and set seed earlier than native perennial grasses (Finch 2012). This creates an uncharacteristic, continuous fine fuel load that is combustible by early summer, burning native perennial grasses often before they have matured and set seed (Bradley 2008; Chambers et al. 2007). Other nonnative species, such as spotted knapweed (*Centaurea melitensis*), Dalmatian toadflax (*Linaria dalmatica*), butter-and-eggs (*Linaria vulgaris*), and sulphur cinquefoil (*Potentilla recta*) respond favorably after fire and can increase in cover and density.

Nonnative, invasive plant species will probably expand particularly in the lower elevation grassland communities as these communities become warmer and drier since resistance to invasion may decrease (Chambers et al. 2014). Greater disturbance will likely increase the rate and magnitude of infestation (Bradley 2008). In addition, drier site conditions coupled with ungulate effects (grazing, browsing, hoof damage) may increase bare ground along with associated increases in surface soil erosion (Washington-Allen et al. 2010). Low-elevation grasslands may shift in dominance towards more drought tolerant species. Some model output, such as MC2 (Bachelet et al. 2001) suggests that cool season (C3) grasslands will decline and that warm season (C4) grasslands will expand based solely on temperature trends. However, research indicates that elevated CO₂ favors C3 grasses and enhances biomass production, whereas warming favors C4 grasses due to increased water use efficiency (Morgan et al. 2004a, 2007). Although C3 grasses dominate Western montane grasslands, a warmer and drier climate may allow C4 grasses (primarily northern Great Plains species) to expand westward into montane grasslands. In general, it is likely that with increased warming and more frequent fires, grasslands will become a more dominant landscape component as shrublands and lower montane conifer forests are burned more frequently and unable to regenerate. Increasing fire would also encourage more invasive species in grasslands (Bradley 2008; D'Antonio and Vitousek 1992).

Risk Assessment

Magnitude of effects: High

8818 Likelihood of effects: High

8819 **Communities Dominated by Montane Shrubs**

8820 Montane shrubs are typically associated with montane and subalpine forests, and occur as large
8821 patches within forested landscapes. Species such as Rocky Mountain maple (*Acer glabrum*), oceanspray
8822 (*Holidiscus discolor*), tobacco brush (*Ceanothus velutintis* var. *velutinus*), Sitka alder (*Alnus viridis*
8823 subsp. *sinuata*), thimbleberry (*Rubus parviflorus*), chokecherry (*Prunus virginiana*), serviceberry
8824 (*Amelanchier alnifolia*), currant (*Ribes* spp.), snowberry (*Symphoricarpos albus*), Scouler willow (*Salix*
8825 *scouleriana*), and mountain ash (*Sorbus scopulina*) are common.

8826 Montane shrubs persist on sites where regular disturbance kills the top of plants. This, along with full
8827 sunlight and adequate soil moisture, stimulates regrowth from the root crown, rhizomes and roots.
8828 Stressors include fire exclusion and conifer establishment, browsing by both native and domestic wildlife,
8829 and insects and disease. Loss of topsoil following frequent, hot fires, can lead to loss of these species over
8830 time (Larsen 1925; Wellner 1970). Mesic shrubs are well adapted to frequent fire, and under the right
8831 conditions can expand and outcompete regenerating conifers. However, with declining snowpack and
8832 warmer temperatures, fires may be hotter and sites may be drier, causing variable amounts of mortality,
8833 depending on site conditions.

8834 Mesic shrubs are well adapted to frequent fire (Smith and Fisher 1997) and sprout vigorously
8835 following fire enabling them to quickly regain dominance on the site. As sites become drier and fires
8836 become more frequent and severe, however, there may be a shift away from mesic species to more xeric
8837 specie such as rubber rabbitbrush (*Ericameria nauseosa*), green rabbitbrush (*Chrysothamnus*
8838 *viscidiflorus*), and spineless horsebrush (*Tetradymia canescens*). Nonnative invasive plant species may
8839 also expand into these communities, particularly following fire (Bradley 2008; D'Antonio and Vitousek
8840 1992). With warmer temperatures and drier soils, some mesic shrub species (e.g., Sitka alder and Rocky
8841 Mountain maple) may shift their distribution up in elevation or to cooler, moister sites (e.g., northeast
8842 facing depressions).

8843 *Risk Assessment*

8844 Magnitude of effects: Moderate

8845 Likelihood of effects: High

8846 **Communities Dominated by Short Sagebrushes (Black and Low Sagebrush)**

8847 The current distribution of low sagebrush ecosystems in the Northern Rockies is restricted to about
8848 one percent of the total sagebrush habitat as indicated in the LANDFIRE existing vegetation type (EVT)
8849 database. The western portion of the Northern Rockies contains 50 percent of the low sagebrush habitat,
8850 but limited patches are also found in the Eastern Rockies subregion and in the Greater Yellowstone Area
8851 subregion, especially on the western edge. Most of these sites support low sagebrush but not black
8852 sagebrush. Low sagebrush sites are characterized as relatively low production areas over shallow, claypan
8853 soils that restrict drainage and root growth. Low sagebrush is found on altitudinal gradients from 2,300 to
8854 more than 11,500 ft (Beetle and Johnson 1982), and it is generally found between 6000 to 9000 ft in
8855 Montana and Idaho. In contrast, black sagebrush is considerably more restricted in ecological amplitude
8856 and is found on shallow, dry, infertile soils. Current stressors are predominantly improper use by
8857 livestock and invasion by nonnative species.

8858 Despite growing across large altitudinal gradients, low and black sagebrush exhibit a relatively more
8859 limited distribution than other sagebrush systems. Thus, it is reasonable to assume that as climates
8860 change, ranges could be further restricted, resulting in small islands being isolated, although this is more
8861 likely for black sagebrush because of its poor competitive ability (West and Mooney 1972). Both species
8862 depend heavily on seeding for reproduction (Wright et al. 1979) and recovery from disturbance. In
8863 addition, several traits make low sagebrush sensitive to climate change. There is high mortality in the first
8864 year of growth (Shaw and Monsen 1990). Establishment is probably greatest when a thin layer of soil
8865 covers the seeds, and if erosion increases from drought-induced reductions of plant cover, the already thin
8866 soils may not provide suitable seedbeds for germination. Seed development and establishment is best in
8867 years with ample precipitation, and if unfavorable conditions for seeding persist following disturbance, it
8868 is reasonable to assume that low sagebrush may disappear from some stands, especially if annual grass
8869 invasion occurs concomitantly with unfavorable growth conditions.

Climate change will result in shifts in the distribution of conditions suitable to support low sagebrush and hence the spatial configuration of low sagebrush habitats. Both low and black sagebrush are intolerant of fire and do not resprout. Therefore, increased fire activity will have negative consequences for both species. Fire return intervals vary considerably among communities dominated by low sagebrush. Estimates of fire-return intervals for xeric sagebrush communities of the Great Basin range from 35 to over 100 years (Brown 2000; Riegel et al. 2006), but intervals of 100 to 200 years for low-productivity black sagebrush communities have been reported. Especially for black sagebrush, which usually occupies quite unproductive sites with small buildup of fuels, these fire return intervals may be overestimated (Baker 2013). Within the boundaries and on the periphery of the Greater Yellowstone Area subregion, MC2 results indicate that the proportion of landscape burned will increase substantially in the future (fig. 7.5), allowing a higher likelihood of ignition and flaming fronts to reach some low sage communities. The extent to which these sites will carry fire depends on herbaceous production and probably on magnitude of invasion by annual grasses (especially cheatgrass). In summary, climate change may influence low sagebrush systems by reducing seedling establishment in unfavorable years. In addition, projected increased fire activity will decrease the abundance of low sagebrush relative to other species, especially if nonnative annual grasses, such as medusahead (*Taeniatherum caput-medusae*) and cheatgrass, become more prevalent.

Relative to other sagebrush species, low and black sagebrush have limited adaptive capacity. Black sagebrush hybridizes with silver sagebrush, and sprouting is thought to be a heritable trait in crosses between non-sprouting and sprouting sagebrushes (McArthur 1994). However, in the Northern Rockies, it is unlikely that silver sagebrush will exhibit a significant presence in areas that support low sagebrush, since the distribution of these species is usually disjunctive so the possibility of inheriting sprouting traits is unlikely. In addition, the relatively low productivity characterizing low sagebrush sites may also limit adaptive capacity, especially if other risk factors are present.

Risk Assessment

Magnitude of effects: High. The resiliency of many of these areas is low given the thin and argillic soil properties characterizing these sites. The magnitude of effects will likely increase if other perturbations such as improper recreational or grazing schemes are present. The low adaptive capacity of this sagebrush type, intolerance of fires, and low rate of reproduction act in concert to increase the magnitude of effects.

Likelihood of effects: Moderate to high. Models suggest increased production at higher elevations (Reeves et al. 2014), increasing the likelihood of fires carrying through otherwise relatively unburnable landscapes. The problem of increased flammability will increase, especially if invasive annual grasses exhibit a significant presence on low sagebrush sites in the future.

Shrublands Dominated by Sprouting Sagebrush Species (Threetip and Silver Sagebrush)

Significant areas of threetip and silver sagebrush shrublands have been converted to agricultural lands. Those that remain are often used for domestic livestock grazing because of the palatable herbaceous undergrowth in this sagebrush type. Those that have had chronic improper grazing typically have a large amount of bare ground, low vigor of native herbaceous species, and as a result, nonnative plant species present in varying amounts. Prolonged improper livestock grazing, native ungulate herbivory, and nonnative invasive plants are the primary stressors. Loss of topsoil can occur if vegetation cover and density declines and bare ground increases, primarily caused by ungulate impacts (e.g., grazing and mechanical/hoof damage) (Sheatch and Carlson 1998; Washington-Allen et al. 2010).

Both species can sprout from the root crown following top kill (primarily from fire) (Bunting et al. 1987) but this trait depends on site conditions and fire severity. Silver sagebrush is a vigorous sprouter (Rupp et al. 1997), whereas threetip sagebrush is less successful as a sprouter, and its response varies based on site characteristics (Akinsoji 1988; Bunting et al. 1987). Both species occur on mesic sites; threetip sagebrush is often associated with mountain big sagebrush communities, and silver sagebrush typically occupies moist riparian benches or moist toe slopes. Although these species will sprout, increased fire frequency and severity (particularly in threetip communities) may cause a shift in community composition to dominance by fire-adapted herbaceous species or nonnative species. Other

fire-adapted shrub species (e.g., rubber rabbitbrush, green rabbitbrush, spineless horsebrush) may increase, particularly following fire. In addition, more spring and winter precipitation may facilitate exotic annual grasses to establish and set seed earlier than the native perennial grasses, particularly in lower-elevation communities (Bradley 2008; D'Antonio and Vitousek 1992). This creates an uncharacteristic, continuous fine fuel load that can burn by late spring/early summer, burning sagebrush and native grasses often before they have matured and set seed (Chambers and Pellant 2008). Other nonnative invasive species (e.g., spotted knapweed, Dalmatian toadflax, butter-and-eggs, sulphur cinquefoil) respond favorably after fire, and if present, will increase in cover and density.

Historical fire return intervals for both species are relatively short and research shows that threetip sagebrush cover can return to preburn levels 30-40 years after fire (Barrington et al. 1988; Neuenschwander, n.d.). Lesica et al. (2007) found that after a fire in southwest Montana, threetip sagebrush cover did not increase (presumably from resprouting), but instead established from seed. These generalizations will vary considerably depending on site conditions and postfire management. All three subspecies of silver sagebrush sprout after fire, and along with threetip, also typically occur on more mesic sites. With a warmer and drier climate, frequent, high severity burns may not only cause initial mortality, but sites may not be as favorable for postfire vegetation regeneration (from sprouting, regrowth, or from seed). Invasive species will likely either expand into these communities after fire or increase in abundance in altered conditions that are less favorable to the native plant community.

Understory composition in both communities may possibly shift to more xeric grassland species (e.g., bluebunch wheatgrass, needle-and-thread), which are more adapted to warmer and drier conditions. Both of these sagebrush species may shift landscape position to sites with more moisture and cooler temperature (e.g., higher elevation, lower landscape position, and northeast aspects).

Risk Assessment

Magnitude of effects: Moderate

Likelihood of effects: High

Communities Dominated by Wyoming Big Sagebrush and Basin Big Sagebrush

The current distribution of Wyoming big sagebrush ecosystems in the Northern Region is generally patchy throughout most of Montana with more spatially consistent cover in the Eastern Rockies and Grassland subregions (Comer et al. 2002). As previously mentioned, the distribution of basin big sagebrush habitats is generally restricted to deeper soils, often including alluvial fans. Stressors to both Wyoming and basin big sagebrush communities include prolonged improper livestock grazing, native ungulate herbivory, and nonnative invasive plants. Loss of topsoil can occur if vegetation cover and density decline and bare ground increases, primarily caused by ungulate impacts (e.g., grazing and mechanical/hoof damage). Compared with mountain and basin big sagebrush habitats, Wyoming big sagebrush habitats spatially coincide with oil and gas development, which is prominent on the eastern edge of its distribution. The Grassland and Greater Yellowstone Area subregions contain the largest extent of big sagebrush, although the Western Rockies subregion may contain the largest amount of basin big sagebrush.

Big sagebrush ecosystems have decreased in spatial extent in the 20th century (Bradley 2010; Knick et al. 2003; Manier et al. 2013; Noss et al. 1995) because of oil and gas development leading to habitat destruction and fragmentation (Doherty et al. 2008; Walston et al. 2009), big sagebrush removal to increase livestock forage (Shane et al. 1983), plant pathogens and insect pests (Haws et al. 1990; Nelson et al. 1990), improper grazing (Davies et al. 2011), invasive species (D'Antonio and Vitousek 1992, Davies 2011), and changes in disturbance regimes (Baker 2011; Balch et al. 2013). Oil and gas development, along with urbanization and land conversion for agriculture and livestock grazing, not only lead to habitat loss, but to fragmented habitat patches (Naugle et al. 2011), resulting in barriers to plant dispersal, greater sage-grouse avoidance, and loss of obligate and facultative wildlife species (Rowland et al. 2006). In addition to habitat destruction of big sagebrush ecosystems, several stressors can cause big sagebrush dieback and reduce its biomass and density, including insect pests (Haws et al. 1990), plant pathogens (Cárdenas et al. 1997; Nelson et al. 1990), and frost damage (Hanson et al. 1982). Improper use by domestic livestock alters the structure and composition of big sagebrush ecosystems through the loss of palatable components of the plant community (i.e., perennial grasses and forbs), along with reducing or

increasing big sagebrush cover (Anderson and Holte 1981; Brotherson and Brotherson 1981), and increasing the probability of nonnative annual grass invasion (Cooper et al. 2007; Davies et al. 2011; Knapp et al. 1996). Cheatgrass has reduced the spatial distribution and habitat quality of sagebrush ecosystems throughout much of the western United States (Balch et al. 2013; Brooks et al. 2004).

Cheatgrass invasion poses a continued and heightened threat to big sagebrush ecosystems in the future, because its biomass production and fire frequency are projected to increase in response to rising temperature and CO₂ levels (Westerling et al. 2006; Ziska et al. 2005). Although less studied, field brome (*Bromus arvensis*) can also negatively affect big sagebrush plant communities, because it can colonize readily after stand-replacing fires that eliminate big sagebrush (Cooper et al. 2007).

Several life history traits of big sagebrush make it sensitive to direct and indirect effects of climate change. Amount and timing of precipitation control seeding establishment at low elevation, whereas minimum temperature and snow depth control germination and survival at high elevations (Nelson et al. 2014; Poore et al. 2009, reviewed by Schlaepfer et al. 2014a). Drought events are projected to increase in the western United States in the future (IPCC 2014), although the likelihood of increased drought in the Northern Rockies is uncertain (see chapter 3). Thus, big sagebrush ecosystems remain vulnerable to drought, which may affect germination and survival of seedlings, because soil water content primarily controls seedling survival (Schlaepfer et al. 2014a). Big sagebrush seedling survival may be highest in intermediate temperature and precipitation regimes (Schlaepfer et al. 2014b). Even after seedling establishment, drought and increased summer temperature can affect survival and growth of adult plants, because growth is positively correlated with winter precipitation and winter snow depth (Poore et al. 2009). As a result, if drought events increase in frequency and severity in the Northern Rockies, big sagebrush biomass and the abundance and diversity of perennial grasses and forbs may decrease.

It is uncertain if big sagebrush can move in concert with shifting temperature and precipitation regimes and disperse to available habitat patches and colonize them. Most big sagebrush seeds (50-60 percent) are not viable in the seedbank after two years, with few viable seed in the upper soil (Wijayratne and Pyke 2009, 2012). Furthermore, big sagebrush is a poor disperser (Schlaepfer et al. 2014a; Young et

al. 1989) and seed production is episodic (Young et al. 1989). Even if big sagebrush seeds successfully disperse and germinate in response to a changing climate, probabilities of seedling establishment and adult survivorship are uncertain, because big sagebrush is a poor competitor relative to associated herbaceous species (Schlaepfer et al. 2014a).

Big sagebrush is sensitive to fire and cannot resprout (Shultz 2006), and because recovery from seed dispersal can take 50-150 years (Baker 2006, 2011), postfire recovery may become a problem in the future, if the frequency and intensity of fires increase as projected (Abatzoglou and Kolden 2011; Westerling et al. 2006). Regeneration of big sagebrush postfire is strongly linked to winter precipitation (Nelson et al. 2014), which is expected to increase by 10-20 percent in the Northern Rockies by 2100 (IPCC 2014; Shafer et al. 2014). Although more frequent fire may result in larger losses of big sagebrush habitat in the future, recovery of big sagebrush may be less impeded. It is also possible that much of this increased precipitation will come as rainfall (Klos et al. 2014), which could, in turn, promote herbaceous growth which might suppress sagebrush recovery in some instances.

Climate change will result in shifts in the distribution of conditions suitable to support big sagebrush and hence the spatial configuration of big sagebrush habitat, with direct and indirect effects on sagebrush-dependent species (e.g., greater sage-grouse). Several studies using species distribution modeling (SDM) have projected that big sagebrush will move northward and up in elevation in response to increased winter temperatures and summer drought associated with climate change (Schlaepfer et al. 2012; Shafer et al. 2001). Although big sagebrush may expand northward and upslope, its habitat is predicted to contract significantly due to increased soil moisture stress, primarily at southern latitudes and lower elevations (fig. 7.6).

The probability of big sagebrush regeneration has been projected to increase at the leading edge of its range (i.e., northern range limit) under future climate conditions, suggesting potential northward range expansion with climate change (Schlaepfer et al. in review). This is in part due to changes in habitat suitability, because soil water conditions at the leading edge will be similar to current soil water patterns in big sagebrush systems. Habitat suitability for big sagebrush is predicted to increase primarily in

northeast and north-central Montana (Schlaepfer et al. in review; Schrag et al. 2011) (fig. 7.6). In contrast, habitat suitability is predicted to decrease in parts of the Western and northwest Greater Yellowstone Area subregions (fig. 7.6), primarily from summer drought (Schlaepfer et al. 2012; Schlaepfer et al. in review). However, expansion of big sagebrush out of unsuitable habitat and into suitable habitat is contingent on its ability to disperse to available habitat patches and compete with other species.

In addition to changes in big sagebrush distribution, shifts in community composition and productivity are expected with climate change. Since there is uncertainty about length and severity of drought events in the future, the projected shifts in community composition and productivity in big sagebrush ecosystems in response to climate change remain uncertain. If drought events do increase in the Northern Rockies, native herbaceous plant diversity and cover may be reduced. In contrast, in non-drought years, warming temperatures and increased levels of CO₂ may lead to increased biomass production (Reeves et al. 2014), more frequent fires, and increases in herbaceous biomass at the expense of fire-intolerant shrubs, such as big sagebrush.

Paleoecological studies have shown that species move individually and at different rates in response to climate change, resulting in novel combinations of species (Delcourt and Delcourt 1981). Even species in the same functional group (e.g., grasses) may respond differentially to climatic change (Anderson and Inouye 2001). Thus, big sagebrush plant communities are unlikely to migrate as a unit in response to altered temperature and precipitation. The response of individual species to climate change will depend on both physiological tolerances and competitive ability.

Shifts in disturbance regimes (e.g., fire, insects, pathogens) associated with climate change may affect big sagebrush ecosystems in the future. Disturbances affect vegetation directly by killing individuals and removing aboveground biomass, and indirectly by altering soil conditions. Climate change and disturbance may have additive effects on soil water balance in big sagebrush ecosystems, decreasing soil water content (Bradford et al. 2014) and resulting in diminished growth and regeneration (Poore et al. 2009). Since big sagebrush is incapable of resprouting after disturbance (Shultz 2006), increased disturbance frequency could reduce the spatial extent of big sagebrush in the future, despite increased

habitat suitability and regeneration potential. As with other vegetation types, there is great uncertainty and variability regarding estimates of fire return intervals of stands dominated by big sagebrush. For example, in the Northern Rockies, Lesica et al. (2007) suggest that fire return intervals for Wyoming big sagebrush are longer than for basin big sagebrush and mountain big sagebrush, and range from 50 to 150 years while (Baker 2011, 2013; Bukowski and Baker 2013) estimate ranges of 200 to about 350 years.

The long fire return intervals to which Wyoming big sagebrush is adapted are related to its very slow postfire recovery, as low as two percent recovery 23 years after fire (Lesica et al. 2007). The slow recovery of these systems is partly due to slow growth rates and harsher environmental conditions in many sites in the Northern Rockies. In contrast, basin big sagebrush canopy cover development and growth are faster than for Wyoming big sagebrush (Booth et al. 1990; Lesica et al. 2007; McArthur and Welch 1982). Invasive annual grasses such as cheatgrass may exacerbate slow growth.

Big sagebrush ecosystems have some capacity to adapt to climate change. Big sagebrush occurs over a large geographic area with high diversity in topography, soils, and climate, suggesting that it can withstand a relatively broad range of ecological conditions and may tolerate shifting climates. Various subspecies of big sagebrush often hybridize and have a high level of polyploidy, providing it with the capacity to undergo selection and adapt to shifting climatic regimes relatively quickly (e.g., Poore et al. 2009).

Although lower soil water availability may pose a threat to big sagebrush ecosystems, long periods of sustained drought would be needed to cause mortality (Kolb and Sperry 1999). In addition, big sagebrush habitat suitability is projected to change across space (e.g., decreasing suitability in northwest Wyoming and across much of western Montana), big sagebrush may still persist in relatively “unsuitable” habitat for some time, perhaps in a degraded state.

Risk Assessment

Magnitude of effects: Highly variable. In northwestern Wyoming and western Montana, the effects of climate change will likely be low to moderate, because lower water availability may cause declines in big sagebrush growth and regeneration, facilitating some habitat contraction. However, big sagebrush may

expand northward into northern and eastern Montana, as habitat suitability increases in future decades. Despite this generalization, it is also possible that an increase in fire activity will decrease the extent of big sagebrush communities in many locations.

Likelihood of effects: Variable. Some contraction in big sagebrush habitat may occur in northwest Wyoming and western Montana, particularly at lower elevations because of increased temperature and evapotranspiration. However, if big sagebrush can successfully exploit changing climatic conditions, the total area covered by big sagebrush in the Northern Rockies may increase by the end of the 21st century. Potential expansion may be tempered by faster rates of loss if the cheatgrass-fire cycle tracks new habitats in the northeastern part of region. It is conceivable that drier sites, such as those with sandy soils, may lose the ability to regenerate sagebrush, whereas more mesic sites might still be able to regenerate.

Mountain Big Sagebrush Shrublands

Some areas of mountain big sagebrush shrublands have been converted to agricultural lands, and those that remain are used for domestic livestock grazing, primarily because of the palatable herbaceous undergrowth. Those that have had chronic improper grazing typically have high bare ground, low vigor of native herbaceous species, and as a result, have nonnative plant species present in varying amounts. Prolonged improper livestock grazing, native ungulate herbivory, and invasive nonnative plants are the primary stressors. Loss of topsoil can occur if vegetation cover and density decline and bare ground increases, primarily caused by ungulate impacts (e.g., grazing and mechanical/hoof damage). In addition, lack of fire is also a chronic stressor, facilitating conifer establishment which increases in density and cover over time (Arno and Gruell 1986; Heyerdahl et al. 2006), while grass cover declines (Arno and Gruell 1983).

Mountain big sagebrush is killed by fire. With increased fire severity and frequency, there will be a shift in community composition to dominance by fire-adapted shrub and herbaceous species and possibly nonnatives. Fire-adapted shrub species (e.g., rubber rabbitbrush, green rabbitbrush, white horsebrush) may increase in abundance following fire (Fischer and Clayton 1983; Smith and Fischer 1997). In addition, more spring and winter precipitation may facilitate nonnative annual grasses (particularly

cheatgrass which germinates in winter/early spring)) establishment, although this is less likely in cooler, moister mountain big sagebrush communities compared to lower elevation Wyoming and basin big sagebrush communities. However, with a warmer, drier climate, the conditions may be conducive to cheatgrass establishment. An abundance of cheatgrass creates an uncharacteristic, continuous fine fuel load that can burn by late spring/early summer, burning sagebrush and native perennial grasses often before they have matured and set seed (Chambers et al. 2007; Pellant 1990; Whisenant 1990), especially in the Great Basin. However, other research in the northern edge of the Great Basin indicates that some sagebrush communities may be less susceptible to cheatgrass invasion following fire, at least under the current climate (Lavin et al. 2013; Seefeldt et al. 2007). Other nonnative species (e.g., spotted knapweed, Dalmatian toadflax, butter-and-eggs, sulphur cinquefoil) respond favorably after fire and if present, will increase in cover and density.

Historically, the fire return intervals were relatively short but variable—a few decades (Lesica 2007) to more than 100 years (Baker 2013)—compared to Wyoming big sagebrush (more than 100 years) (Heyerdahl et al. 2006; Lesica et al. 2005, 2007). Mountain big sagebrush regenerates from seeds shed from nearby unburned plants. It will fully recover between 15-40 years after fire (Bunting et al. 1987), depending on site characteristics and fire severity. In a warmer and drier climate, frequent, high-severity burns (facilitated by cheatgrass) may not cause initial mortality and create unfavorable conditions for postfire regeneration (from sprouting, regrowth, or seed). Since there is no viable sagebrush seed bank, if fires burn large areas and there are no live, seed-bearing sagebrush nearby, there may be a type conversion to grassland. In addition, invasive, nonnative species will likely either expand into these areas after fire, or they will increase in abundance due to altered conditions that no longer favor the native plant community (Bradley 2008; D'Antonio and Vitousek 1992).

Mountain big sagebrush is not fire adapted, and may decline in cover and density or becomes extirpated in response to warmer temperatures and increased fire frequency and severity. Over time, especially if fine fuels such as senesced cheatgrass are present, more frequent fires may eliminate mountain big sagebrush from a community (Chambers and Pellant 2008; D'Antonio and Vitousek 1992;

Whisenant 1990). However, because mountain big sagebrush occurs at higher elevations, typically on more productive cooler, mesic sites, these communities are typically less invaded by nonnative species. However, if these sites become warmer and drier, herbaceous understory composition could shift to more xeric species that are better adapted, and bareground may increase (Chambers et al. 2014). As a result, invasive species, particularly cheatgrass, could expand into and establish dominance in these altered communities.

It is possible that mountain big sagebrush distribution may shift to cooler and moister sites (e.g., higher elevation, northeast-facing snow-filled depressions). With climate change, it may be able to persist only in sites with higher moisture and deeper soils than the surrounding landscape. Understory composition may shift to more xeric grassland species (e.g., bluebunch wheatgrass, needle-and-thread), which are more tolerant of warmer, drier conditions.

Risk Assessment

Magnitude of effects: Moderate

Likelihood of effects: Moderate

Northern Great Plains, Dominated by Mixtures of Cool-Season and Warm-Season Grasses

Eastern grasslands are expansive across the northern Great Plains extending from the foothill grasslands along the east slope of the northern and central Rocky Mountains in Montana to the Red River basin in eastern North Dakota. Annual precipitation increases from west to east changing from dry temperate steppe to humid temperate prairie parkland provinces along this gradient (ECOMAP 2007). Grasslands are the predominant potential vegetation type, occupying approximately 80 percent of the northern Great Plains landscape. Küchler (1975) divides the potential natural vegetation of this area into shortgrass prairie, northern mixed grass prairie, and tallgrass prairie, reflecting the changing precipitation regime. The shortgrass prairie borders the foothills grassland and extends to eastern Montana. The typical grassland vegetation types are characterized by grama (*Bouteloua* sp.)/needlegrass/wheatgrass and a mix of C3 and C4 plant species. The northern mixed grass prairie borders the shortgrass prairie in eastern Montana and extends to eastern North Dakota. Typical grassland vegetation types are characterized by

wheatgrass/needlegrass in the west and wheatgrass/bluestem (*Andropogon* sp.)/needlegrass to the east, including a mix of C3 and C4 plant species. The tallgrass prairie borders the northern mixed grass prairie in eastern North Dakota and South Dakota and borders the eastern hardwood forest to the east. The typical grassland vegetation types are characterized by bluestem and a dominance of C4 grasses, although C3 grass species are present.

Frequent fire was a major factor in maintaining grassland dominance, particularly in the eastern Great Plains. Settlement in the late 19th and early 20th centuries altered fire regimes by reducing fire frequency and changing the seasonality of fire. The predominant land use and land cover changed from grasslands to crop agriculture and domestic livestock production, affecting the continuity of fuels and fire spread. Reduced fire coupled with increased CO₂ has encouraged woody plant encroachment, primarily in the eastern Great Plains (Morgan et al. 2008).

Other stressors include increased presence and abundance of competitive invasive grass and forb species. These species reduce plant diversity of native grasslands and alter grassland structure. Noxious weeds such as leafy spurge (*Euphorbia esula*) are abundant in places, and other invasive nonnative species include Kentucky bluegrass (*Poa pratensis*), Japanese brome, and cheatgrass. Additionally, energy development and the associated infrastructure fragments grassland patterns where it occurs locally. Roads and traffic increase opportunities for introduction and spread of invasive species.

Soil water availability and water stress are principal driving factors in semi-arid grasslands, influencing plant species distribution, plant community composition and structure, productivity, and associated social and economic systems of the northern Great Plains. Soil water availability is influenced by complex interactions among temperature, precipitation, topography, soil properties, and ambient CO₂ (Ghannoum 2009; Morgan et al. 2011). These physical factors interacting with plant species physiological mechanisms, particularly those of C3 and C4 plants, will influence how grasslands will respond to climate change and elevated atmospheric CO₂ levels (Bachman et al. 2010; Chen et al. 1996; Ghannoum 2009; Morgan et al. 2011).

Available soil water is unevenly distributed across landscapes and a function of landform, topography, and soil properties. Soil moisture loss through evapotranspiration is influenced by slope, aspect, and solar loading at the ground surface, and water holding capacity is influenced by soil properties. These characteristics in the northern plains may modify the effects of climate change and enhanced CO₂ locally. Landscape patterns of available soil water may result in uneven patterns of vegetation change and productivity under changing temperature and moisture regimes and elevated CO₂ levels. The desiccating effect of higher temperature and increased evaporative demand (Morgan et al. 2011) is expected to offset the benefit of higher precipitation, resulting in lower soil water content and increased drought throughout most of the Great Plains (Morgan et al. 2008). Elevated CO₂ may counter the effects of higher temperatures and evaporative demand by improving water-use efficiency of plants (Morgan et al. 2011).

Rising CO₂ and temperature combined with increased winter precipitation may favor some herbaceous forbs, legumes, and woody plants (Morgan et al. 2008). Plant productivity is expected to increase with projected changes in temperature and moisture combined with elevated CO₂ (Morgan et al. 2008). Forage quality may decline as a result of less available forms of soil nitrogen and changes in plant species and functional groups (Morgan et al. 2008). A major shift in functional groups from C3 to C4 plants is possible but uncertain, because warmer temperature and longer growing seasons favor C4 grasses, but the effects of higher CO₂ on water-use efficiency may benefit C3 grasses. Since most invasive species are C3 plants, they may become more problematic with the benefits of increased CO₂ (Morgan et al. 2008).

The adaptive capacity of Great Plains grasslands during the 1930s and 1950s drought was documented for the central plains (Weaver 1968). There was a shift in C4 grasses, in which big bluestem (*Andropogon gerardii*) and little bluestem (*Schizachyrium scoparium*) were replaced by the shortgrass species blue grama (*Bouteloua gracili*) and buffalograss (*Bouteloua dactyloides*). Shifts from tallgrass prairie to mixed grass prairie were also documented with an increase in the C3 plants western wheatgrass and needlegrass. This shift was later reversed during the higher precipitation period of the 1940s,

indicating an adaptive capacity of Great Plains grasslands to the effects of long-term drought. These shifts were also affected by grazing condition of the grasslands prior to the drought.

Risk Assessment—

Magnitude of effects: Moderate magnitude for change from temperate grassland to sub-tropical grassland by 2050 under no fire suppression. Change toward increased woody vegetation by 2050 with fire suppression. High magnitude for change from temperate grassland to sub-tropical grassland by 2100. Moderate magnitude for change towards woody vegetation by 2100.

Likelihood of effects: Moderate likelihood for a change from temperate grassland to sub-tropical grassland by 2050 under no fire suppression; change toward increased woody vegetation by 2050 with fire suppression. The response of C3 and C4 species to the combined effects of higher temperature and elevated CO₂ is uncertain.

ADAPTING RANGELAND VEGETATION MANAGEMENT TO CLIMATE CHANGE IN THE NORTHERN ROCKIES

Rangeland vegetation in the northern Rockies will likely be affected by changing fire regimes, increased drought, and increased establishment of invasive species in a changing climate. Effects of climate change will also compound existing stressors on rangeland ecosystems caused by human activities. Thus, adaptation strategies and tactics for rangeland vegetation focused on increasing the resilience of rangeland ecosystems, primarily through invasive species control and prevention (table 7.3).

To control invasive species in rangelands, managers stressed the importance of using ecologically based invasive plant management (EBIPM) (Krueger-Mangold et al. 2006; Sheley et al. 2006). The EBIPM framework focuses on strategies to repair damaged ecological processes that facilitate invasion (James et al. 2010). For example, prescribed fire treatments can be used where fire regimes have been altered, and seeding of desired natives can be done where seed availability and dispersal of natives is low.

Another adaptation strategy is to increase proactive management actions to prevent establishment of invasive species. Early detection, rapid response (EDRR) for new invasions was the most frequently suggested tactic to prevent invasive species establishment. Other tactics include implementing weed free

policies, conducting outreach to educate employees and the public about invasives (e.g., teach people to clean their boots), and developing weed management areas that are collaboratively managed by multiple agencies, non-governmental organizations, and the public.

In addition to invasive species control and prevention, grazing management will be important in maintaining and increasing resilience of rangelands to climate change. Climate changes will lead to altered availability of forage, requiring some reconsideration of grazing strategies. For example, reducing grazing in July and August may encourage growth of desired perennials in degraded systems. Livestock grazing can also be managed through the development of site-specific within-season triggers and end point indicators that would inform livestock movement guides and allow for the maintenance and enhancement of plant health.

A changing climate has led to a decline of pollinators in some communities (Potts and others 2010) and may lead to phenological mismatches between pollinators and host plants (Forrest 2015). Pollinator declines may negatively affect the health of grasslands in the Northern Rockies, and encouraging native pollinators may be key to sustaining these ecosystems. Tools to promote native pollinators include re-vegetation with native species, appropriate herbicide and insecticide use, and education. Implementing long term monitoring of pollinators can help to identify where treatments can be prioritized.

In montane shrublands, existing stressors include fire exclusion and conifer establishment, browsing by both native and domestic ungulates, and insects and disease. Characteristic species can be lost in these systems with loss of topsoil following frequent, hot fires. Warmer temperatures and drier conditions with climate change may lead to an increase in high-severity fires. Adaptation tactics include implementing fuel reduction projects such as brush cutting, slashing, mastication and targeted browsing, and reestablishing appropriate fire regimes may prove beneficial in maintaining these shrublands and increasing their resiliency. To control invasives, EDRR and EBIPM can be applied, along with maintenance of adequate shrub cover, vigor, and species richness. Educating specialists on ecology and disturbances affecting shrublands, effects of repeated burns, reforestation needs, and reporting on weeds will also help to maintain these systems.

9258 More specific details on adaptation strategies and tactics for the NRAP subregions are in Appendix
9259 7A.

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Chapter 8: Effects of Climate Change on Ecological Disturbance

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INTRODUCTION

This chapter describes the ecology of important disturbance regimes in the region encompassed by the Northern Rockies Adaptation Partnership, and potential shifts in these regimes as a consequence of observed and projected climate change. The term *disturbance regime* describes the general temporal and spatial characteristics of a *disturbance agent*—insect, disease, fire, weather, even human activity—and the effects of that agent on the landscape (table 8.1). More specifically, a disturbance regime is the cumulative effect of multiple disturbance events over space and time (Keane 2013). Disturbances disrupt an ecosystem, community, or population structure and change elements of the biological and/or physical environment (White and Pickett 1985). The resulting shifting mosaic of diverse ecological patterns and structures in turn affects future patterns of disturbance, in a reciprocal, linked relationship that shapes the fundamental character of landscapes and ecosystems. Disturbance creates and maintains biological diversity in the form of shifting, heterogeneous mosaics of diverse communities and habitats across a landscape (McKinney 1998), and biodiversity is generally highest when disturbance is neither too rare nor too frequent on the landscape (Grime 1973).

A changing climate may already be altering characteristics of disturbance agents, events, and regimes, with additional effects expected in the future (Dale et al. 2001). Climate changes can alter the timing, magnitude, frequency, and duration of disturbance events, as well as the interactions of disturbances on a landscape. Interactions among disturbance regimes, such as the co-occurrence in space and time of bark beetle outbreaks and wildfires, can result in highly visible, rapidly occurring, and persistent changes in landscape composition and structure. Understanding how altered disturbance patterns and multiple

disturbance interactions might result in novel and emergent landscape behaviors is critical for addressing climate change impacts and for designing land management strategies that are appropriate for future climates (Keane et al. 2015).

We summarize five disturbance types present in the Northern Rockies that are sensitive to a changing climate. Wildfires, bark beetles, white pine blister rust (*Cronartium ribicola*), other forest diseases, and nonnative plant invasions acting individually or synergistically can transform landscape patterns and ecological functions. This chapter provides background that can help managers understand the important role of disturbances on Northern Rockies landscapes, and anticipate how, when, where, and why climate changes may alter the characteristics of disturbance regimes.

WILDFIRE

Overview

Wildland fire is ubiquitous throughout forest ecosystems of the Northern Rockies and was historically the most important and extensive landscape disturbance in the region (Helj et al. 1995). Wildfire emerged as a dominant process in North America after the end of the last glacial period, about 16,500-13,000 years before present, commensurate with rapid climate changes and increased tree cover (Marlon et al. 2009). In the Northern Rockies, many forest types are fire prone and fire adapted, meaning that fire is an integral and predictable part of their maintenance and ecological functioning. Wildfire, as well as other disturbances such as insect outbreaks, disease, drought, invasive species, and storms, is part of the ecological history of most forest ecosystems, influencing vegetation age and structure, plant species composition, productivity, carbon (C) storage, water yield, nutrient retention, and wildlife habitat (Agee 1993).

Climate and fuels are the two most important factors controlling patterns of fire in forest ecosystems. Climate controls the frequency of weather conditions that promote fire, whereas the amount and arrangement of fuels influence fire intensity and spread. Climate influences fuels on longer time scales by shaping species composition and productivity (Dale et al. 2001; Marlon et al. 2008; Power et al. 2008) and large-scale climatic patterns such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal

Oscillation (PDO) are important drivers of forest productivity and susceptibility to disturbance (Collins et al. 2006; Kitzberger et al. 2007). Current and past land use, including timber harvest, forest clearing, fire suppression, and fire exclusion through grazing have affected the amount and structure of fuels in the United States (Allen et al. 2002; Falk et al. 2011; Pausas and Keeley 2014).

Disturbance impacts can overwhelm the direct effects of climate changes on ecosystems. As described in other chapters in this publication, climate changes influence forests directly; for example, it has been suggested that drought and heat stress are linked to increased tree mortality, shifts in species distributions, and decreased productivity (Allen et al. 2010; Van Mantgem et al. 2009; Williams et al. 2013). However, the most visible and significant short-term effects of climate changes on forest ecosystems will be caused by altered disturbances, often occurring with increased frequency and severity. Climate changes are likely to increase fire frequency, fire season length, and cumulative area burned in the coming decades in the western United States, in response to warmer, drier conditions (Flannigan et al. 2006; McKenzie et al. 2004). Climate changes may also increase the frequency or magnitude of extreme weather events that affect fire behavior (Kurz et al. 2008; Lubchenco and Karl 2012). Although shifts in vegetation composition and distribution caused by climate alone may occur over decades or centuries, wildfires can temporarily or persistently reorganize landscapes over a period of days (Overpeck et al. 1990; Seidl et al. 2011).

The role of fire in ecosystems and its interactions with dominant vegetation is termed a fire regime (Agee 1993). Fire regimes are defined by fire frequency (mean number of fires per time period), extent, intensity (measure of the heat energy released), severity (net ecological effect), and seasonal timing (table 8.2). These characteristics vary across vegetation types and depend on the amount and configuration of live and dead fuel present at a site, environmental conditions that favor combustion, and ignition sources (Agee 1993; Krawchuk et al. 2009). Ecosystems in the Northern Rockies have been subject to a range of historical fire regimes, including (1) frequent (1-35 years), low- or mixed-severity fires that replaced less than 25 percent of the dominant overstory vegetation; (2) moderate-frequency (35-200 years), mixed-severity fires that replaced up to 75 percent of the overstory; and (3) infrequent (200+ years), high-

severity fires that replaced greater than 75 percent of the dominant overstory vegetation (fig. 8.1). More detailed information on fire regimes specific to individual vegetation species and vegetation types can be found in chapter 6 of this volume.

Wildland fire behavior is influenced by variability in environmental conditions including vegetation type and distribution, climate, weather, and topography. Despite major human influences on western U.S. wildfires since Euro-American settlement, climate is generally considered to be the primary control on fire regimes in the region, influencing vegetation production and condition as well as the physical environment (Marlon et al. 2012). Where rates of vegetation production outpace decomposition, sufficient biomass is available to support fires, although higher elevation regions with abundant fuels do not always experience sufficiently dry conditions to sustain a fire. In these systems short-duration drying episodes generally do not create sufficiently dry conditions to sustain a fire, but prolonged dry weather conditions (about 40 days without precipitation) can sufficiently dry live fuels and larger dead fuels to carry large, intense fires once they are ignited (Schoennagel et al. 2004). Wildland fuels lose moisture and become flammable in warm and dry summers typical in the Northern Rockies, during which time there are ample sources of ignition from lightning strikes and humans. Therefore, the active fire season (period conducive to active burning) is in the summer, typically from late June through October, with shorter seasons at higher elevation sites where snowpack can persist into July (Littell et al. 2009).

At annual time scales, weather is the best predictor of fire characteristics such as area burned and fire size. Correlations between weather and annual area burned by fire or the number of large fires are similar for both pre-20th century fires and fires that have occurred during the past few decades. Fire-weather relationships exist for forested ecosystems of the Pacific Northwest (Hessl et al. 2004; Heyerdahl et al. 2002, 2008a) and Northern Rockies (Heyerdahl et al. 2008b; Littell et al. 2009; Westerling et al. 2003, 2006), constructed using tree-ring and fire-scar records and independently reconstructed climate, or observed fire events and observed weather occurring in the seasons leading up to and during the fire where records are available. Regionally, widespread fire years are correlated with drought (Heyerdahl et al. 2008b; Morgan et al. 2008), and these regionally synchronous fires have generally occurred in the

Northern Rockies (Idaho and western Montana) during years with relatively warm spring-summer and warm-dry summers (Heyerdahl et al. 2008a; Morgan et al. 2008).

In non-forested systems in the eastern Northern Rockies, precipitation amount, at both short (weeks to months) (Littell et al. 2009) and long (decades to centuries) (Brown et al. 2005) time scales is the dominant control on fire. During the fire season, the amount and timing of precipitation largely determine availability and combustibility of fine fuels, and short periods of dry weather are sufficient to precondition these systems to burn (Gedalof et al. 2005; Westerling and Swetnam 2003). In contrast to the grasslands of the southwestern United States, antecedent precipitation has not been found to be a significant driver of large fires in the northern grasslands; rather, large fires are most strongly correlated with low precipitation, high temperatures, and summer drought (July through September) in the year of the fire (Littell et al. 2009).

Humans are also important drivers of wildfire, via altered ignition patterns associated with land clearing and land cover change, agriculture, introduction of exotic species, and fire management (fuel treatments and fire suppression/exclusion). Grazing and the introduction of nonnative species have altered ecological processes that affect fire, including fuel loading and continuity, forest composition and structure, nutrient cycling, soils, and hydrology (Marlon et al. 2009; Swetnam et al. 1999). For many sagebrush ecosystems of low to moderate productivity, fire intervals are 10 to 20 times shorter today than what is estimated for pre-20th century conditions (Peters and Bunting 1994; Whisenant 1990; chapter 7), because of the spread and dominance of the nonnative annual cheatgrass (*Bromus tectorum*). Dry forests, shrublands, and grasslands in the region exist in a state of “fire deficit” as the result of fire exclusion, leading to less frequent wildfire, higher stand densities, higher fuel quantities, and higher fuel continuity. This has increased the potential for crown fires in forests that historically experienced low-severity fire regimes (Agee 1998; Peterson et al. 2005) and in some forests that experienced mixed-severity regimes (Taylor and Skinner 2003).

Wildfire Shapes Landscape Patterns

The composition and structure of forests in the Northern Rockies is determined by climate, elevation, topographic position, and history of fire. In general, fire regimes vary along environmental gradients, with fire frequency decreasing and fire severity increasing with elevation (although aspect and slope position can influence fire patterns). For example, low-severity fires are typical in many ponderosa pine (*Pinus ponderosa*) forests at low elevations. Historically, fires here burned frequently enough to maintain low fuel loads and an open stand structure, producing a landscape in which fire-caused mortality of mature trees was rare (Agee 1998; Jenkins et al. 2011; Moritz et al. 2011). Adaptive traits such as thick bark also allowed mature ponderosa pines to survive many repeated fires over time. Conversely, high-severity fires occurring at intervals of more than 300 years are typical in subalpine forests and tend to result in high mortality of mature trees (“stand replacement”) because long intervals between fires result in dense, multi-storied forest structures that are susceptible to crown fires (Agee 1998) (fig. 8.2).

Fire exclusion since the 1920s has increased surface fuel loads, tree densities, and ladder fuels, especially in low-elevation, dry conifer forests (Schoennagel et al. 2004) (fig. 8.3). As a result, fires in these forests may be larger and more intense, and may cause higher rates of tree mortality than historical fires. In higher elevation forests where fires were historically infrequent, fire exclusion has not altered fire regimes (Romme and Despain 1989; Schoennagel et al. 2004). For example, lodgepole pine (*Pinus contorta* var. *latifolia*) forests in Yellowstone National Park historically experienced large, stand-replacing fires (Romme 1982), and many (but not all) lodgepole pine trees can regenerate prolifically when heating from fires releases seed from serotinous cones (Schoennagel et al. 2003).

Wildfires and Forest Carbon Sequestration

Concerns about projected changes in global climate have raised an expectation that forests can help mitigate climate changes via management for increased carbon sequestration and storage (Sommers et al. 2014). Forests contain large reservoirs of carbon in soils (~45 percent of total storage), aboveground and belowground live biomass (~42 percent), deadwood (~8 percent) and litter (~5 percent) (Pan et al. 2011). The carbon sequestration potential of Earth’s forests is about 33 percent of global emissions from fossil fuels and land use (Denman 2007), and North American forests currently offset about 13 percent of

annual continental fossil fuel emissions (Pacala et al. 2007). The potential for forests to mitigate climate change depends on human activities such as land use and land management, and environmental factors such as vegetation composition, structure, and distribution, disturbance processes, and climate (Loehman et al. 2014).

Carbon typically accumulates in woody biomass and soils for decades to centuries until a disturbance event like wildfire releases this stored carbon into the atmosphere (Goward et al. 2008). Wildfire in forested ecosystems is one of the primary disturbances that regulates patterns of carbon storage and release (Kasischke et al. 2000). The amount and rate of carbon release from a wildfire depends on the extent and severity of the fire, as well as pre-disturbance site conditions and productivity (Bigler et al. 2005; Dale et al. 2001; Falk et al. 2007). For example, high-severity fires typical of mid- to upper-elevation forests in the Northern Rockies may consume a large amount of aboveground biomass, resulting in an instantaneous pulse of carbon (i.e., the area affected becomes a carbon source to the atmosphere); however, these fires typically occur infrequently, and carbon is stored in woody biomass as forests regrow. Low-severity fires such as those that occur in low-elevation, dry forest types typically release less carbon per fire event (although total emissions are dependent on area burned) at more frequent intervals than with stand-replacing regimes, and favor long-lived and fire-resistant (or tolerant) forest species that typically survive multiple fire events (Ritchie et al. 2007). Carbon losses from wildland fire are balanced by carbon capture from forest regrowth across unmanaged fire regimes and over multiple decades, unless a lasting shift in dominant plant life form occurs or fire return intervals change (Kashian et al. 2006; Wiedinmyer and Neff 2007).

There are several important ideas to consider when managing forests and fires for carbon resources. First, as stated above, unless structural or functional ecosystem shifts occur, net carbon balance in disturbance-adapted systems at steady state is zero when assessed over long time periods and at large spatial scales. Under these conditions, although a fire may result in a temporary loss of stored carbon from a forest to the atmosphere (i.e., be a carbon source), this effect is transitory and balanced by carbon accumulation as the forest regrows. The time required for the postfire environment to shift from carbon

source to sink varies among forest types and climates. For example, in simulations of effects of stand-scale fuel treatments on carbon-fire relationships in Northern Rockies forests, postfire carbon recovery occurred in 10 to 50 years, depending on vegetation type and whether stands were treated before fire to reduce woody fuels (Reinhardt and Holsinger 2010).

Second, quantifying or projecting wildland fire emissions is difficult because their amount and character vary greatly from fire to fire, depending on biomass carbon densities, quantity and condition of consumed fuels, combustion efficiency, and weather (Loehman et al. 2014). Emissions measured for an individual fire event may not be characteristic of large-scale emissions potential, because of complex ecological patterning and spatial heterogeneity of burn severity within fire perimeters. Although long intervals between wildfires can allow carbon to accumulate for years to centuries, disturbance-prone forests will eventually lose stored carbon to the atmosphere, regardless of management strategies designed to limit or prevent disturbance events.

Third, wildfire confers many important ecological benefits not measurable in carbon units (e.g., nutrient release and redistribution, stimulation of plant growth, increased productivity in soil systems from decomposition of burned material, initiation of vegetation succession and forest regeneration, increased availability of resources for surviving trees). Thus, it will be important to develop accounting methods that can assess ecological benefits in carbon-equivalent units so that they can be weighed against carbon losses from disturbance.

Finally, climate changes in combination with other ecosystem stressors may be sufficient to cause structural or functional changes in ecosystems and thus alter carbon dynamics of landscapes. For example, if climate changes increase wildfire frequency, extent, and/or severity in forested ecosystems, forests will likely lose carbon to the atmosphere that will not be rapidly replaced by new growth. This will cause forests to act as carbon sources for a period of time, until disturbance regimes and biomass stabilize. Future landscapes could have the potential to store less, or more, carbon than under current climate and disturbance regimes.

Potential Future Wildfire Regimes and Wildfire Occurrence

Potential mid to late 21st century climate-driven changes to regional fire regimes include longer fire seasons and increases in fire frequency, annual area burned, number of high fire danger days, and fire severity as compared with modern fire patterns (Bachelet et al. 2003; Brown et al. 2004; Dillon et al. 2011; Krawchuk et al. 2009; Rocca et al. 2014; Westerling et al. 2006) (figs. 8.4, 8.5). In particular, lengthening of the fire season (the period of the year when fires can burn) will allow for more ignitions, greater likelihood of fire spread, and a longer burning duration. A longer burning window combined with regionally dry fuels will promote larger fires and increased annual area burned relative to modern recorded fire activity. Earlier onset of snowmelt will reduce fuel moistures during fire season, making a larger portion of the landscape flammable for longer periods of time (McKenzie et al. 2004; Miller et al. 2011). This shift may be especially pronounced in middle to high elevation forested systems where fuels are abundant.

Earlier snowmelt, higher summer temperatures, longer fire season, and expanded vulnerable area of high-elevation forests have produced observed increased wildfire activity compared to the mid-20th century, particularly in the Northern Rockies (Westerling et al. 2006). Annual area burned by western wildfires in the 20th century was greater in years with low precipitation, high drought severity, and high temperatures (Littell et al. 2009). Wildfire activity in the western United States is expected to increase if climates become warmer and drier in the future. Among western United States forests, mid-elevation forests of the Northern Rockies are projected to have a high risk of climate-induced increase in fire (Westerling et al. 2006), and increases in the area burned by fire are likely in lower and middle elevations of mountainous areas (Littell et al. 2009). However, in areas that are fuel limited, fires may become more infrequent where there is insufficient moisture for fine fuel accumulation (Littell et al. 2009).

The potential effects of climate change on wildfire area have been assessed using statistical and ecological process models for the western United States (McKenzie et al. 2004; Spracklen et al. 2009), Pacific Northwest (Littell et al. 2010), Northern Rockies (Holsinger et al. 2014; Loehman et al. 2011a, 2011b; Rocca et al. 2014), and the Greater Yellowstone Area (Westerling et al. 2011). For a mean temperature increase of 4 °F, the annual area burned by wildfires is expected to increase by a factor of 1.4

to 5 for most western states (McKenzie et al. 2004), ultimately leading to greater damage, growth reductions, and mortality in forest ecosystems. The effects of future climate on fire severity (i.e., the proportion of overstory mortality) are less certain because severity may be more sensitive than area burned to arrangement and availability of fuels. The risk posed by future fire activity in a changing climate can be assessed by its likely effects on human and ecological systems. At the wildland-urban interface, higher population and forest density have created forest conditions that are likely to experience more area burned and possibly higher fire severity than in the historical record (Dillon et al. 2011) (figs. 8.4, 8.5).

Although fire size in historic sagebrush landscapes is poorly understood, it is generally accepted that recent large fires have been fueled by woodland encroachment and higher fine fuel loads from weed invasions (e.g., cheatgrass). These changes in fire regime and vegetation-fuel structure affect large areas in the semiarid western United States and cascade through all trophic levels. Effects are particularly harmful on landscapes where postfire recovery is slow. The trend for larger, more damaging fires in sagebrush ecosystems is expected to continue until aberrations in fuel conditions that drive fire are corrected (Keane et al. 2008).

Interactions with Other Disturbance Processes

Wildland fires and insect outbreaks are the two primary natural disturbance processes in conifer forests of western North America (Hicke et al. 2012; Jenkins et al. 2012). The interaction of wildland fire and bark beetles has been studied since the early 20th century (Evenden and Gibson 1940; Miller and Patterson 1927; Weaver 1943), with research primarily focused on the potential for increased fire hazard following outbreaks. Multiple studies have cited changes in fire behavior, extent, and severity resulting from bark beetle-caused mortality in pine forests (see Hicke et al. 2012 for a summary). Drought and increased temperatures are key drivers of both wildland fires and bark beetle outbreaks. Climate change may be a causal factor in recent increases in annual area burned by wildfires (Littell et al. 2009) and area affected by bark beetle outbreaks (Bentz et al. 2010). Projections of warmer temperatures and increased drought stress suggest that the total area susceptible to or affected by beetle outbreaks and large or severe

fires may increase in the coming decades (Williams et al. 2013). Acting independently or synchronously in space and time, wildland fires and bark beetle outbreaks can substantially influence forest structure, composition, and function; abruptly reorganize landscapes; and alter biogeochemical processes such as carbon cycling, water supply, and nutrient cycles (Edburg et al. 2012; Falk 2013; Fettig et al. 2013; Hansen 2013; Kurz et al. 2008a).

Unknowns and Uncertainties

Projections of future climate are somewhat uncertain because the ultimate magnitude of climate change and the severity of its impacts depend strongly on the actions that human societies take to respond to these risks (NRC 2010). Global climate models and their downscaled products may not accurately represent climate and weather at the regional and local scales that influence fire occurrence and behavior. For example, although associations between fire and quasi-periodic patterns such as ENSO and PDO have been identified, there is incomplete understanding of how these will respond to climate warming (McKenzie et al. 2004). In addition, precipitation trends are highly variable, and projections of future precipitation reflect both uncertainty and high variation (IPCC 2007, 2012; Littell 2011). Lightning, an important ignition source for wildland fires, may increase in the future, thus increasing the potential for fire activity – for example, recent projections suggest that lightning strikes in the continental US may increase by about 50 percent over the 20th century as the result of global warming–induced increase in updraft speeds and atmospheric water content (Romps et al. 2014). However, others have concluded that confidence in projections of increased thunderstorms and severe local weather events is low (Seneviratne et al. 2012).

Thus, the influence of climate changes on future fire patterns is not precisely known. Grissino-Mayer and Swetnam (2000) note that “long-term changes in climate.... are unlikely to produce simple linear responses in global fire regimes, e.g., warmer temperatures may not necessarily lead to increased fire frequency,” in large part because fire activity is strongly influenced by precipitation, which can occur at scales not well captured by climate models. Other research suggests that increases in burned area can be expected in a warming climate, but fire activity will ultimately be limited by the availability of fuels

(Brown et al. 2004; Flannigan et al. 2006; Loehman et al. 2011a; McKenzie et al. 2004; Torn and Fried 1992). In addition, climate drivers interact with legacies of human land use and local vegetation and fuel conditions at large spatial scales, making linear climate-fire predictions difficult. Specifically, decades-long fire exclusion and timber harvesting in some forests of the western US have resulted in densely stocked stands and heavy downed fuels accumulation that have likely contributed to the anomalous size and intensity of recent fires (Grissino Mayer and Swetnam 2000; Naficy et al. 2010).

BARK BEETLES

Overview

Bark beetles (Coleoptera: Curculionidae, Scolytinae) comprise a large subfamily of insects, although less than one percent of the more than 6,000 species found worldwide cause significant economic impacts. In the Northern Rockies, bark beetles of economic concern feed in the phloem of living conifers and can have extreme population amplifications over short time periods, the hallmark of outbreak species. Larval feeding, in addition to colonization by beetle-introduced fungi, typically results in death of the tree, and new host material is therefore required for each beetle generation. Historically, pulses of bark beetle-caused tree mortality have been extensive across the northern Rocky Mountain Region. Recently, between 1999 and 2013, bark beetle-caused tree mortality has had substantial impacts in the Northern Rockies across an average of 1.4 million acres each year (fig. 8.6). Mountain pine beetle (*Dendroctonus ponderosae*, hereafter referred to as MPB) caused the majority of tree mortality (82 percent of acres with mortality detected) with a cumulative impact across 8.7 million acres during this time period (fig. 8.7). Across western North America between 1997 and 2010, bark beetle-caused tree mortality resulted in a transfer of carbon that exceeded that of fire-caused tree mortality (Hicke et al. 2013).

Both bark beetle populations and their host trees are being influenced by a warmer climate. Many bark beetle life history traits that influence population success are temperature dependent (Bentz and Jönsson 2015), and warming temperatures associated with climate change have directly influenced bark beetle-caused tree mortality in some areas of western North America (Safranyik et al. 2010; Weed et al.

2015). Host tree distribution across the Northern Rockies, and tree vigor that influences susceptibility to bark beetle attack (Chapman et al. 2012; Hart et al. 2013) will also be influenced as the climate continues to warm.

Bark Beetles in the Northern Rockies

Bark beetles are relative specialists, feeding on a single tree species or several species within a single genus. In the Northern Rockies, multiple tree species are affected by different bark beetle species (table 8.3). Populations of several beetle species, and MPB in particular, began building in 1999, with high populations continuing in some areas through 2013 (<http://foresthealth.fs.usda.gov/portal>; fig. 8.6). Trend analysis indicates that a majority of subwatersheds have declining populations, although some specific locations had increases in 2012 and 2013 (fig. 8.7) (Egan 2014; Egan et al. 2013). Based on 2012 vegetation characteristics, susceptibility of Northern Rockies watersheds to future MPB outbreaks is spatially variable with many areas projected to lose >25 percent of total basal area (Krist et al. 2014).

Drivers of Bark Beetle Outbreaks

Bark beetle population outbreaks require forests with extensive host trees of suitable size and age (Fettig et al. 2013). For most irruptive species, preferred hosts are large, mature trees that provide a large amount of phloem resource for a developing brood. Large landscapes of these mature stands provide the perfect scenario for years of bark beetle population growth.

Although suitable host trees are critical to outbreak development, beetle populations can exist for years at low levels until release is triggered by inciting factors that allow for rapid population growth that makes use of plentiful host trees. Triggers have been difficult to quantify but include factors that make food more readily available, and increase survival and reproduction of the beetles. Stand conditions (Fettig et al. 2013), drought (Chapman et al. 2012; Hart et al. 2013), and pathogens (Goheen and Hansen 1993) can make it easier for low levels of beetles to overwhelm and kill trees. Similarly, large areas of host trees recently killed by fire, wind, or avalanche provide pulses of accessible food, and have resulted in outbreaks of some species such as Douglas-fir beetle (*Dendroctonus pseudotsugae*) and spruce beetle (*D. rufipennis*) (Hebertson and Jenkins 2007; Shore et al. 1999), as well as secondary beetles including

Ips species and fir engraver (*Scolytus ventralis*) (Livingston 1979). Weather favorable to beetle reproduction and survival also influences population fluctuations, and can both initiate and sustain outbreaks (Bentz et al. 2011; Powell and Bentz 2009; Regniere and Bentz 2007).

Given a susceptible forest, climate and weather directly drive bark beetle outbreaks by affecting beetle growth and survival through temperature-dependent life history traits. For example, the process of mass attack needed to successfully overcome tree defenses requires synchronous emergence of adults, a process mediated by temperature (Bentz et al. 1991). Diapause and development rate thresholds help in this synchrony (Bentz and Jönsson 2015; Hansen et al. 2001, 2011; Ryan 1959; Safranyik et al. 1990). These same strategies also reduce the likelihood that life stages most sensitive to cold (eggs and pupae) are not present during winter. Development rates and thresholds also dictate life cycle timing, an important determinant of the number of generations per year.

The western pine beetle (*D. brevicomis*) and *Ips* species can be bivoltine (two generations in one year) in the Northern Rockies (Kegley et al. 1997; Livingston 1991), although multivoltine in more southern parts of their range. Other bark beetle species require at least one year to complete a generation (univoltine), and at higher elevations where temperatures are cooler, two to three years may be required for a complete life cycle. Warm temperatures in the summer and spring extend the time that temperatures are above development thresholds, thereby allowing a reduction in generation time (Bentz et al. 2014; Hansen et al. 2001). Shorter generation times can lead to increased population growth, causing increased tree mortality. Winter temperature also influences bark beetle population success. Larvae cold-harden to survive subfreezing temperatures (Bentz and Mullins 1999; Miller and Werner 1987), although extreme fluctuations in temperature in spring and autumn, in addition to long durations of temperatures below -31 °F, can cause extensive larval mortality (Evenden and Gibson 1940; Regniere and Bentz 2007; Safranyik and Linton 1991).

Bark Beetle Outbreaks Shape Landscape Patterns

Bark beetle disturbances play a significant role in successional pathways and biogeochemical cycles in Northern Rockies forests (DeRose and Long 2007; Edburg et al. 2012; Hansen 2014). At low

population levels, bark beetles act locally as thinning agents, producing forest gaps that promote regeneration and the release and subsequent growth of neighboring host and non-host trees, often producing uneven-aged stands (Mitchell and Preisler 1998). At outbreak population levels, tree mortality can approach 80 percent across landscapes of homogeneous host species and age, changing age-class distributions and overstory and understory species compositions. For example, in seral lodgepole pine forests, removal of the largest trees by MPB can hasten succession by climax species when fire is absent (Hagle et al. 2000; Roe and Amman 1977). Bark beetle disturbance can have long-term effects on forest structure and composition (Pelz and Smith 2012), and future landscape patterns in some forest types will be driven by tree mortality caused by large outbreaks of beetles.

Potential Future Bark Beetle Regimes and Occurrence

Climate change will have direct and indirect effects on bark beetle population outbreaks (table 8.4). Indirectly, changing temperature and precipitation regimes will influence the suitability and spatial distribution of host trees. Community associates important to bark beetle population success, including fungi, predators and competitors, will also be affected by changing climate and thereby indirectly affect beetle population outbreaks. Direct effects will also occur as changing temperature regimes either promote or disrupt bark beetle temperature-dependent life history strategies that evolved through local adaptation for increased beetle population fitness and survival. Future bark beetle-caused tree mortality will therefore depend not only on the spatial distribution of live host trees and heterogeneity of future landscapes (see chapter 6), but also the ability of beetle populations and their associates to adapt to changing conditions when existing phenotypic plasticity is surpassed.

Projected changes in temperature and precipitation, in addition to a potential increase in extreme events such as windstorms, will significantly influence the spatial and temporal distribution of suitable host trees across future landscapes. For example, host tree defenses can be weakened by reduced water availability (Chapman et al. 2012; Gaylord et al. 2013; Hart et al. 2013). Increasing temperature is also associated with changing hydrologic regimes (see chapter 4), including altered inter-seasonal timing of soil water availability facilitated by snow packs that have progressively melted earlier in recent decades,

and changes in the distribution of precipitation falling as rain versus snow (Regonda et al. 2005). These factors, along with other potential climate changes, may enhance physiological drought stress in host trees that could indirectly benefit bark beetles that colonize stressed hosts in the late-spring or summer (Raffa et al. 2008). Similarly, increased wind events could provide a reservoir of stressed trees used by some bark beetle species to surpass the endemic-epidemic threshold. Species currently considered secondary (i.e., infest stressed trees) could become primary tree killers as their favored habitat increases.

Warming temperatures will also directly influence bark beetle population success, although the effects will depend on the beetle species, as well as the seasonal timing, amount, and variability of thermal input. For example, across MPB habitats in the western United States from 1960 to 2011, minimum temperatures increased 6.5 °F. This increase in minimum temperature resulted in an increase in MPB survival and subsequent beetle-caused tree mortality in many areas of the Northern Rockies (Weed et al. 2015). As climate continues to change, however, extreme within-year variability in winter warming, could be detrimental to insect survival. Bark beetles produce supercooling compounds as temperatures decrease and catabolize compounds as temperature warm. Large temperature fluctuations could result in excessive metabolic investment in maintaining appropriate levels of antifreeze compounds, leaving individuals with minimal energy stores at the end of winter. In addition, many species overwinter at the base of tree boles, garnering protection from predators and excessive cold temperatures when insulated beneath snow. Reduced snow levels in a warming climate could therefore add to increased overwinter mortality.

Warming at other times of the year could similarly have both positive and negative effects on bark beetle populations. Phenological flexibility allows some species to shift voltinism pathways, developing on a semivoltine (one generation every two years) life cycle in cool years, and a univoltine lifecycle in warm years (Bentz et al. 2014; Hansen et al. 2001). Warming temperatures could also cause species that are currently bivoltine (e.g., western pine beetle, *Ips* species) to become multivoltine. These types of voltinism shifts can lead to rapid increases in beetle populations and subsequent tree mortality. Some thermal regimes allow these life cycle shifts yet maintain seasonal flights. However, other thermal

regimes that result in voltinism shifts could also disrupt seasonality. For example, warm summers could accelerate development resulting in reduced generation time, but also result in cold-sensitive life stages entering winter. Existing developmental thresholds and diapause strategies that serve synchrony currently reduce the likelihood of this happening. As existing phenotypic plasticity is surpassed, rapid warming without adaptation could lead to lower overall population fitness in some areas as a result of poor seasonal timing (Régnière et al. 2015).

Expected Effects of Climate Change

Although there are many bark beetle species in the Northern Rocky Mountains that can cause economic impact, the influence of climate change on population outbreaks has been most studied in MPB. It is clear that multiple aspects of climate change can positively influence MPB, including increasing winter temperature (Regniere and Bentz 2007; Weed et al. 2015) and reduced precipitation (Chapman et al. 2012). Changing thermal regimes, however, can also have both positive and negative effects on MPB population growth through phenological synchrony and generation timing. Acknowledging potential other climate effects, here we describe expected direct effects of climate change using a temperature-dependent mechanistic demographic model of MPB population growth that is based on phenological synchrony (Powell and Bentz 2009). The effect of future temperatures on univoltine population growth rate relative to historic conditions is projected. Although current climates appear to restrict MPB from successfully completing two generations in a single year (i.e., bivoltinism) (Bentz and Powell 2015; Bentz et al. 2014), we also evaluated if future thermal regimes would promote bivoltinism. The model was driven with downscaled temperatures from two global circulation models (GCMs): CanEMS2, CCSM4, and two emission scenarios (Representative Concentration Pathways RCP 4.5 and RCP 8.5) based on the multivariate adaptive constructed analogs approach (<http://maca.northwestknowledge.net>). Although indirect effects of climate clearly affect host tree vigor, stand composition, and distribution across a landscape, these effects are currently not included our demographic model. We report our model results, however, in conjunction with hazard categories developed by Krist et al. (2014) based on stand conditions conducive to MPB population growth (table 8.5). Model output was considered only for locations where

10142 pines currently grow. Model projections are presented in figures 8.8 and 8.9, and tables 8.4 and 8.5, and
10143 are summarized below. See Bentz et al. (2016) for spatial displays (for the CanEMS2 GCM).

10144 • The proportion of areas with thermal requirements for MPB bivoltinism has historically been low
10145 in the Northern Rockies (figs. 8.8, 8.9).

10146 • Stands at elevations less than 3,300 ft currently have relatively few pines and low hazard to MPB,
10147 and population growth of univoltine populations was historically very low. This is most likely because it
10148 was too warm, and adult emergence synchrony was disrupted. Growth rate is projected to decrease further
10149 in current (2000-2009) and future climates relative to historic periods (fig. 8.8). However, the proportion
10150 of simulation points at less than 3300 ft with thermal regimes that allow for bivoltinism is projected to
10151 increase through 2100, particularly when the RCP 8.5 scenario temperature projections are used (fig. 8.8).
10152 The availability of pines at less than 3,300 ft in future climates may be restricted.

10153 • Pine stands at 3,300-6,600 ft were also projected to have lower univoltine population growth rates
10154 in current and future climates than historically, and some small proportion of stands will have increasing
10155 probability of bivoltinism (fig. 8.8).

10156 • The highest density of pine currently occurs at 6,600-10,000 ft, the elevation range also
10157 associated with a majority of stands with high hazard (56 percent) (table 8.5). These stands are predicted
10158 to have higher univoltine population growth rates than historic, through 2030-2050. Thermal regimes for
10159 bivoltinism are unlikely at this elevation (fig. 8.8).

10160 • Population growth rates were historically very low in stands above 10,000 ft until 2000-2009;
10161 rates are projected to increase through 2100 (fig. 8.8). These stands are too cool for bivoltinism
10162 historically and in future climates.

10163 • Pine forests under 6,600 ft currently have low stand hazard for MPB and low univoltine growth
10164 potential in the near future (2015-2025), although bivoltine potential is moderate. Pine forests above
10165 6,600 ft have high current stand hazard for MPB and high univoltine growth potential between 2015 and

2025, although bivoltine potential is zero. Our results suggest that pine stands above 6,600 ft, particularly between 6,600 and 10,000 ft, have the highest risk to MPB-caused tree mortality in the near future.

- The Grassland subregion contains a small amount of “Great Plains ponderosa pine,” and historically temperatures were too warm for univoltine MPB population success (fig. 8.9). A high proportion of locations in these areas is projected to become thermally suitable for bivoltinism (fig. 8.9), although pine occurrence in future climates may be limited.

- In the Western, Central, and Eastern Rockies subregions, univoltine population growth is projected to decrease beginning in the 2000-2009 period, although a small proportion of locations at the lowest elevations will become thermally suitable for bivoltinism by 2080-2100.

- In the Greater Yellowstone Area subregion, univoltine population growth remains relatively high until the 2080-2100 time period (fig. 8.9) with a small proportion of locations at the lowest elevations with the potential to become bivoltine at that time (fig. 8.9).

Interactions with Other Disturbance Processes

Bark beetle-caused tree mortality is influenced by and can influence fire, although the relationships are complex and dynamic (Hicke et al. 2012; Jenkins et al. 2014). In fact, any disturbance that influences the distribution and vigor of host trees will influence bark beetle outbreaks. Moreover, the pattern of bark beetle-killed trees across a landscape will have cascading effects on a myriad of abiotic and biotic processes such as fire, wildlife habitat, and vegetation succession and dynamics (Saab et al. 2014). During non-outbreak years, many bark beetle species survive in trees infected with root diseases. The amount of root disease in trees stressed by climate change may increase, which in turn can result in higher populations of

bark beetles causing increased tree mortality (see root disease section).

Unknowns and Uncertainties

It is important to acknowledge uncertainties with projections of future climate, in addition to uncertainties in models that describe relationships among climate, bark beetle populations, and their host trees. Mechanistic-based phenology models are good tools for projecting beetle population response in a

changing climate (Bentz and Jönsson 2015). This type of model incorporates the important role of seasonality and allows for emergent population processes when driven by climate change projections. However, data are lacking on temperature-dependent relationships of most bark beetle species in the Northern Rockies, hindering development of conceptual and empirical models. Moreover, one of the greatest uncertainties is a lack of understanding of potential adaptations in bark beetle developmental traits to a rapidly changing climate. With few exceptions (Addison et al. 2013, 2014), little is also known about climatic effects on the wide array of bark beetle community associates including fungi, bacteria, parasites, and predators.

Host trees will also respond to climate change, and responses will have cascading effects on bark beetle populations. Further investigation, especially in water-limited systems, is needed to increase quantitative understanding of how climate-induced changes in trees influence bark beetle population success at different spatial scales. Due to this absence of understanding, predictive models that incorporate the integrated effects of climate and bark beetle disturbances on vegetation pathways are lacking, hindering our capacity for making projections for future forests (Anderegg et al. 2015).

WHITE PINE BLISTER RUST

Overview

White pine blister rust (*Cronartium ribicola*, hereafter referred to as WPBR) is a nonnative fungus that was inadvertently introduced to western North America from Europe around 1910 (Bingham 1983; Tomback and Achuff 2011). The WPBR fungus infects only five-needle pine species, and all nine North American white pine species are susceptible; three white pines are found in the Northern Region: western white pine (*Pinus monticola*), whitebark pine (*Pinus albicaulis*), and limber pine (*Pinus flexilis*). WPBR has been found across most of the ranges of these three pines in the Northern Region, and it has caused over 90 percent mortality in western white pine. Whitebark and limber pine WPBR are variable, but highest in the warmer, moister parts of their ranges (Tomback and Achuff 2010).

The life cycle of WBPR requires two hosts, with two spore-producing stages on white pine and three separate spore producing stages on three potential alternate hosts: *Ribes*, *Pedicularis*, and *Castilleja*. Pine

infection begins when basidiospores produced on *Ribes* leaves in late summer are wind dispersed to nearby pines. The basidiospores germinate on pine needles and fungal hyphae grow through the stomata into the cell tissues, needles, and stem (Patton and Johnson 1970).

Cankers form on white pine branches and main stems as the phloem is first invaded by hyphae and then becomes disrupted by blister-like structures that are filled with powdery yellow aeciospores (Hudgins et al. 2005). As tree branches and stems are girdled, branches and tops die back to the canker. Continued downward growth of the persistent cankers and poor competitive ability then kill infected trees. Depending on where the canker occurs, cone production often decreases or is prevented well before tree death.

The released aeciospores infect *Ribes* and the other alternate host species (Schwandt et al. 2013). This can occur at long distances from infected pines, as aeciospores are hardy and can disperse as much as 60 miles (Frank et al. 2008). At most locations and for most alternate hosts, infected leaves produce urediniospores that spread only short distances from leaf to leaf or plant to plant (Newcomb 2003). These recurrent infections keep rust alive through the growing season until conditions are suitable for pine infection. For most alternate hosts, leaf infections produce hair-like structures (teliospores) that produce basidiospores in fall or when night temperatures are cool while other hosts with less vigorous leaf infections may produce teliospores directly. Locations where synergistic pairs of alternate hosts occur—one that readily spreads urediniospores, and one that produces pine-infecting basidiospores, are especially favorable for pine infection (Zambino 2010).

Basidiospores have a narrow weather window for production, dispersal, and successful infection of pine needles: they infect best in periods of high humidities (greater than 98 percent) with moderate temperatures (between 60 and 68 °F) (Bega 1960). Conditions for infection are determined by temperature, with a 48-hour optimum for infection at 64 °F, though up to 5 days may be required at 39 °F (McDonald et al. 1981). Temperatures exceeding 77 °F are lethal for teliospores. Basidiospores are short-lived and most often cause infections within a few feet of *Ribes* plants, but they can be carried long distances or upslope on moist air masses, lofted in thermals over bodies of water, or carried down slope

on cold air currents to infect trees at the interfaces with temperature inversions (Hunt 1983, Van Arsdell et al. 2005, Zambino 2010).

The time required for WPBR to kill its host varies by species, distance of infection from bole (Schwandt 2013), and bole circumference. Typically WPBR kills western white pine in 5-10 years, and whitebark pines (*P. albicaulis*.) after 20 years (Hoff and Hagle 1990). WPBR-caused tree mortality greatly affects stand structure and species composition, but the most serious impact of WPBR is the long-term impact on white pine regeneration capacity, with direct mortality of rust-susceptible seedlings and saplings and the loss of cone and seed production following branch dieback and top kill. Native pine populations show some heritable resistance to WPBR but the frequency of resistance is low and variable (Zambino and McDonald 2004). Studies in the 1970s of natural stands that originated in the late 1920s estimated that fewer than 1 in 10,000 trees lacked cankers (were rust resistant) (Hoff et al. 1980). However, resistance may have increased in the 35 years since this report as a result of additional rounds of regeneration under natural selection (Klopfenstein et al. 2009; McDonald et al. 2004, 2005; Zambino and McDonald 2005).

Effects of Climate Change on White Pine Blister Rust

Climate changes may cause WPBR infections to occur earlier and with greater incidence in pine stands (table 8.6). Specific weather conditions required for basidiospore germination and infection of pine needles may occur more frequently and for longer periods in the future (Koteen 1999). “Wave” years—hot and humid weather conditions throughout most of the growing season that facilitate infections on pine and alternate hosts, followed by moist but cooler weather events for teliospore and basidiospore production and pine infection—are projected to increase in the future for whitebark pine (Keane et al. [in press]), although Sturrock et al. (2011) speculate that wave years will actually decrease for most temperate pine forests (western white and limber pine) because of hotter, drier projected climates. Helfer (2014) also believes that warmer temperatures could negatively impact rusts and that higher concentrations of atmospheric carbon dioxide (CO₂) could cause declines in rust populations. He also

mentions that the highly variable and extreme weather projected in the future will aid in WPBR spore dispersal, resulting in expansion of its range and higher spore loads on existing pines.

The highly variable and novel climate conditions projected in the future may serve to accelerate mutations of WPBR to create populations that may overcome the native rust resistance in five-needle pines (Simberloff 2000). Alternatively, changing climates may lead to suitable climates for WPBR variants that are in locations other than North America. Since most rust infection and mortality occur regardless of tree condition and vigor, it is doubtful that any direct responses of the tree or the *Ribes* hosts to future climates, such as increased growth, will enhance or degrade the ability of the host to ward off infections. However, climate-mediated changes in host regeneration dynamics could restrict or expand host ranges (Helfer 2014). As a result, this could alter WPBR range. Some predict higher leaf biomass for the two host species with warmer, enriched CO₂ environments, and more leaves could provide additional germination surfaces and a higher chance for rust infection on both hosts.

Distribution and frequency of synergistic alternate host species combinations (Zambino 2010) could also change. Higher elevation areas may experience new climates (i.e., warming temperatures along with high precipitation) that facilitate the expansion of *Ribes* into areas that were historically too cold and snowy to support certain hosts. On the other hand, low elevation upland areas where *Ribes* are currently abundant might experience drought that causes decline of the host. Moreover, drought may cause extended and extensive stomatal closure in the pines, thus preventing hyphae entry. The shifting mosaics of the *Ribes* host populations into new higher elevation areas, driven by drought in lower elevations, may spread WPBR into areas where it has not yet occurred.

Interactions with Other Disturbance Processes

The interaction of fungal pathogens and their hosts with other disturbances may be a key factor in future WPBR infections (Ayres and Lombardero 2000). The interactive effects of wildland fire on WPBR are probably most important, but they are mostly minor and primarily indirect under future climates. The exception is the possibility that smoke may kill rust spores produced at the time of the fire (Hoffman et al. 2013).

10295 *WPBR and Wildland Fire*

10296 Fire indirectly affects WPBR by changing the size, distribution, and abundance of its hosts. Most
 10297 five-needle pines of the western United States are somewhat fire-adapted with thick bark, high canopies,
 10298 and deep roots (Ryan and Reinhardt 1988). Mixed- and high-severity fires are currently common in most
 10299 forests where WPBR is present (Arno et al. 2000; Murray 2007) and are projected to increase in size,
 10300 frequency, and intensity (Westerling et al. 2011). Increases in fires and burned areas can create favorable
 10301 conditions for pine regeneration because most five-needle pine seeds are dispersed by rodents and birds
 10302 and are thus better adapted to spread into postfire landscapes than seeds of their tree competitors (Lanner
 10303 1989, Morgan et al. 1994). *Ribes* populations may increase after fire through regeneration by seed and
 10304 sprouting from roots and rhizomes. Therefore, fire will often favor *Ribes* regeneration over other species
 10305 not adapted to fire. However, re-burns soon after an initial fire can eliminate regenerating *Ribes* before
 10306 they can develop a seed bank for the next forest regeneration cycle (Zambino 2010).

10307 Severe fires that kill rust-resistant pine trees may ensure continued high rust mortality in the future
 10308 because it dampens the rate of rust-resistant adaptations (Keane et al. 2012). However, where rust-resistant
 10309 five-needle pines survive fire they can provide the seeds for populating future landscapes that are resilient
 10310 to both rust infection and fire mortality. Fire exclusion generally increases competition stress (Heward et
 10311 al. 2013), weakening pine trees. Stress from competition does not increase rust infection (Parker et al.
 10312 2006), but may facilitate mortality in pines trees under stress after being girdled by blister rust.

10313 Trees infected with WPBR are weakened, and may be more susceptible to fire-caused damage and
 10314 mortality (Stephens and Finney 2002). Ladder fuels of trees attacked or killed by WPBR may increase
 10315 crowning owing to abundant pitch that can extend from base to rust bole cankers, and from dead red
 10316 crowns of girdled trees. As branches and tops of white pines die back they add dead foliage and wood to
 10317 the fuelbed, which may increase fire intensity and fire-caused tree mortality. In contrast, western white
 10318 pine needles gradually added to the fuel bed are more similar to normal needle shed, and are quickly
 10319 degraded in moist, productive environments. Mortality from WPBR often results in the elimination or
 10320 thinning of the shade-intolerant pine overstory, allowing shade tolerant competitors to occupy the

openings. This creates substantially different canopy fuel conditions, such as lower canopy base heights, higher canopy bulk densities, and greater canopy cover, which facilitate more frequent and intense crown fires (Keane et al. 2002, Reinhardt et al. 2010). Many shade tolerant competitors are also more susceptible to fire damage, resulting in higher postfire tree mortality in rust-infected landscapes.

WPBR and Mountain Pine Beetle

Interactions between native MPB populations and WPBR are rarely studied because they are difficult to quantify over time. In their endemic phase, MPB populations may weaken pines and facilitate infection by WPBR, but these interactions are strongly governed by climate and biophysical environment (Tomback and Achuff 2011). However, the ubiquitous presence of WPBR spores and the resistance to the disease in pine species ensures that most five-needle pines at many sites will eventually become infected and die from WPBR, regardless of MPB endemic levels (Hoff et al. 2001). More importantly, MPB influences WPBR through regulation of the tree species that are host to both disturbance agents and killing of host trees that are resistant to the rust (Campbell and Antos 2000). For example, although whitebark pine stands in the Greater Yellowstone Area show little WPBR-related mortality, levels of MPB-related mortality are high (Kendall and Keane 2001; Macfarlane et al. 2013). Many stands of healthy five-needle pines in Yellowstone have been subjected to a major MPB outbreak over the last decade as a result of high densities of large diameter trees coupled with prolonged warm, dry conditions. These outbreaks resulted in substantial mortality of rust-resistant whitebark pine trees (Logan et al. 2008).

Effects of WPBR on MPB infestations are also highly variable and subtle. Archibald et al. (2013) found less MPB activity in trees that had high WPBR damage, whereas Bockino and Tinker (2012) found that whitebark pine selected as hosts for MPB had significantly higher WPBR infection, but this varied by tree size (diameter), stand type, and disturbance pattern (Larson 2011). Kulhavy et al. (1984) found that over 90 percent of western white pine trees infected by bark beetles had either WPBR or some type of root disease, whereas Six and Adams (2007) found little evidence of interaction effects between MPB and WPBR. Simulations of MPB disturbance under current climate result in a decline in both lodgepole pine and whitebark pine, with a corresponding increase in subalpine fir (*Abies lasiocarpa*) and Douglas-fir

(*Pseudotsuga menziesii*), with little change from the addition of WPBR (fig. 8.10). These trends are enhanced under a warmer climate, in which lodgepole pine declines are greater and stands are mainly replaced by Douglas-fir, but WPBR interaction has minor effects on species composition (Keane et al. 2015).

WPBR, Fire, and Mountain Pine Beetle

Studies of interactions among fire, beetles, and rust are rare, but we posit that MPB and WPBR serve to reduce five-needle pine populations and create fuelbeds that may support wildfires that are more intense than historical counterparts, potentially resulting in high mortality of the dominant vegetation. Although fire reduces pine abundance in the short term, it appears to ensure their long-term persistence by eliminating competitors (Keane and Morgan 1994). Modeling studies have shown that decades to centuries are required to re-establish populations of rust-resistant white pines after die-off (such as would occur with MPB) and increased frequency and extent of wildfire under climate change favored white pine regeneration and persistence over shade-tolerant species in some regions, even in the presence of WPBR and of losses of some WWP from fire (Loehman et al., 2011a,b). The largest decline in whitebark pine has been found in those areas affected by both WPBR and MPB, but not fire (Campbell and Antos 2000).

Interactions among fire, MPB, and WPBR can occur only in areas that have the potential to support five-needle pines, which are rare in many landscapes. However, recent simulation efforts have found that fire frequency under current climate is 10 percent lower when all three disturbances are allowed to interact, and average tree mortality is also lower (fig. 8.10). In a warmer climate, fire frequency decreases, high severity fires increase, and interactions among disturbances create different landscapes than when each disturbance acts separately (or in the absence of disturbance) (Keane et al. 2015) (fig. 8.11).

WPBR Unknowns and Uncertainties

It is difficult to mechanistically simulate WPBR population dynamics because of the disease is governed by fine scale (e.g., microclimate, spore production and germination, tree size and health) to coarse scale (e.g., spore dispersal, wind, alternate host distributions, topographic controls) processes. Therefore, the representation of WPBR in most models will tend to be both stochastic and empirical, and

this will tend to reduce the robustness of model predictions and add to the uncertainty of future WPBR predictions.

White pine trees will also directly respond to climate change, and responses will have interacting effects on WPBR infection potential. The key to the future abundance of white pines on the Northern Rocky Mountain landscapes will hinge on the ability of the three pine species to develop rust-resistant populations that are resilient to climate change. This probably will not happen without human intervention. The rapid pace of predicted climate change coupled with the long maturation times of the three pine species may exacerbate the species decline. It is essential that natural resistance is facilitated by land management agencies to ensure that these valuable species and the forests that they create are not lost forever.

FOREST DISEASES

Overview

Forest diseases are found in all forest ecosystems of the Northern Rockies. They are one of three major disturbance groups that affect ecosystem development and change, but the overall impacts of forest diseases on various resources are difficult to quantify. This is partly due to our inability to separate predisposing effects of some of the most important diseases, which act over a long term, from mortality caused by short-term factors such as insect outbreaks and drought. The effects of forest diseases tend to be more cryptic and chronic in effects, so estimating their occurrence and abundance is difficult. Here we rely mostly on older studies and observations to quantify disease effects in what were formerly called “commercial timberlands.” Spatial distributions of most forest diseases have not changed much, although the effects of individual diseases may change due to effects of climate on disease organisms, hosts, and environmental predisposition.

We focus on the major groups of forest diseases in the Northern Rockies known to have significant effects on ecosystems and ecosystem services, and for which at least some information is available on effects of climate.

Dwarf Mistletoe

Dwarf mistletoes (*Arceuthobium* spp.) are a group of parasitic seed plants that are widespread across the Northern Rockies and mainly cause reduced tree growth and productivity, but in some cases also cause tree mortality. Five species of dwarf mistletoe are found in the Northern Rockies, mostly on these primary hosts: *A. americanum* on lodgepole pine, *A. campylopodum* on ponderosa pine, *A. cyanocarpum* on limber pine (*Pinus flexilis*), *A. douglasii* on Douglas-fir, and *A. laricis* on western larch (*Larix occidentalis*). Mistletoes may occasionally infect trees of other species when they are growing interspersed with infected primary hosts.

Approximately 28 percent of lodgepole pine forest is infested by *A. americanum*. *A. cyanocarpum* occurs primarily east of the Continental Divide, although the area affected has not been estimated. Douglas-fir is infested in over 13 percent of its range by *A. douglasii*. About 38 percent of the western larch type is infested by *A. laricis*. The distribution of *A. campylopodum* is limited to a portion of Idaho where it occurs on ponderosa pine. Drummond (1982) estimated that 2.1 million acres of national forest lands were infested by the three most important species of dwarf mistletoe in the Northern Rockies. An estimated 31 million cubic feet of wood are destroyed by these pathogens each year.

Root Disease

Caused by various species of fungi, root disease is a major cause of tree growth loss and mortality in the Northern Rockies. These diseases are primarily a problem west of the Continental Divide, but also affect local areas east of the Divide. The two most significant native pathogens in the Northern Rockies region are Armillaria and annosus root diseases. These and other root diseases co-occur in many mesic to moist forests west of the Divide. Armillaria kills conifers of all species when they are young, but is especially damaging to Douglas-fir, subalpine fir, and grand fir (*Abies grandis*) because these species remain susceptible throughout their lives (Kile et al. 1991). In addition, root diseases often affect canopy closure and create small gaps. The effects of these root pathogens are persistent on a site and affect multiple generations of trees. Armillaria and other root diseases influence forest species composition, structure, and successional trajectories by accelerating a transition to species that are more tolerant of root

disease or by maintaining stands of more susceptible species in early seral stages (Byler and Hagle 2000).

They can also affect ecosystem services by affecting visual and recreational resources.

At least 3.3 million acres in the Northern Rockies have moderate to severe root disease, with up to 60 percent caused by *Armillaria ostoyae* (Smith 1984; USDA FS 2007). A recent evaluation of Forest Inventory and Analysis data in the Forest Service, U.S. Department of Agriculture Northern Region identified 2.3 million acres of national forest lands with moderate to severe root disease (Lockman et al. in preparation). Shrub fields have replaced forest cover on three percent of forest lands in Idaho and Montana as a result of severe root disease. A study of Ecosection M333d (Bailey 1983) that includes the southern Idaho Panhandle National Forest and southern Kootenai National Forest found evidence of root disease on 94 percent of the area (Byler and Hagle 2000). Root disease has reduced forest canopy cover in affected stands in northern Idaho and western Montana by an average of 20-30 percent.

The National Insect and Disease Forest Risk Assessment (Krist et al. 2014) identified locations where significant tree mortality and basal area losses from insects and diseases could occur between 2013 and 2027, modeling the potential for damage in standing live basal area across all ownerships from a variety of insects and pathogens. Root disease had the highest basal area loss as a percent of total basal area, with projected losses ranging from 0 to 20 percent in most national forests.

Needle Disease

Needle diseases have historically been of limited significance in the Northern Rockies; severe infection years occur only occasionally, and effects are mostly limited to crown thinning and loss of lower branches with some mortality of young trees. Needle casts usually cause loss of needles in the year following a season that has been favorable for infection. In western larch, needle cast and needle blight are observed in the year of infection.

Needle casts and needle blights in lodgepole pine, ponderosa pine, western white pine, Douglas-fir, grand fir, and western larch generally cause little damage in the Northern Rockies, although periodic outbreaks can cause severe damage in local areas (Lockman and Hartless 2008). These diseases are

10449 favored by long, mild, damp springs. Their occurrence at epidemic levels depends on favorable weather
10450 conditions and presence of an adequate host population.

10451 *Abiotic Disease*

10452 Most abiotic diseases result from the effects of adverse environmental factors on tree physiology or
10453 structure. This group of diseases can affect trees directly or interact with biotic agents, including
10454 pathogens and insects. A number of abiotic and environmental factors can affect foliage, individual
10455 branches, or entire trees, tree physiology and overall tree vigor. The most significant abiotic damage is
10456 tree mortality.

10457 Forests in the Northern Rockies periodically experience damage from weather extremes, such as
10458 temperature and drought. Factors such as air pollutants and nutrient extremes occur infrequently or
10459 locally. Conifers on the east side of the Continental Divide, primarily Douglas-fir and lodgepole pine,
10460 often experience injury known as red belt, caused by strong, dry, warm Chinook winds in winter that
10461 induce twig and needle necrosis and desiccation (Bella and Navratil 1987). Drought injury, an abiotic
10462 factor that can cause disease through loss of foliage and tree mortality, can initiate a decline syndrome by
10463 predisposing trees with stressed crowns and roots and low energy reserves to infection by less aggressive
10464 biotic agents, such as canker fungi and secondary beetles. A well-studied decline of western white pine
10465 called pole blight occurred in the Northern Rockies in the 1930s and 1940s (Leaphart and Stage 1971).
10466 This disease occurred on pole-sized trees, often in plantations that were growing on shallow soils with
10467 low moisture storage capacity that were exposed to extended drought.

10468 *Canker Disease*

10469 Canker diseases affect tree branches and boles, typically in trees that are poorly-adapted to the sites in
10470 which they are growing. Damage is caused by breakage at the site of the cankers, or by mortality of
10471 branches and boles beyond girdling cankers. Although canker fungi are most active on trees under stress,
10472 lack of specific data on climate effects makes it difficult to infer the effects of climate change.

10473 **Broad-Scale Climate Drivers of Forest Diseases**

Climatic variability and change can alter patterns of pathogen distribution and abundance through (1) direct effects on development and survival of a pathogen, (2) physiological changes in tree defenses, and (3) indirect effects on abundance of natural enemies, mutualists and competitors (Ayres and Lombardero 2000). Sturrock et al. (2011) suggest that climate change will affect pathogens, hosts, and their interaction; changes in these interactions may become the most substantial drivers of future disease outbreaks.

Fungi cause most forest diseases in the Northern Rockies. Fungus life cycles are significantly influenced by climate-related factors such as timing and duration of precipitation, humidity, and temperature for spore germination, fungus growth, and inactivation. Fungus life cycles are short compared to their hosts, so fungi can respond more rapidly to a changing climate than their hosts, with potentially serious consequences (Boland et al. 2004). Dwarf mistletoe reproduction and infection are also affected by temperature and moisture (Hawksworth and Wiens 1996), and dwarf mistletoes are generally most prevalent in sites that have experienced past disturbances.

Overall health of host trees has a major role in determining if a pathogen successfully infects a tree or kills it. Many forest diseases, such as canker diseases, are caused by “facultative pathogens” that attack weakened hosts under specific environmental conditions. Impacts of climate change on host physiology may modify host resistance and alter stages and rates of development of pathogens (Coakley et al. 1999). Drought, or limited soil moisture availability, is a major driver that affects the incidence and severity of facultative pathogens. Soil moisture deficit, flooding, and water table fluctuation can all predispose trees to pathogens. Even if there are areas that may have a net gain in precipitation, projected longer growing seasons could cause recurring water deficit stress. Some diseases may be considered threshold diseases, that is, they are damaging but only under certain climatic conditions (Hepting 1963). These diseases may become more damaging if thresholds that trigger infections are reached more frequently, such as in recurring drought.

Effects of Climate Change on Forest Diseases

One of the difficulties of predicting sensitivity to a changing climate is that the scales available for GCMs, pathogen/disease models, and microsite environments do not always match (Seem 2004). For example, some GCM projections provide only mean monthly and annual estimates, rather than daily data useful for modeling forest diseases. In addition, pathogen ecology and effects are sensitive to local site and environmental conditions that may not be well represented by GCMs. There is also considerable uncertainty and lack of knowledge of impacts of a changing climate on future forest conditions and interactions with pathogens (Woods et al. 2005, 2010). Compared to trees, for which available soil moisture is critical, pathogens are more affected by precipitation events, especially timing, duration and pattern, all of which are poorly projected by climate models. Facultative pathogens respond to weakened or less vigorous hosts, and their importance could increase if climatic conditions less favorable to tree growth become more frequent.

A changing climate will affect forest disease occurrence and severity, through effects on the pathogen, the host, or their interaction (Sturrock et al. 2011) (table 8.7). Interactions between pathogens and abiotic stressors (e.g., temperature and moisture) may represent the most substantial drivers of increased disease outbreaks (Sturrock 2012). Epidemics also depend on relatively constrained conditions for spread and infection to occur. For example, increased drought could affect host susceptibility to pathogens and predispose hosts to disease outbreaks (Coakley et al. 1999). Although models usually generate mean climatic conditions, it is often the extremes that have the greatest influence on pest conditions (Hepting 1963). Increased host stress could result in increased disease occurrence and interactions among multiple agents (Coakley et al. 1999). There is likely to be an increase in declines and dieback syndromes (Manion 1991) caused by changes in disease patterns involving a variety of diseases.

Indirect effects may be on competitors, antagonists, and mutualists that interact with plant pathogens (Kliejunas et al. 2009). Some of the most profound effects of temperature and moisture changes could be on soil microflora, and on and in roots and shoots where a complex of organisms live in relationships at the transition between pathogenesis, symbiosis, and saprogenesis. The balance among organisms could be upset, for example, turning a normal mycorrhizal association to pathogenesis, shifting pathogens from

saprogenic to pathogenic phases, or shifting the order of ascendancy of competing organisms due to their different temperature or moisture optima, even permitting a pathogen to take dominance from a saprophyte (Hepting 1963). Given that root pathogens of trees can often exploit a large food reserve in a tree once a defense is breached and then use those reserves to bolster attacks on nearby trees, even small changes in the frequency of shifts in relationships among fungal communities could have large effects.

Although considerable knowledge exists on climatic conditions required by specific forest pathogens, little has been done to determine how changing climates may affect these pathogens (Kliejunas et al. 2009). Recent modeling work by Klopfenstein et al. (2009) used a subset of GCMs to project how the geographic distribution of the climate envelope for *Armillaria solidipes* and Douglas-fir could change in the interior northwestern United States. Their analysis suggests that Douglas-fir will have a considerably smaller geographic space that matches its current climate envelope and that this space will shift, while *A. solidipes* will experience only minor changes. They suggest that areas where Douglas-fir is maladapted could increase, which could increase its susceptibility to *Armillaria* root disease.

The methodology used by Klopfenstein et al. (2009) for estimating the potential effects of climate on *A. solidipes* used climatic variable information from the current distribution of the pathogen on its Douglas-fir host based on current pathogen occurrence in a network of plots. Climate space for *A. solidipes* modeled for current and 2060 climate are shown in figure 8.12. These preliminary projections are not necessarily the current or future distribution of *A. solidipes*, but identify only the modeled climate space matching where the pathogen currently occurs. It is unknown how the climate envelope could change, because of changes in distribution of competitor fungi and hosts.

Spring precipitation is projected to increase in most of the mountainous area of the Northern Rockies (see chapter 3). This may increase frequency and severity of years when needle diseases cause significant needle loss in conifer species. This could affect the energy balance of susceptible trees, with potential effects on yield and vigor, particularly for species that normally carry multiple years of needles and cannot re-flush later in the season in response to defoliation.

There may be elevation and location maladaptation in resistance to the increased needle disease pressure resulting from climate change, as areas of tree host ranges and disease occurrences shift in location. *Lophodermella* needle cast in lodgepole pine (caused by *Lophodermella concolor*) occurred in northern Idaho in the early 1980s (Hoff 1985), and has also had outbreaks at high elevation in some Idaho locations in recent years. Lodgepole pine at high elevation normally has only infrequent outbreaks because bud break occurs near or after the time when spring rains that favor infection have ended, whereas needles in lower elevation trees expand when spores are present and able to infect. A provenance study under natural conditions during the outbreak in the 1980s showed that low-elevation populations were generally more resistant and had heritable resistance, but high-elevation populations were susceptible. About six percent of trees in this mixed provenance planting showed no infection, but 5 percent had almost complete defoliation. If moist conditions following bud break continue to occur at high elevation where natural selection for resistance has not occurred, recurrent needle disease outbreaks could stress trees and make lodgepole pine more susceptible to other factors (Hoff 1985).

Another example of a needle disease that may increase in the Region under climate change is Swiss needle cast (caused by *Phaeocryptopus gaeumannii*). This disease severely limits productivity of Douglas-fir west of the Cascade divide in Oregon and Washington, causing growth losses of up to 50 percent (Manter et al. 2005). Needle loss is very highly correlated with increasing winter temperatures and spring needle wetness. The disease, which is expected to become more severe in forests west of the Cascade crest in a warmer climate (Stone et al. 2008), has periods of local occurrence in northern Idaho (Navratil and Bella 1988) and Montana (Weir 1917). Milder winters and wetter springs that could increase the future distributions and severity of the disease might occur, but as yet, investigations and modeling have not been conducted to map and quantify potential effects.

Kliejunas (2011) performed a qualitative risk assessment of the effect of projected climate change on a number of forest diseases, several of which occur in the Northern Rockies. *Dothistroma* needle blight, (caused by *Dothistroma septosporum*), provides a good example of potential effects of climate change. Kliejunas (2011) estimates that the risk potential is low if a warmer and drier climate occurs. A warmer

and wetter climate could increase the risk potential to moderate. His assessment of the effect of climate change on dwarf mistletoes indicated a high risk potential regardless of precipitation levels because dwarf mistletoe survival and infection increases with temperature. His assessment of Armillaria root disease indicated a high to very high risk potential depending on moisture availability, with drier conditions increasing the potential.

Forest Pathogen Interactions

Direct effects of fire on pathogens are generally minimal. Fire directly and indirectly influences distribution, severity, and persistence of forest diseases; similarly, forest diseases influence fire behavior and severity. Since diseases are generally host specific, removal of susceptible tree species by fire will usually reduce disease, whereas improving habitat for susceptible tree species will usually increase disease over time.

Forest pathogens are directly damaged by smoke and heat of fires. Smoke can inhibit dwarf mistletoe seed germination (Zimmerman and Laven 1987), and heat from fire can kill pathogens that cause root disease in the top 3 inches of soil (Filip and Yang-Erve 1997). Forest diseases are affected more by tree mortality from fire. Frequency and intensity of fire can affect persistence, as well as distribution and severity of certain diseases. High intensity fires can completely remove a pathogen with its host, as with lodgepole pine-dwarf mistletoe (Kipfmüller and Baker 1998; Zimmerman et al. 1990), or remove species susceptible to root disease and prepare the site for regeneration of less susceptible seral species, such as pines and western larch (Hagle et al. 2000). Low intensity fires often leave mosaics of pathogens along with their susceptible hosts, which can cause substantial increases of diseases such as dwarf mistletoe (Kipfmüller and Baker 1998). However, low intensity fires in some habitats maintain species tolerant of root disease such as western larch (Hagle et al. 2000).

Human-caused fire exclusion has led to an increase of root disease and dwarf mistletoe (Hagle et al. 2000; Rippey et al. 2005), which can influence fire behavior and severity. Root disease creates pockets of mortality and scattered mortality, resulting in standing and downed woody debris that increases fuel loading, especially large fuels (Fields 2003). Increased litter accumulation and resinous witches' brooms

from dwarf mistletoe infections can provide ladder fuels that may cause a ground fire to move into the canopy (Geils et al. 2002).

Climate effects that increase frequency or intensity of fires may affect incidence and severity of dwarf mistletoes (Zimmerman and Laven 1985). Fire affects dwarf mistletoes by changing canopy structure and stand density (Alexander and Hawksworth 1975; Dowding 1929), eliminating lower branches that may have the heaviest infections and mistletoe seed production, thinning stem density which may reduce lateral spread, and causing mistletoe shoots to abscise. Loss of shoots eliminates some infections directly, but even if infections remain within the bark, loss of shoots prevents seed production for several years, slowing mistletoe intensification within stands. Trees heavily infested with mistletoe often retain low infected branches and are prone to torching in fire, which could increase the risk of crown fire (Conklin and Geils 2008). Alternatively, torching in individual trees could eliminate the most heavily infected sources of mistletoe seed that infect understory regeneration.

An increase in severe weather events or fires could increase occurrence of other diseases. For example, root and bole wounds could be used as “infection courts” for root disease, and such wounds from management, windfalls, and fire are major avenues of infection for true fir and western hemlock (Smith 1989) and lodgepole pine (Littke and Gara 1986). Fire damage and other stresses can release root disease infections that have been walled off by host resistance responses (Hagle and Filip 2010). Relative importance of different root diseases could be altered under some climate change scenarios. Except as a sapling, western larch is considered resistant to *Armillaria* root disease due to its ability to generate multiple corky barriers at infection sites (Robinson and Morrison 2001). This species response to wounds and the thick bark that it generates also make it among the most resistant to fire damage, and a species more likely to persist and regenerate under increased fire frequency.

Illustrating interactions between bark beetles and disease, a study in lodgepole pine forests of central Oregon showed that altered stand structure following an MPB epidemic increases dwarf mistletoe in lodgepole pine stands, thereby reducing stand growth and productivity and slowing stand recovery (Agne et al. 2014). The influence of dwarf mistletoe on stand structure heterogeneity could increase landscape

resistance and resilience to disturbances. Another example of complex interrelationships is the interaction between stem decay, bark beetles and fire frequency in central Oregon lodgepole pine. After fire damaged the roots of lodgepole pines, stem decay fungi infected these damaged roots and over time caused extensive heartwood decay in the boles of these trees. Data show these decay-infected trees grew at a slower rate than uninfected trees and trees with stem decay were preferentially attacked by mountain pine beetles years later (Littke and Gara 1986).

NONNATIVE PLANTS

Overview

Projecting how nonnative plants and climate change may interact to alter native plant communities, ecosystems, and the services they provide is challenging because of our limited ability to project how climate change will alter specific local abiotic conditions that define the fundamental niches of plants (Gurevitch et al. 2011; Thuiller et al. 2008). We start with knowledge of structure and function of current ecosystems, and then apply first principles of ecology to explore how climate change might alter these systems, their susceptibility to invasion, and invasiveness of introduced plants from a general perspective. We do not project changes in individual plant species, but define the parameters that bound potential community change based on climate projections and discuss how community invasibility might be affected across that range of potential conditions.

Effects of Climate Change on Nonnative Species

Hundreds of nonnative species have been introduced into the Northern Rockies (<http://invader.dbs.umt.edu>). Not all of these species are abundant, but recent surveys showed that nonnative plants comprise an average of 40 percent of species present (richness), and 25 percent of those nonnatives have significant effects on native grassland flora (Ortega and Pearson 2005; Pearson et al. in review). Invasive plant species represent a threat to ecosystem integrity, because they compete with native species in many plant communities and can alter ecological processes. These negative impacts can reduce biological diversity, forage for wildlife, and recreation opportunities. Most nonnative invasives are

herbaceous species (graminoids and forbs), but some are shrub and tree species that commonly occur in riparian areas (e.g., Russian olive [*Elaeagnus angustifolia*], tamarisk [*Tamarix ramosissima*]).

Although extensive work has been done to understand the biology of some of the most common nonnatives, such information is far from complete, and few studies have explored how changes in temperature and moisture related to climate change may affect nonnative plant populations in the Northern Rockies.

It has historically been assumed that climate change will favor nonnative plants over natives (Dukes and Mooney 1999; Thuiller et al. 2008; Vila et al. 2007; Walther et al. 2009), but this may be an overgeneralization (Bradley et al. 2009, 2010; Ortega et al. 2012). Numerous attributes associated with successful invaders suggest nonnatives could flourish under certain climate change scenarios. For example, many nonnatives are fast growing early seral species (ruderals) that tend to respond favorably to increased resource availability, including temperature, water, sunlight, and CO₂ (Milchunas and Lauenroth 1995; Smith et al. 2000; Walther et al. 2009). As a result, extensive work shows that nonnatives respond favorably to disturbance (Zouhar et al. 2008) which can increase resource availability (Davis et al. 2000). Nonnatives may also exploit the disturbances associated with postfire conditions better than many natives (Zouhar et al. 2008), despite native plant adaptations to fire. In bunchgrass communities, many nonnative plants recruit more strongly than do natives when native vegetation is disturbed, even under equal propagule availability (Maron et al. 2012). Successful invaders also commonly have strong dispersal strategies and shorter generation times, both of which can allow them to migrate more quickly than slow growing and slowly dispersed species (Clements and Ditommaso 2011). Greater plasticity of successful invaders could also favor their survival in place and ability to expand their populations (Clements and Ditommaso 2011). Collectively, these attributes suggest that many nonnatives would benefit if climate change results in increased disturbance.

Few studies have manipulated CO₂, moisture, or temperature to quantify the effects of climate change on nonnative versus native plants in the northern Rockies. Of the work that does exist, most has targeted grassland and sagebrush communities, presumably because these are among the most susceptible to

invasion (Forcella 1992, chapter 7). Experimentally increasing temperatures in a Colorado meadow system resulted in increases in native upland shrubs with big sagebrush (*Artemisia tridentata*) increasing in drier conditions and shrubby cinquefoil (*Dasiphora fruticosa*) in wetter conditions (Harte and Shaw 1995). These different responses indicate the importance of background moisture in driving species-specific responses to elevated temperatures.

Recent experimental work in western Montana showed that reduced precipitation can significantly impact spotted knapweed (*Centaurea melitensis*), whereas native bluebunch wheatgrass (*Pseudoroegneria spicata*) populations were unaffected by the same drought stress (Ortega et al. 2012; Pearson et al. unpublished data). This result is consistent with historic observations of spotted knapweed declines following drought conditions (Pearson and Fletcher 2008). In Wyoming sagebrush-steppe systems, bluebunch wheatgrass outperformed both cheatgrass and medusahead (*Taeniatherum caput-medusae*) in dry years, but the opposite was true in wet years (Mangla et al. 2011). Community-level studies in other grasslands have shown that drought periods can shift vegetation away from annual grasses and forbs and toward drought-tolerant native perennial grasses (Tilman 1992). Hence, heating and drying could favor drought-tolerant natives in dry grassland and sagebrush systems and reduce their susceptibility to nonnatives (see chapter 7). However, these same conditions might increase susceptibility of native vegetation to invasive species in wetter locations.

Xeric Grasslands and Shrublands

Of the many dominant cover types that occur in the Northern Rockies, the most vulnerable to weed invasion are typically those on warm, dry (xeric) sites, although riparian and wetland sites can be invaded by several invasive plant species. The most susceptible plant communities tend to have low vegetation cover, high bare ground, and unproductive soils; various nonnative plant species exploit these more open sites. However, disturbances resulting from fire or vegetation management can provide opportunities for invasion in most kinds of dominant vegetation. Hundreds of nonnative plant species occur in the Northern Rockies, the most serious of which are described in table 8.8.

Xeric grasslands and shrublands are highly vulnerable to establishment of nonnative species (see chapter 7). Many of the native plants in Northern Rockies grasslands are perennials that tolerate environmental variability over long time scales versus the life history strategies of weedy invasive species (Grime 1977; MacArthur 1967). Whether natives or nonnatives benefit, or more specifically, which natives or nonnatives benefit, will likely depend on the specific ways in which climate change plays out.

If temperature increases but precipitation does not, this will likely reduce resource availability and increase stress, potentially favoring native species. Projections of the effects of climate change needs to consider how nonnative plants respond, as well as how recipient communities and their invasibility may change. Many successful nonnatives flower later and have different phenologies than natives, allowing nonnatives to potentially exploit an empty niche (Pearson et al. 2012). Therefore, nonnatives may increase if this niche expands with climate change, or decline if the niche is disrupted.

Invasive species primarily spread into disturbed areas with sufficient bare ground and sunlight for germination and establishment, although some species such as spotted knapweed, houndstongue (*Cynoglossum officinale*), yellow sweet clover (*Melilotus officinalis*), and yellow toadflax (*Linaria vulgaris*) can readily establish in undisturbed plant communities. Non-forested vegetation (e.g., shrublands, grasslands) has been invaded in many areas of the Northern Rockies and Northern Great Plains (see chapter 7). As fires and other disturbances increase in intensity and frequency, invasive species can occupy and potentially dominate native plant communities that were previously resistant to invasion, although numerous factors such as fire resistance of native species, propagule availability, and variation in burn severity can affect establishment (Zouhar et al. 2008). Native and domestic livestock grazing and browsing of native species can reduce plant vigor and open up sites for establishment of invasive species. Silvicultural prescriptions that decrease canopy cover also increase the likelihood that invasive species may establish and increase in both cover and density, although subsequent succession may suppress those species as canopy closure returns.

Climate change is likely to result in a range of responses among invasive species, due to differences in their ecological amplitude and life history strategies (table 8.9). Bioclimatic envelope modeling

indicates that climate change could result in both range expansion and contraction for five widespread and dominant invasive plants in the western U.S. Yellow starthistle (*Centaurea solstitialis*) and tamarisk are likely to expand, whereas leafy spurge (*Euphorbia esula*) is likely to contract, and cheatgrass and spotted knapweed are likely to shift in range, leading to both expansion and contraction (Bradley 2009; Bradley et al. 2009). Invasive species are generally inherently adaptable and capable of relatively rapid genetic change, which can enhance their ability to invade new areas in response to ecosystem modifications (Clements and Ditomaso 2011), including short-term disturbance (fire) or long-term stressors (e.g., prolonged drought, increased temperatures, chronic improper overgrazing). Increased concentrations of CO₂ in the atmosphere have been shown to increase the growth of weed species, which could have an influence on their invasiveness (Ziska 2003).

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Chapter 9: Climate Change and Wildlife in the Northern Rocky Mountains

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HOW CLIMATE AFFECTS WILDLIFE

Temperature and moisture affect organisms through their operational environment and the thin boundary layer immediately above their tissues, and these effects are measured at short time scales (fig. 9.1). When a human (a mammal) wearing a dark insulative layer walks outdoors on a cold but sunny day, s/he feels warm because the sun energy is interacting with the dark clothing, creating a warm boundary layer to which his/her body reacts. Conditions beyond that thin boundary layer are physiologically irrelevant. Walk into the shade, and suddenly one is cold because the warm boundary layer has been replaced with one at the ambient temperature of the air. This example demonstrates a number of factors to consider when evaluating the degree to which a change in climate will affect an organism. Climate is defined as the long-term average of temperature, precipitation, and wind velocity. “Long term,” when applied to climate, is a relative term and can refer to periods of weeks to centuries. In the context of climate models, results are generally reported as averages across 30-year intervals, which for many animal species represents multiple generations. Our ability to infer the biological effects of projected long-term changes in temperature and precipitation relies both on our abilities to directly relate these multi-year averages to biological responses, and the trophic distance between climate-induced ecological change and its effects on specific biological relationships.

As noted above, a human’s response to change in radiant energy is fast, measured in seconds to minutes, so its relation to 30-year average temperature is obscure. Climate changes the frequency of weather events, which in turn change the frequency of nearly instantaneous shifts in boundary layer conditions around one’s body. In aggregate, these changes in frequency either lead to conditions that you can navigate or tolerate or not. This is further complicated for endotherms (warm blooded animals) which maintain a constant body temperature. Cold or excessive heat affects endotherms by requiring them to

burn more calories to maintain the required core temperature. Thus, endotherms can function in a wide variety of environmental conditions if they have enough food to supply the necessary energy. Endotherm physiology responds directly to a change in temperature, whereas effectiveness and sustainability of the physiological response is related to the quality and quantity of available food. Fish, reptiles, and amphibians are ectotherms (cold blooded), which react to the cold not by feeling cold and metabolizing energy to maintain core temperature, but by having their metabolism slow until they are torpid.

Many of the species described here occupy terrestrial habitats. Terrestrial organisms can manipulate their operational environment in a myriad of ways, choosing to stand in the sun or shade, moving uphill or down, changing aspect, or seeking cooler or warmer environments by digging into a burrow in the ground or under the snow. Endothermic animals can change the thickness of the boundary layer by modifying their hair or feathers, both seasonally and on a short-term basis, thus responding to variable thermal conditions while minimizing energy expenditures. The ability of terrestrial organisms to manipulate their operational environment contrasts with aquatic organisms that have a harder time avoiding adverse temperatures because water is an excellent conductor of heat. In addition, aquatic ectotherms have no way to avoid overheating when water temperatures rise, so it is more straightforward to evaluate the effects of climate change for fish with known warm-water limits than it is for terrestrial endotherms (see chapter 5).

Due to the flexibility of terrestrial endotherms in dealing with changes in temperature, these species are more likely to experience effects associated with changes in precipitation amounts and types, because water produces physical features that serve as habitat. In the Northern Rockies, and in other areas with cold winters, snow provides physical habitat for which a number of organisms have specific adaptations. An obvious adaptation is seasonal color change in pelage: being white in a snowy landscape enhances the likelihood of escaping detection if you are prey, and approaching prey if you are a predator. Therefore, white pelage in winter confers specific fitness advantages if pelage change is properly timed to coincide with snow cover, but is a disadvantage if mistimed (see discussion of snowshoe hare [*Lepus americanus*] below) (fig. 9.2). Specific morphological features such as oversized feet, long legs, and light bone

structures also provide benefits in snow-covered landscapes but may be disadvantageous in environments without snow.

Deep snow provides a relatively warm, stable environment at the interface between snow and soil; soils in areas characterized by deep snow generally remain above freezing throughout the winter (Edwards et al. 2007), and the subnivean environment (beneath the snow surface) is used by many organisms to den or feed. For organisms that depend on a stable subnivean environment, or who have specific phenological adaptations to snow, reduced snowpack caused by a shift in precipitation from snow to rain represents a loss of critical habitat (see discussion of American pika [*Ochotona princeps*] below). Similarly, water bodies provide physical habitats for a wide variety of animals, providing features such as safety from predation, temperature control, and sources of prey. In addition, open or flowing water can provide important microclimates. For example, pika can be found in what appear to be hot, dry environments if water flow beneath the talus produces cool microsites (Millar and Westfall 2010a).

Physical features associated with snow and water integrate across longer time periods and are therefore closely associated with projected climate. For example, depth of snowpack integrates seasonal moisture and temperature. Seeps, springs, bogs, and persistent streams dependent on continuous sources of groundwater can integrate longer climatic periods. In some areas, water features are dependent on glaciers, which integrate seasonal weather and long-term climate. Therefore, areas with these features and the species that depend on them are vulnerable to climate change, reacting at time scales reasonably consistent with the temporal projections of global climate models (GCM) and providing opportunities to project effects on habitats and species.

As noted above, terrestrial endotherms have many options for controlling both their operational environments and the physiological effects of these environments. Terrestrial plants are stationary ectotherms, and lacking the behavioral and physiological plasticity of endothermic animals, are more directly affected by climate changes (see chapter 6). Therefore, climate effects on wildlife will frequently occur due to changes in plant assemblages that comprise wildlife habitat (fig. 9.1). For predators, these effects may be either direct (e.g., changes in the number and locations of vegetation boundaries used by

predators) or indirect through changes in prey densities or prey availability to predators. Climate-induced changes in trophic structures are expected to be common, complex, and interactive, but are at least one step removed from climate (e.g., Post et al. 1999).

The effects of these changes on a specific animal are difficult to project and require specific understanding of the functional roles that ecological attributes play in the animal's life history, and the consequences associated with alternative life history strategies. These types of data are often lacking, and although current behaviors can be studied, they may not be informative relative to climate change effects, and responses may be novel and unanticipated. For example, polar bears (*Ursus maritimus*) are historically adapted to pack-ice hunting for seals, but with recent reductions in pack ice, they have in some areas shifted to feeding on the eggs of snow geese (*Chen caerulescens*) (Rockwell and Gormezano 2009), whose populations have erupted because of their ability to feed in agricultural fields (Fox et al. 2005).

In addition to changes in vegetation and prey, trophic effects include the presence and abundance of disease and parasitic organisms. For example, for greater sage-grouse (*Centrocercus urophasianus*), the potential spread of West Nile virus (*Flavivirus* spp.) associated with climate change may increase stress in grouse populations (Schrage et al. 2011), but the effect is difficult to project. For many organisms, current ranges are often strongly limited by human activities. For example, greater sage-grouse range is limited by conversion of native sagebrush (*Artemisia* spp.) habitat to agricultural uses (Connelly et al. 2004; Miller and Eddleman 2001).

Climate change is likely to alter the nature and location of human activities that affect wildlife. In the western United States, changes in water availability and the amounts required for irrigation can be expected to have profound effects on human activity and settlement patterns (Barnett et al. 2005). In addition, societal effects associated with local changes will occur within the context of societal changes across much larger spatial domains. Changes in technology, standards of living, infrastructure, laws, and the relative effects of climate changes in other areas will all affect local human activities.

In summary, the ways that climate change affects endothermic terrestrial species are likely to be complex and difficult to project. In addition to the uncertainty of future climate itself (see chapter 3), effects on most species will be indirect through proxies such as ecological disturbance, habitat structure, prey availability, disease dynamics, and shifts in human activities.

THE IMPORTANCE OF COMMUNITY IN DEFINING HABITAT

Our understanding of wildlife ecology, particularly at broad spatial scales, is generally limited to the correlation of occurrence patterns rather than direct studies of those factors that limit species distributions. In some cases, patterns of occurrence are clear, consistent, and highly correlated with climate (see section on wolverine [*Gulo gulo*] below), but the causal relationships remain obscure. Many passerine birds, for example, nest only in specific habitats, such as Brewer's sparrow (*Spizella breweri*) (see section below), which is obligate to sagebrush. Although the pattern is clear and invariant, the nature of the obligate links to sagebrush are unknown. Species such as ruffed grouse (*Bonasa umbellus*) (see section below) clearly have northern distributions, but the factors that define the southern limits of their current distributions are not well understood (Lowe et al. 2010).

This lack of causal understanding may be unimportant for current management of these species, because management occurs only in areas where they currently exist or where they existed in the recent historical past. Based on observed patterns of use and distribution, enough information exists to identify and manage current habitat. However, it cannot be assumed that measured correlations will persist in an altered climate. We typically characterize habitat elements that exist in assemblages of mostly unmeasured plants and animals. Assume that an organism's occurrence is strongly correlated with mature Douglas-fir (*Pseudotsuga menziesii*) forests. These forests contain other specific tree and understory species, animal communities, and successional trajectories (e.g., habitat types; Daubenmire [1952]). However, Douglas-fir projected onto a future landscape may be associated with different plant and animal communities. Due to the correlational nature of most of our habitat knowledge, it is difficult to know which of these community members are critical to habitat quality of a target species and thus the habitat quality of novel species assemblages.

In addition, factors identified as important are restricted to those that currently limit behavior. Therefore, in correlation-based habitat relationships, changes in non-limiting but essential factors will not produce strong correlations with behaviors. For example, distance to water may be a strong habitat correlate in desert environments but may not be correlated with habitat quality in a rainforest. Water may be no less important in the rainforest, but it is currently not limiting. As climate change alters biophysical attributes of landscapes, limiting factors and definitions of what constitutes habitat may change.

In addition to potentially changing vegetation communities and limiting factors, the effects of climate on future habitats are further complicated by altered disturbance regimes. Regeneration, growth, and disturbance patterns collectively create landscapes that provide habitats. Changing disturbance dynamics (see chapter 8) alter the characteristics of landscape mosaics and fundamentally alter habitats. As climate change causes shifts in plant and animal distributions, a temporal mismatch between decrease of current habitat and increase of new habitat may occur, a mismatch that will be exacerbated by increased levels of disturbance. Wildfire can destroy current habitat in a day, but generation of new habitat may require centuries, depending on the time necessary to create critical elements through regeneration, growth, and succession. The fisher (*Martes pennanti*) provides an example of these uncertainties. In Idaho and Montana, fishers are currently limited to mature forests in the Inland Maritime climatic zone. However, GCMs indicate that this zone will move to the east, and mature forest may require a century or more to grow in this location, creating uncertainty about the future range of fisher (see discussion below).

Given the uncertainty associated with determining likely trajectories of species and their habitats under climate change, assessments of general vulnerability and projected changes can be viewed as hypotheses to be tested. Therefore, it is desirable to develop a trajectory focused on proactive management strategies that maintain valued species and landscape attributes, including objectives such as creating resilience to disturbance. Prioritizing which things are measured can improve the connection between environmental change and management. A monitoring program designed to test specific hypotheses associated with specific organisms (Nichols and Williams 2006) can improve our

understanding of relationships between climate change and landscapes, providing data that inform science-based management.

EVALUATING SPECIES SENSITIVITY TO CLIMATE CHANGE

Evaluating the potential effects of climate change on animal species begins with determining which species are of interest, collecting biological information about them, and paying special attention to biological traits that might lead to changes in distribution and abundance in a warmer climate (e.g., Glick et al. 2011). Some species have received significant attention and have generated peer-reviewed articles that formally analyze the effects of climate change, although this is relatively uncommon.

Foden et al. (2013) identify three dimensions associated with climate change vulnerability—sensitivity, exposure, and adaptive capacity—and apply a framework based on assessing these attributes to nearly 17,000 species. Other expert systems have been developed to evaluate the relative degree of climate sensitivity and vulnerability for various species including the Climate Sensitivity Database (<http://climatechangesensitivity.org>) and NatureServe Climate Change Vulnerability Index (<http://www.natureserve.org/conservation-tools/climate-change-vulnerability-index>). These tools do not seek to understand specific responses of animals to climate, but rather to identify species that are likely to be vulnerable based on current habitat associations, life history traits, and distributions (Foden et al. 2013). Bagne et al. (2011) formalized this process in the System for Assessing Vulnerability of Species (SAVS) to climate change. In SAVS, species are assessed based on a large number of traits associated with habitat (7 traits), physiology (6 traits), phenology (4 traits), and biotic interactions (5 traits). For each of these 22 traits, a score of -1, 0, or 1 is assigned; positive scores indicate vulnerability, and negative scores indicate resilience. The raw scores are multiplied by correction factors associated with the number of traits in a category and possible scores across traits, to achieve a standardized score between -20 and 20 that indicates the relative vulnerability of the species.

Formalizing traits that can lead to vulnerability provides a framework for collecting biological data associated with a species and for considering the effects of climate change. However, existing expert systems cannot be used to infer that sensitivities for disparate topics such as habitat and phenology are

proportionally important or if estimated vulnerability has quantitative meaning (Bagne et al. 2011; Case et al. 2015). Even if these issues were considered unimportant, for most of the species evaluated below, accurately identifying vulnerability (Foden et al. 2013) would not be possible given current biological understanding. Since data on climate-species relationships are so sparse, this assessment focuses primarily on evaluation of each trait as it relates to the biology of animal species.

Below are assessments for animal species identified as high priority by Forest Service, U.S. Department of Agriculture Northern Region resource specialists, and for additional species identified by participants in five workshops convened by the Northern Rockies Adaptation Partnership (see chapter 1). Species were not necessarily chosen based on their perceived level of vulnerability. In many cases, species are associated with specific habitats that were considered vulnerable; for example, some species are associated with sagebrush communities, others with snow depth and cover, et al. with dry forests that have large trees. The assessment summaries below contain projections of climate change effects based on interpretation of the pertinent literature. Level of detail differs considerably among species and is mostly driven by the degree to which the species have been evaluated in the context of climate change. Species are listed in alphabetical order within each taxonomic class.

American Beaver (*Castor canadensis*)

Since beavers tend to spend most of the winter in their lodges or swimming to retrieve food, climate may be more influential during spring through autumn than during winter (Jarema et al. 2009). However, body weights of juvenile European beavers were lighter when winters were colder (Campbell et al. 2013). The cost of thermodynamic regulation may be greater for juveniles because they have higher surface area-to-volume ratios than adults (on whom winter temperature had no effect) (Campbell et al. 2013).

In Quebec (Canada), beaver density was highest in areas with the highest maximum spring and summer temperatures (Jarema et al. 2009). Conversely, European beavers in Norway achieved heavier body weights when spring temperatures were lower, and the rate of vegetation green-up was slower (Campbell et al. 2013). This apparent contradiction may have been caused by the timing and measurement of climate and response variables. Although beavers create and require ponds, survival and

body weight in European beavers has been linked to lower, and more consistent, April-September precipitation (Campbell et al. 2012, 2013). Higher water levels during high precipitation years were thought to lead to decreased riparian plant growth caused by waterlogging (Campbell et al. 2012).

Climate can indirectly influence beavers through effects on vegetation. Climate change and climate-driven changes in streamflow are likely to reduce an abundance of dominant, early-successional tree species in riparian habitats (Perry et al. 2012), reducing food and building materials for beaver. Beavers can be used as a management tool to buffer riparian systems from drought (Lawler 2009) (fig. 9.3). Beaver ponds increase the amount of open water (Hood and Bayley 2008), and beaver management can be used as a surrogate for amphibian conservation (Stevens et al. 2007).

American Pika (*Ochotona princeps*)

The American pika is a small (5-8 oz) lagomorph that often inhabits rocky alpine areas in western North America (Smith and Weston 1990) (fig. 9.4). The species has been extensively studied in the Great Basin where pika habitat typically occurs as small islands near mountaintops. Relatively little study of pikas had occurred in the Northern Rockies until recently, with the exception of research on occupancy and abundance in relation to microclimate, topography, and vegetation in the Bighorn Mountains and Wind River Range (Wyoming) (Yandow 2013). Currently, studies are in process in the Bridger-Teton National Forest and Greater Yellowstone Area (Beever, U.S. Geological Survey, Northern Rocky Mountain Science Center, personal communication).

Pikas appear to depend on moist, cool summer conditions and winter snow (Beever et al. 2011), and on low water-balance stress and green vegetation (Beever et al. 2013). Across paleontological time scales (Grayson 2005) and during the 20th century, pikas across the Great Basin have reacted to increasing temperature by moving upslope or becoming locally extirpated when the climate becomes hot and dry (Beever et al. 2011). Results from field research in 2012-2014 in the Great Basin indicate that local extirpations and retractions are continuing (Beever, U.S. Geological Survey, Northern Rocky Mountain Science Center, personal communication). Local changes in pika distribution have also been recorded in

Utah, the southern Sierra Nevada, and southern and central Cascade Range (Beever et al. 2011 and references therein).

In the Great Basin, pika extirpation (1994-2008) occurred in microsites that were generally hotter in summer (more frequent acute heat, and hotter average temperature across the whole summer) and were more frequently very cold in winter than in locations where pikas persisted. In the latter case, warming reduced insulating snow, causing temperatures near-ground temperature to decrease (Beever et al. 2010). Furthermore, density of pikas in surveys during 2003-2008 was best predicted by maximum snow-water equivalent and growing-season precipitation (Beever et al. 2013). Some extirpations have occurred at sites with low annual precipitation (Beever et al. 2011, 2013), reinforcing studies in the southern Rocky Mountains (mostly Colorado), where surveys indicated that four pika extirpations (among 69 total sites with historical records) occurred at the driest sites (Erb et al. 2011).

Winter snowpack not only insulates pikas during cold periods, but also provides water during the summer, when plant senescence at drier sites occurs earlier in the year, eliminating available metabolic water for pikas. Surveys, mostly in the Sierra Nevada, found that pika extirpations were associated with sites with higher maximum temperatures and lower annual precipitation (Millar and Westfall 2010b). Chronic stresses (average temperature during summer, maximum snowpack, and growing-season precipitation), acute temperature stresses (hot and cold), and vegetation productivity appear to affect pika declines in the Great Basin (Beever et al. 2010, 2011, 2013).

Individual mountain ranges are believed to act as discrete areas without any pika migration between adjacent ranges across valley bottoms (Castillo et al. 2014), although disjunct metapopulations of pikas separated by short distances may exist. In a study of pika populations in ore dumps separated by tens to hundreds of yards, individual populations that were extirpated were recolonized, and abundance across all ore piles remained constant (Smith 1980). This process appears to occur only at very short distances because habitats isolated by more than 1150 ft were generally unoccupied, although populations in the southern group of ore piles subsequently collapsed. Connectivity of pika populations appears to be context dependent, with lower connectivity between sites that occur in hotter, drier landscapes (Castillo et

al. 2014; Henry et al. 2012). Thus, recolonization may occur at distances less than 0.5 mi and in areas where between-population dispersal occurs within cool, moist landscapes, whereas recolonization at longer distances is rare. In the Great Basin, across 21 years of contemporary research, once pikas have been extirpated from a site, they have never been detected in subsequent surveys (Beever et al. 2011).

At the broadest spatial scales, there is genetic evidence for historical isolation in which pikas across the Intermountain West separate into five distinct groups (Galbreath et al. 2010). At smaller scales, in British Columbia, inbreeding and high levels of genetic structure exist between high- and low-elevation populations, even when the populations are geographically proximal. Castillo et al. (2014) found that gene flow is restricted primarily by topographic relief, water, and west-facing aspects, suggesting that physical restrictions related to small body size and mode of locomotion, as well as exposure to relatively high temperatures, limited pika dispersal.

Studies in the Sierra Nevada (Millar and Westfall 2010a,b) and southern Rocky Mountains (Erb et al. 2011), at sites in which pikas were common and not generally subject to extirpation across most of the landscape, indicated that physiological limits for this species had not been reached. This will probably be the case for most pika populations in the Northern Rockies in the near term. Although hot, dry climate may limit pika distributions, local moisture sources, rock-ice features, aspect, and the physical structure of talus fields may climatically buffer pikas from macroclimatic stresses (Millar and Westfall 2010a). Existence of pikas at Lava Beds National Monument, Craters of the Moon National Monument, and the Columbia River Gorge—all of which have warm, dry climate—underscore the importance of microclimate for species vulnerability assessments, and indicate that microclimate and macroclimate are decoupled in some locations (Rodhouse et al. 2010; Simpson 2009; Varner and Dearing 2014).

Since pikas are sensitive to high temperature, we expect that pika populations will respond to climate change in the Northern Rockies. However, site-specific factors contribute to highly variable microclimates, so response to climate change will vary considerably over space and time. A large amount of data has been collected on this species over the past decade, and it should be possible to develop more accurate projections of population response as monitoring data continue to accrue.

Canada Lynx (*Lynx canadensis*)

The Canada lynx is a mid-sized cat with a number of specific adaptations that allow it to travel across soft snow. The most obvious adaptation is oversized feet: foot loading is 0.5 times that of the similar sized bobcat (*L. rufus*) (Buskirk et al. 2000). Canada lynx prey nearly obligately on snowshoe hares (*Lepus americanus*) (fig. 9.2). Not only do snowshoe hares constitute 33-100 percent of lynx diet (Mowat et al. 2000), but a low proportion of hares in the diet indicates scarcity of hares, not diet plasticity (Mowat et al. 2000). Studies of lynx winter diet in the Clearwater River watershed (western Montana) found 94-99 percent of the diet consisted of snowshoe hare (Squires and Ruggiero 2007). Snowshoe hares are also specially adapted to snowy environments. When compared to similar sized leporids, they have oversized feet. They also exhibit seasonal pelage change from brown to white. Due to the close association between lynx and hares, and because both species have specialized adaptations to allow survival in snowy environments, climate relationships for both species are explored in this section.

Canada lynx is found exclusively in North America, its distribution extending across the interior of Canada and Alaska and northward into tundra vegetation. In the conterminous United States, both current and likely historical populations are located in the extreme northern portions of this region: Maine, historically New York and New Hampshire, Minnesota north of Lake Superior, western Montana, and northern Washington (McKelvey et al. 2000). Periodically, in the years immediately following major population eruptions in the north, lynx distributions expand and lynx are found ephemerally in North Dakota, and populations temporarily increase in Montana (McKelvey et al. 2000). Since bobcats (*Lynx rufus*) and lynx were not well differentiated in the fur market (Novak et al. 1987), with large bobcats often recorded as “lynx,” trapping records are typically untrustworthy (McKelvey et al. 2000). Recently, a population was translocated to Colorado, and appears to be persisting; after initial high mortality rates, annual survival has exceeded 90 percent (Devineau et al. 2010). However, the historical evidence for lynx in Colorado is weak, with most of the verified records occurring in years consistent with immigration from the north (McKelvey et al. 2000). Hare densities in Colorado are generally less than the 0.5 hare ac⁻¹

threshold (Ivan et al. 2014) thought to be the minimum hare density associated with stable lynx populations (Mowat et al. 2000).

When evaluating the potential distribution of lynx, it is important to note that large populations of lynx are located in the interior of the continent. Lynx are common in Alberta and Saskatchewan (Canada) where over 20,000 were trapped per year in recent eruptions (Novak et al. 1987), but were rare along both the Atlantic and Pacific coasts. Lynx are more common in areas with a northern continental climate, probably because soft powdery snow is more common there.

Maintaining population connectivity is central to lynx conservation. However, maintaining connectivity may become increasingly difficult as southern populations of boreal species become more isolated with climate change (van Oort et al. 2011). This is of particular concern because disturbance processes that include wildfire, insects, and disease make some boreal forests vulnerable to climate change (Agee 2000; Carroll et al. 2004; Fishlin et al. 2007; Fleming et al. 2002; IPCC 2007a,b; Logan et al. 2003).

In the Northern Rockies, lynx exist in only a few areas: the Clearwater River watershed, Bob Marshall Wilderness, and northwestern corner of Montana. Dens are located in boulder fields and spruce-fir forests with high horizontal cover and abundant coarse woody debris. Eighty percent of dens are in mature forest and 13 percent in mid-seral regenerating stands (Squires et al. 2008). For winter foraging, lynx preferentially forage in mature, multilayer spruce-fir forests composed of larger diameter trees with high horizontal cover, abundant snowshoe hares, and deep snow (Squires et al. 2010). During summer, lynx occupy young forests with high horizontal cover, abundant total shrubs, abundant small diameter trees, and dense spruce-fir saplings (Squires et al. 2010). Lynx select home ranges with vegetative conditions consistent with those identified for foraging and denning, primarily at mid elevations (Squires et al. 2013). Assuming that preferences for movement between home ranges are similar to those associated with moving within the home range, dispersal pathways consist of areas with similar properties to those used for foraging (Squires et al. 2013).

The range of snowshoe hare (Hall and Kelson 1959) is more extensive than that of lynx, extending into the mid Sierra Nevada and areas such as the Olympic Peninsula where there are no records of lynx occurrence (McKelvey et al. 2000). The more extensive hare distribution, which includes areas with limited snow (e.g., the Pacific coast), is likely caused by greater genetic differentiation for snowshoe hares than for lynx. Across the continent, lynx exist in a single, largely panmictic (random mating) population (Schwartz et al. 2004), whereas hares are subdivided into six subspecies (Wilson and Reeder 2005).

Hares exhibit variation in timing of pelage change across western North America, but variation is low in any specific location, and timing appears to be genetically controlled and linked to photoperiod (e.g., Hall and Kelson 1959; Zimova et al. 2014). Timing of pelage change is critical for hare survival, because mismatches—a white hare on a dark background and vice versa—cause most hares to die from predation (Hodges 2000) (fig. 9.2). Initiation of pelage change appears to be driven by photoperiod rather than background color, so the ability of hares to shift the timing of pelage change to match patterns of snow cover is limited (Mills et al. 2013). Given projections of snow cover by 2100 (see chapters 3 and 4), current patterns of pelage change in the Northern Rockies will be mismatched with the period of snow cover. Unless a significant change occurs in the population genetics of hares, they will be the wrong color for approximately two months per year (one month in spring, one month in autumn) in the Northern Rockies (Mills et al. 2013).

Both lynx and hares require specific amounts and duration of winter snow. An example of this for lynx occurs in Minnesota where current and historical populations are limited to the “arrowhead” north of Lake Superior (McKelvey et al. 2000; Schwartz et al. 2004). This area is characterized by lake-effect snow, and outside of it, bobcats dominate and lynx are not found. Both lynx and hares require forests with dense understory canopies. In western Montana, lynx and hares use older spruce-fir forests. If climate change and associated disturbance reduce the abundance of these forest types, habitat loss could be significant, reducing populations of lynx and hares.

Fisher (*Martes pennanti*)

The fisher is a mid-sized, forest-dwelling mustelid whose range covers much of the boreal forest in Canada, a broad area of the northeastern United States extending from the Lake States to Maine, and a scattered distribution in the western United States. Males and females are similar in appearance but the males are larger. Males are 35-47 in long and weigh 8-13 lb; females are 30-37 long and weigh 4-6 lb (Powell 1993).

Fishers are common and often associated with urban environments in the eastern United States, but are uncommon in the western United States and appear to have very specific habitat associations. Although the current distribution of fishers is reduced from its historical range, its populations have typically been disjunct. Genetic studies have shown that fisher populations in California have been historically isolated from those in Washington, and fishers in the southern Sierra Nevada have been isolated from those in the Klamath region (Tucker et al. 2012). Fisher in Montana contains unique haplotypes (DNA variations that tend to be inherited together) not found elsewhere (Schwartz 2007; Vinkey et al. 2006) and therefore were apparently isolated both from large populations in northern British Columbia and coastal populations in Washington. Common attributes for resting sites across eight studies of Western fishers were: steep slopes, cool microclimates, dense forest canopy cover, high volume of logs, and prevalence of large trees and snags (Aubry et al. 2013). Although these features are important for managing fisher habitat, they do not necessarily explain the fragmented historical distribution in the West (Tucker et al. 2012).

Fishers have long been thought to have specific climatic associations. Krohn et al. (1995) compared fisher and marten (*Martes americana*) distributions in the Sierra Nevada, and found that areas occupied predominantly by marten were closely associated with forested areas with the deepest snow (>9 in per winter month), whereas areas occupied predominantly by fishers were forested areas with low monthly snowfall (<5 in). There is direct evidence that fishers avoid deep snowpack (Krohn et al. 1995, 2005; Raine 1983) and that deep snow can limit fisher dispersal (Carr et al. 2007). Fishers also avoid dry habitats (Jones and Garton 1994; Schwartz et al. 2013).

12078 Presence in warmer, wetter forests appears to be common in both macro and micro distributions of
12079 fishers in the western United States, although large populations in northern interior British Columbia and
12080 Alberta are not associated with these specific climates. Therefore, defining fisher habitat in climatic terms
12081 and projecting future habitat is more challenging than for animals with more obvious climatic associations
12082 (Copeland et al. 2010; McKelvey et al. 2011).

12083 In a recent modeling study of fisher habitat in an area consistent with its distribution in the Northern
12084 Rockies, Olson et al. (2014) built occurrence models for fisher populations in northern Idaho and western
12085 Montana that included variables such as canopy cover, climatic variables such as minimum winter
12086 temperature, and topographic variables such as slope. They found that most of the variability in the model
12087 was explained by mean annual precipitation (34 percent), topographic position index (29 percent), and
12088 mean temperature of the coldest month (27 percent). Therefore, fisher habitat was projected to be best in
12089 areas with high annual precipitation, low relief, and mid-range values for mean temperature in the coldest
12090 month. Krohn et al. (1997) and Olson et al. (2014) both projected similar areas of fisher habitat and in
12091 similar places.

12092 Olson et al. (2014) used downscaled data from a single GCM (Collins et al. 2001; Hadley Centre
12093 Coupled Model, version 3; HCCM3) and two emission scenarios (A2-high, B2-low) (IPCC 2007b),
12094 projecting habitat for 2030, 2060, and 2090. At the macro scale, results for both scenarios are similar: in
12095 the near term, habitat currently occupied by fishers might improve, but by 2090, habitat in areas that are
12096 currently occupied (primarily central Idaho) decline sharply, and new habitat is created in to the east in
12097 northwestern Montana. The main difference between the scenarios at this level of detail is the rate at
12098 which changes occur. In the A2 scenario, the change is visibly apparent by 2060, but not for the B2
12099 scenario. As habitat shifts, it becomes increasingly fragmented, and the amount of usable habitat is
12100 strongly affected by how acceptable minimum patch size is defined (Olson et al. 2014).

12101 Olson et al. (2014) bracketed the emission scenarios, providing some measure of the potential range
12102 of results, but between-model variability exceeds variability between emission scenarios. In addition, the
12103 performance of specific GCMs varies considerably at the regional scale (Mote and Salathé 2010), and the

Hadley family of GCMs is considered to be on the hot-dry side of climate projections for the Northern Rockies (Alder and Hostetler 2014). As a result, details within the model can influence patterns of projected habitat.

Additional uncertainties exist about the ability of habitat components to track climate. Given that fishers are associated with mature forests, significant time lags may exist between the loss of current habitat and formation of new habitat in areas that currently are unsuitable. If large trees cannot survive the shift in climate, mature forests may become rare for many decades. In climatic zones suitable for fishers, forests may be dominated by young trees and shrubs whose suitability for fisher habitat is unknown. Therefore, projections in Olson et al. (2014) are an optimistic view of habitat availability under climate change, and it is uncertain if fishers would disperse into new habitat should it occur.

Moose (*Alces alces*)

A number of species fall into categories for which the effects of climate change are apparent, but difficult to assess, including species whose ranges are clearly northern but for which the southern range limitations are not linked either to physiological constraints or to specific vegetative communities. Some organisms with broad historical distributions are currently limited to northern distributions because of southern extirpation, such as gray wolves (*Canis lupus*) and brown bears (*Ursus arctos*). These species are considered to be climate limited, although human populations are low in boreal forests and tundra, and interaction with large carnivores is minimal. Were climates to warm, and people to relocate into these northern systems, this would obviously affect species such as wolves and brown bears.

For other species whose northern ranges are not defined by human impacts, both direct and indirect climate limits may not have been identified. Moose provide an example of a well-studied animal that has a northern distribution but whose dependency on boreal environments is not immediately obvious. We suspect that other species with northern distributions may exhibit similar constraints that define the southern extents of their ranges.

A limited amount of climate change research has been conducted on moose (Murray et al. 2006, 2012). Several factors have been identified as influencing the biogeographical distribution of moose

including food supply, climate, and habitat. Based on metabolic research, moose are intolerant of heat but well adapted to cold, and summer temperatures may define their southerly distribution (Renecker and Hudson 1986). When winter temperatures were $>23^{\circ}\text{F}$ or summer temperatures were $>57^{\circ}\text{F}$, moose experienced an increase in metabolism and heart and respiration rates (Renecker and Hudson 1986, 1990), reduced feed intake (Belovsky and Jordan 1978; Renecker and Hudson 1986), and reduced body weight (Renecker and Hudson 1986). When ambient air temperatures exceeded 68°F moose resorted to open-mouthed panting to regulate core body temperature (Renecker and Hudson 1986). Heat stress was particularly difficult in the spring when moose were still in their winter coats (Schwartz and Renecker 1997). These temperature thresholds represent physiological thresholds that, when exceeded, represent heat stress that increases the energy expenditure needed to stay cool.

However, it is unknown if moose are able to avoid being exposed to high mid-day summer temperatures. In Minnesota, Lenarz et al. (2009) found that temperature was highly correlated with moose survival, but winter temperature was more critical than summer heat. High temperatures in January were inversely correlated with subsequent survival and explained >78 percent of variability in spring, fall, and annual survival. In northern Minnesota, moose populations were not viable, largely because of disease and parasite related mortality (Murray et al. 2006). However, in nearby southern Ontario (Canada), moose populations appeared to be viable with favorable growth rates (Murray et al. 2012). Warming temperatures favor white-tailed deer (*Odocoileus virginianus*) expansion into moose range, and increased transmission of deer parasites to moose (Lankester 2010), although separating direct and indirect climate effects is difficult (Murray et al. 2012).

Northern Bog Lemming (*Synaptomys borealis*)

As the name implies, northern bog lemmings inhabit wet meadows, bogs, and fens within several overstory habitat types (Foresman 2012). Generally these places have extensive sphagnum (*Sphagnum* spp.), willow (*Salix* spp.), or sedge components. These mammals likely occupy places that retained high water levels after the last glacial retreat (Foresman 2012). Given their dependence on wet habitats, it follows that climate changes that decrease the amount of surface water will likely have negative impacts

on northern bog lemmings. Management practices that maintain surface water may therefore be beneficial. However, documented studies of climate and management effects are lacking.

Pronghorn (*Antilocapra americana*)

The pronghorn (*Antilocapra americana*) is an ungulate native to the prairies, shrublands, and deserts of the western United States occupying a broad range of climatic conditions from southern Canada (Dirschl 1963) to Mexico (Buechner 1950). Although pronghorns occupy a broad climatic region and their diet is generalized, they are prone to epizootic diseases, notably bluetongue (a viral disease transmitted by midges [*Culicoides* spp.]) (Thorne et al. 1988). Bluetongue is thought to be cold weather limited, and recent extensions of bluetongue in Europe have been attributed to climatic warming (Purse et al. 2005). Given their current range and food habits, the emergence of new disease threats caused by a warmer climate probably poses the greatest risk to pronghorns.

Pygmy Rabbit (*Brachylagus idahoensis*)

The pygmy rabbit is one of the smallest leporids in the world and is endemic to big sagebrush (*Artemisia tridentata*) (Katzner and Parker 1997), which is critical for food and cover. In southeastern Idaho, areas selected by pygmy rabbits had a significantly higher woody cover and height than other areas, with lower quantities of grasses and higher quantities of forbs. Sagebrush was eaten throughout the year, comprising 51 percent of the diet in summer and 99 percent in winter (Green and Flinders 1980). These findings are similar to those reported for southern Wyoming (Katzner and Parker 1997) and Utah (Edgel et al. 2014). In addition, areas used by pygmy rabbits accumulate more snow than unused areas, and rabbits use the subnivean environment to access food and avoid predators (Katzner and Parker 1997). The presence of significant snow for thermal protection may be important for winter survival, because of small body size, lack of metabolic torpor, and lack of food caching (Katzner and Parker 1997).

Structural characteristics of sagebrush are considered more important than food availability for pygmy rabbits (Green and Flinders 1980; Katzner and Parker 1997). Although large, dense sagebrush would seem to be associated with older stands, Edgel et al. (2014) found no difference in age between occupied and unoccupied sites; structure was important, but age was not. As a result, processes that

reduce the size and density of sagebrush are likely to have negative effects on pygmy rabbits, and processes that fragment sagebrush stands may decrease habitat quality. For example, Pierce et al. (2011) found that burrows, observed rabbits, and fecal pellets decrease in density with proximity (<300 ft) to edges.

Paleoecological studies show that both sagebrush and pygmy rabbits are sensitive to climate change. Both species decreased in the mid-Holocene, characterized in the Great Basin by extreme aridity (Grayson 2000). Big sagebrush is sensitive to fire, and 100 percent mortality and complete stand replacement after burning are common (Davies et al. 2011; see chapter 7). In addition, big sagebrush cannot resprout from the root crown after a fire, so recruitment of sagebrush relies on wind dispersal of seeds from adjacent seed sources, and on composition of the seed bank in the soil (Allen et al. 2008; Ziegenhagen and Miller 2009). Mountain big sagebrush (*A. tridentata* ssp. *vaseyana*) required 13-27 years after spring prescribed burning to return to conditions suitable for pygmy rabbit habitat (Woods et al. 2013). In areas where fire has been suppressed for many decades, sagebrush habitat can be displaced by conifer incursion (Miller and Rose 1999).

Pygmy rabbits are likely to be sensitive to climate change for several reasons. First, they depend on a single species (big sagebrush) and habitat condition (tall, dense stands). Climatic variability has affected sagebrush communities and pygmy rabbits in the past (Grayson 2000), and this could happen again in the future. Second, pygmy rabbit habitat is sensitive to altered disturbance. Increased fire frequency and area burned are projected as the climate continues to warm (see chapters 6, 7, and 8). Finally, changes in winter snow depth could affect overwinter survival by altering the protection provided by the subnivean environment.

Townsend's Big-Eared Bat (*Corynorhinus townsendii*)

Climate change can affect foraging ability, drinking water availability, and timing of hibernation in bats (Sherwin et al. 2013). Townsend's big-eared bats generally require cavern-like structures for diurnal, maternal, and hibernation roosting, although they also use large tree cavities, buildings, and bridges (Gruver and Keinath 2003). They forage for insects along riparian and forest edge habitats (Fellers and

Pierson 2002). Their distribution appears to be limited by the availability of suitable roosting sites, as western populations have declined (O'Shea and Vaughan 1999) coincidental with the closure of mines (Gruver and Keinath 2003). Townsend's big-eared bats are not able to produce highly concentrated urine (Geluso 1978) and therefore require daily access to water sources for drinking (Gruver and Keinath 2003). Man-made water holes and mining ponds may serve as water sources (Geluso 1978), metal contaminants in the latter have may cause some bat mortality (Pierson et al. 1999).

Bioaccumulation of pesticides in fat tissue appears to be one cause of declines in Townsend's big-eared bat populations (Clark 1988). Human activities that reduce moth populations can also negatively affect bat populations because moths are a primary food source of Townsend's big-eared bats (Burford and Lacki 1998; Whitaker et al. 1977). Bats may be especially sensitive to human disturbance during hibernation (Thomas 1995).

In Colorado, the reproductive success of *Myotis* spp. declined during warmer and drier conditions, which are projected to be typical of future climate conditions (Adams 2010). However, in other instances, warmer spring temperatures have led to earlier births, which promotes juvenile survival (Lucan et al. 2013). Higher summer precipitation may reduce reproductive success (Lucan et al. 2013). Future warming may also reduce the effectiveness of some bat echolocation calls (Luo et al. 2014).

Ungulates (Elk, Mule Deer, White-tailed Deer)

Rocky Mountain elk (*Cervus canadensis*), Rocky Mountain mule deer (*Odocoileus hemionus hemionus*) and white-tailed deer (*O. virginianus*) provide the core of big game hunting in the Northern Rockies. All three have very broad ranges in North America. The current range for elk, which includes most of the Rocky Mountain West, also includes areas in the eastern and southwestern United States that were historically occupied by other sub-species. Rocky Mountain mule deer extends from the Yukon (Canada) to northern Arizona. White-tailed deer extend across most of North America and into northern South America, including 38 recognized sub-species (De la Rosa-Reyna 2012).

Based on their broad ranges, it is clear that all three species exhibit a high degree of flexibility towards habitat. Habitat use by elk in forested areas is associated with edges (Grover and Thompson

1986; Irwin and Peek 1983; Thomas et al. 1979, 1988) in which areas containing high quality forage and areas with forest cover are in proximity. In open habitats, they select areas of high vegetative diversity with intermixed patches of shrubs and grasslands (Sawyer et al. 2007). Both patterns of habitat use appear to be maximized by a disturbance regime with spatial heterogeneity at relatively fine scales.

A study of Rocky Mountain mule deer found that home range size increased in areas with few large patches and was smallest in fine-grained vegetation mosaics (Kie et al. 2002). Mule deer depend on disturbance to create forage (e.g., Bergman et al. 2014), but the size and juxtaposition of patches are important. Fine-grained disturbance mosaics appear to be optimal for white-tailed deer, especially in areas where thermal cover is important. In the Northern Rockies, thermal cover prevents heat loss during winter, although in warmer climates, thermal cover reduces daytime heating. In Texas, male white-tailed deer chose areas with high cover and poor foraging opportunities during the mid-day, but chose areas with higher forage quantities during crepuscular and nocturnal periods (Wiemers et al. 2014).

Ungulates generally respond positively to disturbance (fig. 9.5), but the types of disturbance and the resulting landscape condition and species composition are equally important. Just as wildfire intensity affects patchiness in the postfire landscape, it also affects which plant species are likely to revegetate burned areas. For example, Emery et al. (2011) found that at lower temperatures several native plant species exhibited enhanced germination, whereas nonnative plant species did not. Vegetation growth after disturbance is important where nonnative species are common. For example, Bergman et al. (2014) found that treatments that removed trees and controlled weeds produced better mule deer habitat than treatments that removed only trees.

Climate change is expected to alter fire regimes, but for ungulates the exact nature of those changes will be critical. For example, in the Greater Yellowstone Area subregion, wildfires are infrequent, large, and intense. If climate change causes more frequent fires (Westerling et al. 2011), then the landscape will be patchier compared to the current condition, and the distribution and abundance of forest species could change. In the short term, novel fire-climate-vegetation relationships can be expected. In the long-term,

the effects of altered vegetation on ungulate populations are uncertain, but it is unlikely that there will be highly negative consequences.

Wolverine (*Gulo gulo*)

The wolverine is the largest mustelid, occurring throughout the Arctic, as well as subarctic areas and boreal forests of western North America and Eurasia. At the southern extent of its distribution in North America, populations occupy peninsular extensions of temperate montane forests. Monitoring programs in Fennoscandia (Flagstad et al. 2004) and surveys in Canada (Lofroth and Krebs 2007) inform our understanding of wolverine occurrence in those regions, but the limits of wolverine distribution in other portions of its range are less understood.

Wolverines are often considered to be generalists with respect to habitat, and their occurrence has been associated with remoteness from human development (Banci 1994; May et al. 2006; Rowland et al. 2003). However, unlike brown bear and gray wolf, whose northern distributions are the result of recent human hunting and habitat alteration, there is no historical evidence for wolverine presence in areas not characterized by arctic or boreal conditions (Aubry et al. 2007). Fossil evidence is consistent with this understanding (Alvarez -Lao and Garcia 2010), and it appears that wolverines have always been associated with cold northern climates.

Wolverines den in snow, and deep snow throughout the denning period is thought to be essential (Magoun and Copeland 1998). The strong, perhaps obligate relationship between wolverine den selection and deep snow in the late spring has been reinforced by recent studies (Copeland et al. 2010; Dawson et al. 2010; Inman et al. 2012). A proxy for spring snowpack (areas where snow persisted through mid May) effectively describes den site selection, current range limits, and year-around habitat use at the southern periphery of their range (Copeland et al. 2010). These same areas are associated with successful dispersal (Schwartz et al. 2009) and historical range (Aubry et al. 2007). Although not all biological aspects of this association are understood, its universal nature in both space (it applies to populations in Alaska, Idaho, and Scandinavia) and time (it describes both historical and contemporary distributions) indicate that snow persistence will be associated with future distributions as well. Since wolverines apparently travel within

these areas when dispersing and strongly minimize travel through low-elevation habitat, we can project both current and future travel routes based on altered snowpack.

McKelvey et al. (2011) modeled future spring snowpack within the Columbia, Upper Missouri, and Colorado River basins, and projected changes in habitat and connectivity associated with future landscapes based on existing wolverine habitat relationships (Copeland et al. 2010) and dispersal preferences (Schwartz et al. 2009). A projection derived from an ensemble mean of 10 GCMs under an intermediate emission scenario (A1B) (Mote and Salathé 2010) was used to produce climate projections (Elsner et al. 2010; Littell et al. 2011). Historical data across the area were reconstructed following methods in Hamlet and Lettenmaier (2005), and changes from historical patterns were modeled using the “delta” method of downscaling, resulting in regionally averaged temperature and precipitation change for 2030-2059 and 2070-2099. Downscaled climate data were input to the Variable Infiltration Capacity (VIC) model (Hamlet and Lettenmaier 2005; Liang et al. 1994), which was used to project snowpack. Historical modeled snowpack depth was fit to most closely match the persistent snow cover data from Copeland et al. (2010), and this fit was then used to identify areas of future habitat for wolverines.

In the Columbia and Upper Missouri River Basins, where most of the Northern Rockies is located, snowpack projection indicated a loss of 35 percent and 24 percent, respectively, for spring snow by the mid 21st century, and 66 percent and 51 percent, respectively, by the end of the century. Central Idaho was projected to lose nearly all snow by the end of the century, whereas northern Montana, the southern Bitterroot Mountains, and the Greater Yellowstone Area retained significant spring snow (McKelvey et al. 2011). The ensemble mean model output was similar to results associated with the Parallel Climate Model (pcm1; a cool extreme; <http://www.cgd.ucar.edu/pcm>), but at the warm extreme, little spring snow was retained at the end of the century. A connectivity model (Schwartz et al. 2009) in conjunction with ensemble climate model projections indicated that all remaining habitat would be genetically isolated by the end of the 21st century (McKelvey et al. 2011).

The threshold between rain and snow causes estimates of snowpack loss to differ greatly between GCMs, because timing of moisture and the temperature when it occurs affect model performance. Cool

models (e.g., Goddard Institute for Space Studies model E; Schmidt et al. 2006) indicate increases in January snowpack at high elevation (e.g., Yellowstone Plateau, Colorado) through the mid-21st century, whereas warmer models (e.g., Model for Interdisciplinary Research on Climate; Watanabe et al. 2011) show large losses in snowpack across all regions (Alder and Hostetler 2014). All models, including the coolest and wettest, indicate a continuing reduction in spring snow, a pattern that has been ongoing since at least the 1950s (Mote et al. 2005).

Brewer's Sparrow (*Spizella breweri*)

Brewer's sparrow appears to be a sagebrush obligate during the nesting period when nest occupancy is positively related to tall, dense stands of sagebrush (Petersen and Best 1985; Reynolds 1981) (fig. 9.6). In areas where other sage obligate species exist (e.g., sage thrasher [*Oreoscoptes montanus*]), these sparrows may compete for nest locations (Reynolds 1981). In many areas, however, Brewer's sparrow is the most abundant bird species (Norvell et al. 2014). Some consider the closely related timberline sparrow (*Spizella breweri taverneri*) to be a species (i.e., *S. taverneri*) or sub-species, but in any case, no genetic mixing occurs between the alpine and sagebrush variants (Klicka et al. 1999).

Reasons for the obligate relationship of Brewer's sparrow with sagebrush are obscure. Although this relationship appears to be robust, especially patterns of nest occupancy (Petersen and Best 1985), evidence for why Brewer's sparrow nests in sagebrush rather than in other brush species is lacking. Therefore, we rely on correlative associations to project climate change effects and cannot speculate as to the flexibility of this species to shift to alternative shrub species should sagebrush become scarce. Within sagebrush communities, Brewer's sparrows do exhibit flexibility in response to nest predation, shifting locations of sequential nests in response to previous predation (Chalfoun and Martin 2010).

Brewer's sparrow populations appear to be reasonably stable range-wide, although they have been in decline in some areas in Colorado (USGS 2013). Although Brewer's sparrow selects for areas with tall, dense sagebrush, sparrow abundance was unaffected by treatments designed to modify sagebrush cover and improve habitat for greater sage-grouse (Norvell et al. 2014). Similarly, a study of the effects of (nonnative) smooth brome (*Bromus inermis*) found that nest success was higher in areas with brome

establishment (Ruehmann et al. 2011). In general, the effects of climate change on Brewer's sparrow will probably depend to a great degree on changes in the distribution, abundance, composition, and structure of sagebrush communities. Increased wildfire will likely reduce the distribution, abundance, and age of sagebrush stands in a warmer climate.

Flammulated Owl (*Otus flammeolus*)

The flammulated owl is a small nocturnal owl, approximately 6 inches long with a 14-inch wingspan. It is migratory but breeds in montane areas across much of western North America, ranging from southern British Columbia to central Mexico (Ridgely et al. 2003). It is a cavity nester, associated with mature forests with large diameter trees. It is also associated with open forests, but does not appear to be specific to any particular tree species. In New Mexico, it is found in pinyon pine (*Pinus edulis*) (McCallum and Gehlbach 1988), ponderosa pine (*P. ponderosa*) (Bull et al. 1990; Linkhart et al. 1998) and Douglas-fir (Powers et al. 1996; Scholer et al. 2014) forest. In the Sierra Nevada, it has been associated with (from low to high elevation) black oak (*Quercus kelloggii*), mixed conifer, Jeffrey pine (*P. jeffreyi*), white fir (*Abies concolor*), and red fir (*A. magnifica*) forest (Stanek et al. 2011).

Flammulated owls are thought to be obligate secondary cavity nesters, although it has been anecdotally observed to nest in the ground (Smucker and Marks 2013). Flammulated owls feed almost exclusively on insects, primarily Lepidoptera, which they gather from trees, on the ground, or in flight (Linkhart et al. 1998). During the nesting period, males are single-trip, central-place foragers, so the energetics of prey selection are important, with distance traveled and energy content of prey differing by forest type. Little information is available on the diet of flammulated owls and their relationships to forest habitat. Interactions with other owl species appear minimal (Hayward and Garton 1988).

The extensive latitudinal range of flammulated owls, lack of specific forest associations, and generalized insect diet indicate that straightforward links to specific climatic regimes are unlikely. If climate change is to affect flammulated owls, then it will most likely be through disturbance processes that remove large diameter trees. Shifts to denser forest structure would be problematic for this species, but there is little evidence that this would occur, because drought and wildfire are projected to increase

throughout the Northern Rockies (Alder and Hostetler 2014). Like other long-lived owl species (Linkhart and Reynolds 2004), flammulated owl populations will be very sensitive to adult survival (Noon and Biles 1990).

Greater Sage-Grouse (*Centrocercus urophasianus*)

Greater sage-grouse is the largest grouse in North America (Mezquida et al. 2006). Considered an obligate with sagebrush (Miller and Eddleman 2001), its distribution is currently about half of its pre-settlement range (Schroeder et al. 2004), and many populations have been steadily declining in recent decades (Braun 1998; Connelly and Braun 1997; Connelly et al. 2004). In some areas, land conversion that eliminated sagebrush appears to have caused the declines (Connelly et al. 2004; Miller and Eddleman 2001). Extirpation of sage-grouse is more likely in areas with high human population densities, land conversion to cropland, severe droughts (Aldridge et al. 2008), sagebrush displacement by conifers, and corvid predation. It is also more likely in areas with <25 percent sagebrush cover proximal to the edge of the historical range.

Declines in sage-grouse have also occurred in areas still dominated by sagebrush (Miller and Eddleman 2001). In addition to reduced sagebrush cover, declines have been attributed to nonnative plants (Connelly et al. 2004; Knick et al. 2003; Wisdom et al. 2002), energy exploration and extraction (Braun et al. 2002; Doherty et al. 2008; Holloran et al. 2005; Lyon and Anderson 2003; Walker et al. 2007a), grazing (Beck and Mitchell 2000; Hayes and Holl 2003), altered fire regimes (Connelly et al. 2000, 2004), and a warmer climate (Neilson et al. 2005). In recent years, West Nile virus has also been implicated (Naugle et al. 2004, 2005; Walker et al. 2007b).

Assessing the effects of climate change is challenging, because so many factors potentially affect sage-grouse population dynamics. Nevertheless, Schrag et al. (2011) produced a detailed climate change assessment for greater sage-grouse that evaluated changes in distribution of sagebrush and transmission of West Nile virus. They first built bioclimatic models for sagebrush distribution, then West Nile spread was modeled based on temperature thresholds. They used six GCMs and one emission scenario (A1B), and GCM output was statistically downscaled to 7.5-mi pixels. Both the envelope model and temperature

thresholds were projected to 2030 based on the downscaled GCM output. Results varied greatly across models, but it was concluded that the cumulative effects of projected climate change on both sagebrush and West Nile virus transmission would reduce suitable sage-grouse habitat in the Northern Rockies and northern Great Plains (Schrage et al. 2011). Since sage-grouse require large areas of mature sagebrush, future increases in wildfire are expected to significantly reduce habitat.

Creutzburg et al. (2015) evaluated the likely trajectory of greater sage grouse habitat in southeastern Oregon. They simulated the effects of climate change, disturbance, and cheatgrass (*Bromus tectorum*) invasion by coupling a linked dynamic global vegetation model, climate envelope model, and state-and-transition simulation model, based on three climate models, chosen to cover a range of possible futures. In the near term, loss of sagebrush from wildfire and cheatgrass invasion leads to habitat deterioration. However, in all three climate projections, native shrub-steppe communities increased circa 2070 leading to habitat improvement. In this simulation, all projected climate futures had better long-range prospects for sage-grouse than was simulated based on current climate.

Harlequin Duck (*Histrionicus histrionicus*)

Harlequin ducks in the intermountain west breed and summer on fast-flowing mountain streams and winter on rocky coastal areas (Robertson and Goudie 2015). In Grand Teton National Park, breeding pairs used streams with dense shrubs along the banks (Wallen 1987). During summer they feed primarily on larval insects on stream bottoms and in winter on a variety of small food items including snails, small crabs, barnacles, and fish roe (Robertson and Goudie 2015). They are relatively rare in Montana, with a concentration in Upper McDonald Creek in Glacier National Park (Reichel 1996). Climate change may alter the timing, duration, and levels of streamflows. In Glacier National Park, harlequin duck reproductive success declined with higher and less predictable streamflows (Hansen 2014).

Mountain Quail (*Oreortyx pictus*)

The mountain quail (*Oreortyx pictus*) is a small ground-dwelling bird that occupies upland forest and woodland habitats in the western United States and northern Mexico (Brennan et al. 1987). In the Pacific Northwest, its range extends into deep canyons such as Hells Canyon of the Snake River (Pope and

Crawford 2004) where their populations have been declining. Population augmentation through translocation is common. Population studies have focused on survival, but connections to climate-related change are minimal. Stephenson et al. (2011) found that climate-related variables were important to survival, with lower survival being linked both to hot, dry conditions and cold winter weather. Seasonal movements to avoid snowpack led to increased rates of movement, which were also important predictors of survival.

Pygmy Nuthatch (*Sitta pygmaea*)

The pygmy nuthatch, a small bird about 4 inches long, is found throughout montane coniferous forests in western North America and as far south as central Mexico (McEllin 1979; Ridgely et al. 2003). It is a cavity nester, often associated with ponderosa pine forests (McEllin 1979) but also found in other forest types such as quaking aspen (*Populus tremuloides*) (Li and Martin 1991). Pygmy nuthatches can exhibit a social structure of cooperative breeding in which “helpers” aid breeding birds by feeding the incubating female, feeding nestlings and fledglings, and defending nesting territory (Sydeman et al. 1988).

Pygmy nuthatches nest in cavities in both live and dead trees (Li and Martin 1991; study site in Arizona), and population responses to disturbance are modest. For example, Hurteau et al. (2008; study site in Arizona) found that population densities across a variety of thinning and fuel treatments remained constant except in thin-and-burn treatments, where densities increased by over 500 percent. Saab et al. (2007; information from interior western United States) found that nuthatches showed a negative response to fire the first year after wildfire, but a neutral response in subsequent years. Due to their apparent neutral response to disturbance, coupled with flexibility in habitat and wide latitudinal range, it is difficult to project whether pygmy nuthatch will respond positively or negatively to climate change. Other than the effects of conversion from forest to non-forest, extirpation of this organism from climate change appears unlikely.

Ruffed Grouse (*Bonasa umbellus*)

Ruffed grouse are characterized by a boreal distribution that includes peninsular extensions into the Rocky Mountains and Appalachian Mountains (USGS 2014). Throughout much of their range, ruffed grouse occupy aspen forest (Kubisiak 1985; Stauffer and Peterson 1985; Svoboda and Gullion 1972), which provides important food sources (Jakubas and Gullion 1991). Although ruffed grouse exist in forests that contain no aspen (e.g., oak-dominated forest) (Haulton et al. 2003), they are mostly limited to aspen habitats in many areas of the West (e.g., Mehls et al. 2014). Since ruffed grouse were identified as a species of concern in the Northern Rockies in the context of aspen-dominated forest, we focus here on the use of aspen by ruffed grouse.

In central Wisconsin, ruffed grouse densities were highest in young (<25 years) aspen stands (Kubisiak 1985). Similarly, ruffed grouse preferred stand structures characteristic of early successional stages in Idaho (Stauffer and Peterson 1985) but also use aspen stands of all ages (Mehls et al. 2014). Thus, optimal grouse habitat consists of aspen forests with stands in a variety of age classes, including a large component of young stands.

Aspen may be sensitive to heat and drought in some locations (Anderegg et al. 2013; Huang and Anderegg 2011). Although higher temperature is expected to cause increased stress in aspen, differences in forest structure and age affect the relationship between aspen mortality and drought (Bell et al. 2014), and mortality can be reduced by controlling stand densities and ages and limiting competition from conifers. If climate change causes decreased extent of aspen in the Northern Rockies, reduced habitat would have detrimental effects on ruffed grouse populations. However, it appears that significant options exist to mitigate these changes through silviculture that favors aspen over conifers and through active manipulation of stand densities and ages.

Columbia Spotted Frog (*Rana luteiventris*)

The Columbia spotted frog (*Rana luteiventris*) breeds in montane ponds throughout western North America (Green et al. 1996, 1997) (fig. 9.7). Funk et al. (2008) built a phylogeny for this species based on samples across western North America. Populations separated into three distinct clades; within the analysis area, all samples were associated with the northern clade and were fairly closely related. The

effects of climate change on Columbia spotted frogs are unclear. In Utah, they were more likely to occur in persistent, shady ponds that maintained constant temperatures (Welch and MacMahon 2005). In Yellowstone National Park, pond desiccation led to sharp declines in frog populations (McMenamina et al. 2008), and throughout their range, populations in large stable water bodies were doing well, whereas those in smaller more ephemeral ponds were subject to rapid declines (Hossack et al. 2013). In Montana, warmer winters were associated with improved reproduction and survival of Columbia spotted frogs (McCaffrey and Maxell 2010). This species does not appear to be sensitive to stand-replacing fires (Hossack and Corn 2007).

Columbia spotted frog populations are stable in areas with stable water supplies, and are capable of rapid population expansion into restored wetlands (Hossack et al. 2013). However, the amphibian chytrid fungus (*Batrachochytrium dendrobatidis*, hereafter referred to as Bd), is prevalent in many populations (Pearl et al. 2009; Russell et al. 2010) and warming waters would, in most systems, favor Bd (see section on western toad below). Although the fungus is common, the population effects of infection are unclear.

Western Toad (*Anaxyrus boreas*)

Western toads (*Anaxyrus boreas*) are montane amphibians broadly distributed across the western United States (Muths et al. 2008); in the southern Rocky Mountains, the subspecies boreal toad (*A. b. boreas*) is recognized. The western toad appears to have suffered widespread declines, particularly at the southern extent of its range (Corn et al. 2005), a phenomenon well documented in Colorado (Carey 1993). This species suffers from the amphibian chytrid fungus, which is often fatal. Laboratory studies of Bd have found that it grows optimally at 63-77 °F, and colonies are killed at 86 °F (Piotrowski et al. 2004). Although Bd can grow in temperatures as cold as 39 °F, warming waters would increase its prevalence.

In a study across Colorado, Wyoming, and Montana, Bd was consistently found in western toad tissues, and was more prevalent in warmer, lower elevation sites (Muths et al. 2008). A warmer climate may allow Bd to spread to higher elevations and become even more widespread, although there is some question about how susceptible the western toad is to the effects of Bd, because increased mortality is not

always associated with high infection rates. Recent studies indicate that the skin of the toad contains bacterial colonies that inhibit Bd (Park et al. 2014).

ASSESSING SUBREGIONAL DIFFERENCES IN VULNERABILITY

When considering how climate change would affect wildlife populations in their subregion, Northern Rockies Adaptation Partners (NRAP) workshop participants tended to think in terms of pathways through which climate could exert an influence (fig. 9.1, black text and arrows). These pathways can interact with each other, and with population characteristics (fig. 9.1, blue text and arrows) to produce an effect on the population of interest (fig. 9.1, red text). However, a given pathway influences multiple species, and multiple pathways influence a given species. Below we summarize the subregional workshop discussions.

Upper temperature thresholds for moose were discussed for the Greater Yellowstone Area subregion (GYA). This was the only species and subregion with a discussion of direct physiological sensitivities to climate. However, it was noted in all subregions that there is a general lack of understanding of direct physiological sensitivities to climate for most wildlife species. However, even when these sensitivities have been measured (e.g., the lower thermoneutral limits for wolverines (e.g., Iversen 1972) it is unclear how this laboratory-derived knowledge can be interpreted in the context of habitat use and demographic performance.

Position within a species' niche can influence population vulnerability. Some species are at the climatological limits of their range in particular subregions. Exposure to climate change in these places has a strong effect on species ability to persist, whereas the same amount of change in the center of its range has less effect. The Western Rockies and Central Rockies subregions are at the junction of maritime and continental climates, and many species are at the edges of their ranges. For example, participants in the Central Rockies workshop discussed how future climate change is expected to increase habitat suitability for the fisher, such that this species may expand its range into the subregion.

Some species had different habitat associations in different subregions. For example, in the GYA, ruffed grouse was linked to aspen habitat but was associated with a broader range of habitats in the

Central Rockies subregion. Therefore, ruffed grouse were seen as more sensitive to climate effects on aspen in the GYA than in the Central Rockies.

The importance of previous habitat loss, potentially caused by recent warming, differed across the subregions. In the Eastern Rockies subregion, extensive lodgepole pine (*Pinus contorta* var. *latifolia*) mortality has been caused by mountain pine beetles (*Dendroctonus ponderosae*), likely caused by warmer winters (Bentz et al. 2010). Cavity nesting birds were thought to be more sensitive to potential future habitat loss, because they have already lost a substantial portion of their habitat. Prior habitat loss was not discussed in the other subregions.

Another pathway for habitat loss, discussed in the Central Rockies workshop, was an increase in invasive species. For example, the flammulated owl feeds on insects that depend on understory plant composition, and that composition could be altered by increased abundance of invasive plants such as cheatgrass.

Negative effects on wildlife populations from an increase in disease occurrence and transmission caused by climate change (e.g., West Nile virus) was discussed in three of the five subregions. Participants also noted there was relatively little known about disease ecology and the future potential for disease to affect wildlife populations.

Connectivity was a primary concern in four of the five subregions. Participants considered different scales of connectivity to be important: the ability for individuals to move through the landscape to meet their daily needs, the ability to complete seasonal migrations, and the ability to track potentially shifting habitat. Numerous indirect influences on each of those scales of connectivity were discussed.

Indirect pathways that increase vulnerability to climate change can also arise when a changing climate influences landscape configurations such that species are then more at risk from other stressors. In the GYA and Central subregions, participants discussed the need to understand how potential shifts in residential development (e.g., into riparian habitats) could affect wildlife. Changing demands for energy sources and the influence of energy development on wildlife habitat were discussed in the Central and Grassland subregions.

Another source of regional variation was the importance of multiple collaboratives focused on conservation issues in the Central subregion. Forest Service participants stated that these collaboratives increased their range of achievable management tactics.

There were differences in the amount of climate change expected (exposure), the response of individuals and populations to that change (sensitivity), and the ability of organisms and organizations to adapt to that change (adaptive capacity) across Northern Rockies subregions. However, participants agreed there is a lack of understanding about mechanisms of climate influence. Identifying and contrasting the importance of *pathways* of climate influence across subregions can suggest potential *mechanisms* of climate influence. Hypotheses can be developed to account for these mechanisms, and management actions can be monitored to test those hypotheses. Based on the results of those tests, decisions can be made to continue with management actions, or develop new actions or hypotheses, creating an adaptive monitoring program (Lindenmayer and Likens 2009). Sensitivities listed in tables 9.2-9.9 provide a starting point for identifying potential hypotheses.

ADAPTING WILDLIFE MANAGEMENT TO THE EFFECTS OF CLIMATE CHANGE

Adaptation to climate change for wildlife resources in NRAP subregions was focused on maintaining adequate habitat and healthy wildlife populations, and increasing knowledge of species needs and climate sensitivities. Workshop participants identified the major habitats in their subregion and then developed adaptation strategies for species they regarded as important and for which they believed viable management options exist. For example, participants in the GYA workshop discussed climate sensitivities of American pika, but decided not to work through adaptation options because they did not see how management efforts could influence pika population viability. Participants tended to address species or habitats that had not been covered in prior workshops, even if some were important in their subregion. Adaptation options are summarized according to major habitats, (tables 9.2 through 9.7) which can then be associated with individual species (table 9.1).

Riparian habitats are important across the Northern Rockies. The primary strategy for improving riparian habitat resilience is maintaining healthy American beaver populations (table 9.2). Beaver

complexes can buffer riparian systems against both low and high streamflows, and provide habitat structure and foraging opportunities for multiple species. Non-riparian wetlands were discussed as important habitats, but no adaptation strategies were developed.

Quaking aspen habitats are common in the four western subregions and occur occasionally in the Grassland subregion. Aspen was identified as important because of its high productivity, role in structural diversity, and habitat for cavity-nesting birds. In the GYA, ruffed grouse were identified as strongly tied to aspen habitats. Reduction in the distribution and abundance of aspen is projected for some locations (especially lower elevation) in a warmer climate (see chapter 6). The most common tactics for promoting aspen resilience were allowing wildfire or using prescribed fire in older aspen stands, protection from grazing, and reducing conifer encroachment in any age stand (table 9.3).

Dry ponderosa pine forests are common in the Central Rockies and Eastern Rockies subregions and provide habitat for cavity nesting birds such as the flamulated owl. These habitats have experienced encroachment by Douglas-fir as a result of fire exclusion, increasing vulnerability of pine to future fires. Tactics for promoting ponderosa pine resilience included reducing competition from Douglas fir through understory burning and cutting, protecting mature stands, and planting ponderosa pine where it has been lost (table 9.4).

The Western Rockies and Central Rockies subregions support older, mesic forests because they experience a maritime climate influence (see chapter 3). These forests, which provide important habitat for fisher, may have younger age classes (caused by increased disturbance; see chapter 8) and different species composition in a warmer climate (see chapter 6). Adaptation strategies included restoring historical structure, conserving current structure, and promoting potential future mesic forest habitats (table 9.5).

Mountain sagebrush-grassland habitat occurs in all regions except the Grassland. In the Western Rockies subregion, mountain sagebrush-grassland habitats are unique in that they have less of a sagebrush component, primarily occur in steep mountain canyons, and support populations of mountain quail; differences in aspect have a strong influence on climate in these canyons. In a warmer climate, these

habitats could lose some of their forb component, making them vulnerable to increased abundance of nonnative species (see chapter 7). Specific tactics for restoring historical habitat and maintaining current habitat included managing fire, controlling nonnative species, and restoring formerly cultivated lands (table 9.6).

Sagebrush habitats are common in the Eastern Rockies, GYA, and Grassland subregions, supporting gallinaceous birds (greater sage-grouse, Brewer's sparrow, greater prairie chicken [*Tympanuchus cupido*], sharp-tailed grouse [*T. phasianellus*) and pygmy rabbits, among other species. Tactics for maintaining adequate sagebrush habitat included managing fire, controlling nonnative species, preventing fragmentation, and restoring degraded habitat (table 9.7). Current focus on conservation of greater sage-grouse within sagebrush habitat in the western United States will benefit from including a climate-smart approach to management.

Developing on-the-ground management tactics requires understanding how climate change will influence species. In all subregions, and independent of habitat association, participants identified the need for better understanding of species requirements and the mechanisms of climate change impacts. In addition, connectivity and the potential for increases in disease were identified as important processes affecting multiple habitats and species in each subregion, although climate sensitivities of diseases are not well understood. Accordingly, several adaptation strategies were suggested to fill knowledge gaps (table 9.8). There is wide agreement on the need to better understand the mechanisms of climate sensitivities relative to the life histories of individual species. Examples of tactics to accomplish this objective include analyzing female Canada lynx home ranges to determine the necessary distribution and size of habitat patches, quantifying and monitoring pygmy rabbit distribution, and understanding sagebrush succession following fire. The influence of low-snow years on wolverine denning success is an example of a mechanistic relationship with climate that needs more data.

Connectivity, although not tied to a particular habitat type, is considered an important conservation strategy for most species in all Northern Rockies subregions, although climate influences on connectivity are uncertain. Several forms of connectivity were identified: daily, seasonal, dispersal, and range shift.

Connectivity can be affected by changes in water supply, habitat loss, habitat shifts, vegetation phenology shifts, human population expansion and redistribution, and snowpack dynamics. Specific tactics for increasing knowledge that would enable the maintenance of connectivity include monitoring connectivity with genetic, tracking, and remote-sensing tools; identifying dispersal habitats; and identifying and removing or mitigating barriers to connectivity (table 9.9).

Disease is also important in most subregions, not tied to a particular habitat, and not well understood. Specific tactics for addressing disease include monitoring the presence of white-nose syndrome (caused by the fungus *Pseudogymnoascus destructans*) in bat hibernacula (currently ongoing through collaboration of U.S. Forest Service, other agencies, and Northern Rocky Mountain Grotto), monitoring disease trends in moose and bighorn sheep, and coordinating with state agencies to monitor West Nile virus.

More specific details on adaptation strategies and tactics for each NRAP subregion are in Appendix 9A.

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DRAFT

Chapter 10: Effects of Climate Change on Recreation

Michael S. Hand and Megan Lawson

INTRODUCTION

Outdoor recreation is an important benefit provided by federal agencies and other public lands in the Northern Rockies. National forests in the Northern Region and Greater Yellowstone Area see an estimated 13.3 million visits per year; Yellowstone, Grand Teton and Glacier National Parks account for an additional 8 million visits per year. National forests and national parks provide recreation opportunities at sites that offer a wide variety of characteristics. Recreation on public lands in the Northern Rockies and Greater Yellowstone Area is inseparable from ecosystems and natural features. Whether skiing, hiking, hunting, or camping, visiting developed sites or the backcountry, or simply driving through a park or forest, natural and ecological conditions in large part determine the overall recreation experience.

Climatic conditions and environmental characteristics that depend on climate are key factors that determine the availability of and demand for different recreation opportunities (Shaw and Loomis 2008). Changing climate conditions may alter the supply of and demand for recreation opportunities, resulting in changes visitation patterns and the benefits derived from recreation in the future. Climate change is projected to increase outdoor recreation participation in general (Bowker et al. 2013). Benefits provided by recreation are expected to increase under climate change scenarios due to increases in summer and warm-weather activities outweighing losses in winter activities (Loomis and Crespi 2004; Mendelsohn and Markowski 2004).

Public lands managers will face a complex task of managing recreation opportunities under changing recreational preferences and ecological conditions. Investments in infrastructure, the provision and maintenance of facilities, and decisions about recreation development are important inputs that determine recreational setting and the type of recreational opportunities available to visitors. These inputs can be classified using the Recreation Opportunity Spectrum (ROS), which has been used for decades by public

lands managers for planning and allocation of recreation opportunities (Clark and Stankey 1979). Recreation visitation behavior and values can be mapped to the ROS, providing managers with information about the tradeoffs associated with different types of investments and development (Rosenthal and Walsh 1986; Swanson and Loomis 1996). A changing climate may alter types of recreation experiences desired and the opportunities that can be provided by public lands.

Although broad trends in recreation participation under climate change scenarios may be borne out at the regional scale, little is known about how recreation in the Northern Rockies will change. This chapter describes the broad categories of recreation activities that may be sensitive to climate-related changes in the Northern Rockies, and assesses the likely effects of projected climate changes on recreation participation.

RELATIONSHIPS BETWEEN CLIMATE CHANGE AND RECREATION

The supply of and demand for recreation opportunities are sensitive to climate through (1) a direct effect of changes in temperature and precipitation on the availability and quality of recreation sites, and (2) an indirect effect of climate on the characteristics and ecological condition of recreation sites (Loomis and Crespi 2004; Mendelsohn and Markowski 2004; Shaw and Loomis 2008) (fig. 10.1).

Direct effects of changes in temperature and precipitation patterns are likely to affect most outdoor recreation activities in some way. Direct effects are important for skiing and other snow-based winter activities that depend on seasonal temperatures and the amount, timing, and phase of precipitation (Englin and Moeltner 2004; Irland et al. 2001; Stratus Consulting 2009). Warm-weather activities are also sensitive to direct effects of climate change. Increases in minimum temperatures have been associated with increased national park visits in Canada, particularly during non-peak “shoulder” seasons (Scott et al. 2007). The number of projected warm-weather days is positively associated with expected visitation for a national park in the United States, although visitation is expected to be lower under extreme-heat scenarios (Bowker et al. 2012; Richardson and Loomis 2004). Temperature and precipitation may also directly affect the comfort and enjoyment that participants derive from engaging in an activity on a given day (Mendelsohn and Markowski 2004).

Indirect climate effects tend to be important for recreation activities that depend on additional ecosystem inputs, such as wildlife, vegetation, and surface water. Cold-water fishing is expected to decline in the future due to climate effects on temperature and streamflow that threaten cold-water fish species habitat (Jones et al. 2013) (see chapter 5). Surface water area and streamflows are important for water-based recreation (e.g., boating), and forested area affects several outdoor activities (e.g., camping and hiking) (Loomis and Crespi 2004). Recreation visits to sites with highly valued natural characteristics, such as glaciers or popular wildlife species (see chapters 4 and 9) or scenic and aesthetic qualities, may be reduced in some future climate scenarios if the quality of those characteristics is threatened (Scott et al. 2007). The indirect climate effect on disturbances, and wildfire in particular (see chapter 8), may also play a role in recreation behavior, although the effect may be diverse and vary over time (Englin et al. 2001).

IDENTIFYING CLIMATE-SENSITIVE OUTDOOR RECREATION ACTIVITIES

People participate in a wide variety of outdoor recreation activities in the Northern Rockies. The National Visitor Use Monitoring (NVUM) survey, conducted by the Forest Service, U.S. Department of Agriculture (USFS) to monitor recreation visitation and activity on national forests, identifies 27 different recreation activities in which visitors may participate. These include a wide variety of activities and ways that people enjoy and use national forests and other public lands.

NVUM surveys roughly one-quarter of forest units in each region every year, and each unit is re-surveyed every five years. For this analysis, we used the latest survey data available for each forest. Sample years for the units included in this analysis are as follows: 2008 – Bridger-Teton, Custer, Helena; 2009 – Gallatin, Idaho Panhandle, Shoshone; 2010 – Beaverhead-Deerlodge, Caribou-Targhee, Flathead; 2011 – Clearwater, Lolo, Nez Perce; 2012 – Bitterroot, Kootenai, Lewis and Clark. Visitors are sampled using a stratified random sampling technique designed for assessing use on national forests. Sampling sites are stratified according to type of recreation site and times of day and week. Visitors are asked about different categories of trip-related spending incurred within 50 miles of the site where they are

interviewed. Interviewees are selected at random, and interviewers conduct as many surveys as possible (English et al. 2001).

All outdoor recreation activities depend to some degree, directly or indirectly, on climate conditions or environmental conditions that are determined by climate. For example, skiing opportunities depend on the availability of areas with snow-covered terrain, which is determined by patterns of temperature and precipitation as snow. As climate change affects seasonal trends in temperature and precipitation, the availability of certain skiing sites may change in the future.

To assess how recreation patterns may change in the Northern Rockies, categories of outdoor recreation activities are identified that may be sensitive to climate changes (fig. 10.2). For the purposes of the recreation assessment, a recreation activity is sensitive to climate change if changes in climate or environmental conditions that depend on climate would be an important factor affecting the demand for or supply of that recreation activity within the study area. However, there is no hard rule on which activities satisfy this requirement, and other types of activities not explicitly covered in this chapter may be affected by climate changes.

The 27 recreation activities identified in the NVUM survey are grouped into five climate-sensitive categories of activities, plus an “other” category of activities that are less sensitive to climate changes. Each category includes activities that would likely be affected by changes to climate and environmental conditions in similar ways. Table 10.1 lists the activities that comprise the climate-sensitive categories and summarizes their sensitivity to climate changes. The categories were developed to capture the most common types of recreation that people engage in on public lands in the Northern Rockies that would be affected by climate changes. In total, 17 activities were identified as sensitive to climate changes.

These 17 activities account for the primary recreation activities for 83 percent of visits to national forests in the study area. Activities in the “Other” category were judged to be less sensitive to climate changes and tend to be less frequently listed as a primary recreation activity in the study area. Although participation in many of these activities is likely linked to climate in some way, other factors are likely to be more important determinants of participation (for example, maintenance of infrastructure for visiting

interpretive sites). Warm-weather activities are the most popular, and include hiking/walking, viewing natural features, developed and primitive camping, bicycling, backpacking, horseback riding, picnicking, and other non-motorized uses. These were the main activity for 35.9 percent of national forest visitors (4.8 million visitors per year) (table 10.1). Of these, hiking/walking was the most popular, and is the primary reason for a visit for 16.9 percent of visitors (2.2 million people). Snow-based winter activities are also a large draw, and include downhill skiing, snowmobiling, and cross-country skiing. They were the primary activity for 25 percent of all visitors (3.3 million people). Wildlife-related activities, including hunting, fishing, and viewing wildlife, were the primary activity for 18.5 percent of visitors (2.5 million people). Of these, hunting was the most popular with 11 percent of visitors (1.5 million people). Gathering forest products such as berries and mushrooms was the primary activity for 2.4 percent of visitors (300,000 people). Motorized and non-motorized water activities (other than fishing) comprised 0.7 percent of visitors (97,000 people) (table 10.1).

Non-local visitors – those who report a home zipcode that is more than 30 miles from the forest boundary – spend \$601 million (in 2014 dollars) per year within 50 miles of the forest boundaries. The non-local definition is applied based on reported home zipcode; some non-local respondents may have second homes near the forest boundary that would qualify as local had they reported the zipcode associated with the second home (Stynes and White 2005). Table 10.2 summarizes expenditures by visitors to national forests in the Northern Rockies and Greater Yellowstone Area. We focus on spending by non-local visitors because these individuals spend money in local communities that would not have occurred otherwise. Lodging expenses comprise nearly 31 percent of total expenditures, followed by restaurant (18 percent), gas and oil (17 percent), and groceries (12 percent). The remaining expenditure categories of other transportation, activities, admissions and fees, and souvenirs comprise 21 percent of all spending.

CLIMATE CHANGE VULNERABILITY ASSESSMENT

The overall effect of climate change on recreation activity is likely to be an increase in participation and increase in the benefits derived from recreation. This is due primarily to warmer temperatures and

increased season length appropriate for warm-weather activities, outweighing decreased winter activities that depend on snow and consistently cold temperatures (Mendelsohn and Markowski 2004). However, these general findings mask potential variation in the effects of climate on recreation between types of activities and geographic locations (boxes 10.1, 10.2).

This section provides an assessment of the likely effects of climate on major climate-sensitive recreation activities in the region. Two sources of information are used to develop assessments for each category of recreation activity. First, reviews of existing studies of climate change effects on recreation and studies of how recreation behavior responds to climate-sensitive ecological characteristics are used to draw inferences about likely changes for each activity category. Second, projections of ecological changes specific to the Northern Rockies, as detailed in the other chapters contained in this volume, are paired with the recreation literature to link expected responses of recreation behavior to specific expected climate effects.

Current Conditions and Existing Stressors

Public lands in the Northern Rockies provide an abundance and variety of recreational options, offering opportunities for people of all interests and abilities. Opportunities range from high-use developed sites near urban areas and popular tourist destinations, to vast areas of remote wilderness and seldom-used sites off the beaten path. The facilities and services available also exhibit a wide range of conditions and characteristics. Some sites are developed with modern amenities and staffed by agency employees or volunteers. Others may exhibit scant evidence of human influence other than a trailhead.

Current conditions reflect wide variation in intra- and inter-annual (within and between years) weather and ecological conditions. Temperature, precipitation, water flows and levels, wildlife distributions, vegetative conditions, and wildfire activity may exhibit wide ranges of variation. Recreationists are likely already accustomed to some degree to making decisions with a significant degree of uncertainty about conditions at the time of participation.

Several existing challenges and stressors affect recreation in the Northern Rockies. Increased population, particularly in proximity to public lands, can strain visitor services and facilities due to

increased use; projected population increases in the future may exacerbate these effects (Bowker et al. 2012). Increased use due to population growth can also reduce site quality because of congestion at the most popular sites (Yen and Adamowicz 1994). Changes in land use may alter access to public lands, fragmentation of landscapes and habitat, and disturbance regimes that relate to recreation activities.

The physical condition of recreation sites and natural resources are constantly changing due to human and natural forces. Recreation sites and physical assets need maintenance, and deferred or neglected maintenance may increase congestion at other sites that are less affected or increase hazards for visitors who continue to use degraded sites. Unmanaged recreation can create hazards and contribute to natural resource degradation (U.S. Department of Agriculture 2010). This stressor may interact with others, such as population growth and maintenance needs, if degraded site quality or congestion encourages users to engage in recreation that is not supported or appropriate at certain sites or at certain times of the year. Natural hazards and disturbances may create challenges for the provision of recreation opportunities. For example, wildfire affects recreation demand (due to site quality and characteristics), but may also damage physical assets or exacerbate other natural hazards such as erosion (see chapters 4 and 12).

Current Management

Recreation is an important component of public land management in the Northern Rockies. For lands managed by the USFS, sustainable recreation serves as a guiding principle for planning and management purposes (U.S. Department of Agriculture 2010, 2012b). Recreation is included among other major multiple uses of national forests, such as timber products and livestock grazing. Sustainable recreation seeks to “sustain and expand benefits to America that quality recreation opportunities provide,” (U.S. Department of Agriculture 2010). At the heart of this principle is the desire to manage recreational resources to increasingly connect people with natural resources and cultural heritage, and adapt to changing social needs and environmental conditions. Recreation managers aim to provide diverse recreation opportunities that span the recreation opportunity spectrum, from modern and developed to primitive and undeveloped (Clark and Stankey 1979)

Warm-Weather Activities

Warm-weather activities as a category are the most common recreation activities in national forests and national parks in the Northern Rockies. Slightly more than one-third of all visits involve one of these activities as the primary activity of visitors. Warm-weather recreation is sensitive to the length of appropriate season, depending on the availability of snow- and ice-free trails and sites, and the timing and number of days with temperatures within minimum and maximum comfortable range (which may vary with activity type and site). The number of warm-weather days has been shown to be a significant predictor of expected visitation behavior (Richardson and Loomis 2004), and studies of national park visitation show that minimum temperature is a strong predictor of monthly visitation patterns (Scott et al. 2007).

Participants are also sensitive to site quality and characteristics, such as the presence and abundance of wildflowers, conditions of trails, and vegetation and cover (e.g., cover for shade, wildfire effects). The condition of unique features that are sensitive to climate changes, such as glaciers, may affect the desirability of certain sites (Scott et al. 2007). Forested area is positively associated with warm-weather activities, such as camping, backpacking, hiking, and picnicking (Loomis and Crespi 2004), and is sensitive to future climate changes (U.S. Department of Agriculture 2012a).

Wildfire can also affect participation in warm-weather activities through changes to site quality and characteristics (fig. 10.3). Wildfires have a diverse and temporally nonlinear effect on recreation (Englin et al. 2001). The presence of recent wildfires has differential effects on the value of hiking trips (positive) and mountain biking (negative), although recent wildfire activity tends to decrease the number of visits (Hesseln et al. 2003, 2004; Loomis et al. 2001). The severity of fire may also matter; high-severity fires have been associated with decreased recreation visitation, whereas low-intensity fires are associated with slight increases in visitation (Starbuck et al. 2006). Recent fires are associated with initial losses of benefits for camping (Rausch et al. 2010) and backcountry recreation activities (Englin et al. 1996) that are attenuated over time. Visitation in Yellowstone National Park tends to be lower following months with high wildfire activity, although there is no discernable effect of previous-year fires (Duffield et al. 2013).

Overall demand for warm-weather activities is expected to increase due to a direct effect of climate change on season length. Temperatures are expected to increase 5 to 12 °F across the region by the year 2100 (see chapter 3), which is expected to result in earlier availability of snow- and ice-free sites and an increase in the number of warm-weather days in spring and autumn. For example, higher minimum temperatures are associated with increased number of hiking days (Bowker et al. 2012). More extreme summer temperatures can dampen participation during the hottest weeks of the year, and extreme-heat scenarios for climate change are expected to reduce visitation (Richardson and Loomis 2004), and higher maximum summer temperatures are associated with reduced participation in warm-weather activities (Bowker et al. 2012). The temperature that is considered “extreme” may vary between individuals and chosen activities. In Bowker et al. (2012), a linear effect of maximum summer temperature in the visitor’s home county was included in participation models. Extreme heat may shift demand to cooler weeks at the beginning or end of the warm-weather season, or shift demand to alternative sites that are less exposed to extreme temperatures (e.g., at higher elevations).

Indirect effects of climate change on forested area may have a negative effect on warm-weather recreation if site availability and quality (e.g., scenic and aesthetic attributes) are compromised. However, the effect on warm-weather recreation in the Northern Rockies and its various subregions will depend on local effects of climate on forest resources.

Potential increases in the likelihood of extreme wildfire activity may reduce demand for warm-weather activities in certain years because of degraded site desirability, impaired air quality from smoke, and limited site access due to fire management activities. The Northern Rockies are expected to experience increased area burned by wildfire, average fire size, and fire severity (see chapter 8), which tend to have a negative impact on recreation visitation and benefits derived from recreation.

Adaptive capacity among recreationists is high because of the large number of potential alternative sites, ability to alter the timing of visits, and ability to alter capital investments (e.g., appropriate gear). However, benefits derived from recreation may decrease even if substitute activities or sites are available (Loomis and Crespi 2004). For example, some alternative sites may involve higher costs of access

(because of remoteness or difficulty of terrain) or congestion costs if demand is concentrated among fewer desirable sites. In addition, limits on ability to alter seasonality of visits may exist because of the timing of scheduled academic breaks. Although the ability of recreationists to substitute sites and activities is well established, there remains little understanding of how people substitute across time periods or between large geographic regions (e.g., choosing a site in the Northern Rockies instead of the Southwest) (Shaw and Loomis 2008). In some cases, unique features or strong individual attachment to particular places may limit substitutability.

Projected climate scenarios are expected to result in a moderate increase warm-weather recreation activity and benefits derived from these activities. Longer warm-weather seasons will likely increase the number of days when warm-weather activities are viable and increase the number of sites available during shoulder seasons. The effects of a longer season may be offset somewhat by negative effects on warm-weather activities during extreme heat and increased wildfire activity. The likelihood of effects on warm-weather recreation is high; the primary driver of climate-related changes to warm-weather recreation is through direct effects of temperature changes on the demand for warm-weather recreation. Climate scenarios outlined in chapter 3 vary in their projection of the magnitude of warming, but overall project warmer temperatures. Indirect effects on recreation, primarily through wildfire effects, may be harder to project with certainty and precision (particularly at a fine-grained geospatial scale).

Cold-Weather Activities

The Northern Rockies boast a large number of winter recreation sites that in total exhibit a wide range of site characteristics and attract local, national, and international visitors. Several sites support developed downhill skiing and snowboarding operated by special permit on lands administered by the USFS. Sites for cross-country skiing, snowshoeing, and snowmobiling tend to be maintained directly by the Forest Service, although national parks also provide access for these activities.

Snow-based recreation is highly sensitive to variations in temperature and the amount and timing of precipitation as snow. Seasonal patterns of temperature and snowfall determine the likelihood of a given site having a viable season and the length of viable seasons (Scott et al. 2008). Lower temperatures and

the presence of new snow are associated with increased demand for skiing and snowboarding (Englin and Moeltner 2004). Indirect effects of climate, such as changes in scenery and unique features (e.g., glaciers) may also affect winter recreation, although these effects are expected to be small relative to the effect of changes in amount and timing of snowfall.

Climate change is expected to have a generally negative effect on snow-based winter activities, although a wide range of effects at local scales are possible because of variations across the region in site location and elevation. Warmer projected winter temperatures for the region are expected to reduce the proportion of precipitation as snow, even if the total amount of precipitation does not deviate significantly from historical norms (see chapter 4). The rain-snow transition zone (i.e., where precipitation is more likely to be snow rather than rain for a given time of year) is expected to move to higher elevations, particularly in late autumn and early spring (Klos et al. 2014). This effect places lower elevation sites at risk of shorter or non-existent winter recreation seasons (fig. 10.4). However, the highest elevation areas in the region remain snow-dominated for a longer portion of the season in future climate scenarios.

Studies of the ski industry in North America uniformly project negative effects of climate change (Scott and McBoyle 2007). Overall warming is expected to reduce expected season length and the likelihood of reliable winter recreation seasons. Climatological projections for the Northern Rockies (see chapter 3) are consistent with studies of ski area vulnerability to climate change in other regions, where projected effects of climate change on skiing, snowboarding, and other snow-based recreation activities is negative (Dawson et al. 2009; Scott et al. 2008; Stratus Consulting 2009).

Snow-based recreationists have moderate capacity to adapt to changing conditions given the relatively large number of winter recreation sites in the region. For undeveloped or minimally developed site activities (for example, cross-country skiing, backcountry skiing, snowmobiling, snowshoeing), recreationists may seek higher elevation sites with higher likelihoods of viable seasons. Although developed downhill skiing sites are fixed improvements, potential adaptations include snowmaking, higher elevation development, and new run development (Scott and McBoyle 2007). However, the ability of winter tourism sector businesses to adapt likely varies considerably. Warmer temperatures and

increased precipitation as rain may increase availability of water for snowmaking in the near term during winter, but warmer temperatures may also reduce the number of days per season when snowmaking is viable.

Changes in Northern Rockies sites relative to other regions may also be important. If other regions experience relatively large effects of climate on snow-based recreation, recreationists may view Northern Rockies sites as a substitute for sites in other regions (e.g., the Southwest), although inter-regional substitution patterns for recreation activities are poorly understood (Shaw and Loomis 2008). Further, increased inter-regional substitution combined with shorter seasons may result in concentrated demand at fewer sites on fewer days, creating potential congestion effects.

The magnitude of climate effects on snow-based winter activities is expected to be high. Warmer temperatures are likely to shorten winter recreation seasons and reduce the likelihood of viable seasons at lower elevation sites. Developed sites may have limited ability to adapt to these changes unless additional adjacent area is available and feasible for expanded development. In comparison to other regions, Northern Rockies winter recreation sites may see fewer effects from climate change; inter-regional substitution could mitigate losses in some years if participants from other regions are more likely to visit Northern Rockies sites. The likelihood of effects is expected to be high for snow-based recreation, although variation across sites is possible because of differences in location and elevation. Climate models generally project warming temperatures and a higher-elevation rain-snow transition zone, which would leave additional sites exposed to the risk of shorter seasons.

Wildlife Activities

Wildlife recreation activities involve terrestrial or aquatic animals as a primary component of the recreation experience. Wildlife recreation can involve consumptive (e.g., hunting) or non-consumptive (e.g., wildlife viewing, birding, catch-and-release fishing) activities. Distinct from other types of recreation, wildlife activities depend on the distribution, abundance, and population health of desired target species. These factors influence activity “catch rates,” that is, the likelihood of catching or seeing an individual of the target species. Sites with higher catch rates can reduce the costs associated with a

wildlife activity (e.g., time and effort tracking targets) and enhance overall enjoyment of a recreation day for that activity (e.g., greater number of views of highly valued species).

Participation in wildlife activities is sensitive primarily to climate-related changes that affect expected catch rates. Catch rates are important determinants of site selection and trip frequency for hunting (Loomis 1995, Miller and Hay 1981), substitution among hunting sites (Yen and Adamowicz 1994), participation and site selection for fishing (Morey et al. 2002), and participation in non-consumptive wildlife recreation (Hay and McConnell 1979). Changes to habitat, food sources, or streamflows and water temperature (for aquatic species) may alter wildlife abundance and distribution, which in turn influences expected catch rates and wildlife recreation behavior.

Wildlife activities may also be sensitive to other direct and indirect effects of climate change. The availability of highly valued targets affects benefits derived from wildlife activities (e.g., cutthroat trout [*Oncorhynchus clarkii*] for cold-water anglers) (Pitts et al. 2012), as does species diversity for hunting (Milon and Clemmons 1991) and non-consumptive activities (Hay and McConnell 1979). Temperature and precipitation are related to general trends in participation for multiple wildlife activities (Bowker et al. 2012; Mendelsohn and Markowski 2004), although the precise relationship may be specific to the activity or species. Some activities such as big game hunting may be enhanced by cold temperatures and snowfall at particular times to aid in field dressing, packing out harvested animals, and tracking. Other activities may be sensitive to direct climate effects similar to warm-weather activities, in which moderate temperatures and snow- and ice-free sites are desirable.

Warming temperatures projected for the Northern Rockies are expected to increase participation in terrestrial wildlife activities because of an increased number of days that are desirable for outdoor recreation. In general, warmer temperatures are associated with greater participation in and number of days spent hunting, bird watching, and viewing wildlife (Bowker et al. 2012). However, hunting that occurs during discrete seasons (e.g., elk and deer hunts managed by state seasons) may depend on weather conditions during a short period of time. The desirability of hunting during established seasons

may decline as warmer weather persists later into the fall and early winter and the likelihood of snow cover decreases, reducing harvest rates.

The effects of changes in habitat for target species are likely to be ambiguous because of complex relationships among species dynamics, vegetation, climate, and disturbances (primarily wildfire and invasive species) (see chapter 9), and are likely heterogeneous across species and habitat types. Overall vegetative productivity may decrease in the future, although this is likely to have a neutral effect on game species populations, depending on the size, composition, and spatial heterogeneity of forage opportunities in the future (see chapter 9). Similarly, the effects of disturbances on target species harvest rates are ambiguous because it is unknown exactly how habitat composition will change in the future.

Higher temperatures will likely decrease populations of native cold-water fish species as climate refugia retreat to higher elevations (see chapter 5). This change favors increased populations of fish species that can tolerate warmer temperatures. However, it is unclear whether shifting populations of species (e.g., substituting rainbow trout [*O. mykiss*] for cutthroat trout) will affect catch rates because relative abundance of fish may not necessarily change.

Total precipitation is not projected to change under future climate scenarios (see chapter 3), but increased interannual variability in precipitation, the possibility of extreme drought, and reduced snowpack could result in higher peakflows in winter and lower low flows in summer, creating stress for fish populations during different portions of their life histories. The largest patches of habitat for cold-water species will be at higher risk to shrink and fragment. Increased incidence and severity of wildfire may increase the likelihood of secondary erosion events that degrade waterways and game species habitat. These effects could degrade the quality of individual sites in a given year or decrease the desirability of angling as a recreation activity relative to other activities.

The magnitude of climate effects on activities involving terrestrial wildlife is expected to be low overall for terrestrial wildlife activities and moderate for fishing. Ambiguous effects of vegetative change on terrestrial wildlife populations and distribution suggest that conditions may improve in some areas and decline in others. Overall warming tends to increase participation, but may create timing conflicts for

activities with defined regulated seasons (e.g., big game hunting) unless the timing of seasons is changed. Anglers may experience moderate negative effects of climate change on benefits derived from fishing. Opportunities for cold-water species fishing are likely to be reduced as cold-water refugia retreat to higher elevations or are eliminated in some areas. Cold-water species tend to be the highest value targets, indicating that this habitat change will decrease benefits enjoyed by anglers. Warm-water tolerant species may increasingly provide targets for anglers, mitigating reduced benefits from fewer cold-water species. Warmer temperatures and longer seasons encourage additional participation, but indirect effects of climate on streamflows and reservoir levels could reduce opportunities in certain years. The likelihood of climate-related effects on wildlife activities is expected to be moderate for both terrestrial and aquatic wildlife activities. Uncertainties exist about the magnitude and direction of indirect effects of climate on terrestrial habitat and the degree to which changes in available target species affects participation.

Gathering Forest Products

Forest product gathering for recreational purposes accounts for a relatively small portion of primary visit activities in the Northern Rockies, although it is relatively more common as a secondary activity. Forest products are also important for cultural and spiritual uses, which is discussed in chapter 11. A small but avid population of enthusiasts for certain types of products supports a small but steady demand for gathering as a recreational activity. Small-scale commercial gathering likely competes with recreationists for popular and high-value products such as huckleberries (*Vaccinium* spp.), although resource constraints may not be binding at current participation levels.

Forest product gathering is sensitive primarily to climatic and vegetative conditions that support the distribution and abundance of target species. Participation in forest product gathering is also akin to warm-weather recreation activities, depending on moderate temperatures and the accessibility of sites where products are typically found. Vegetative change due to warming temperatures and increased inter-annual variation in precipitation may alter the geographic distribution and productivity of target species (see chapters 6 and 7). Increased incidence and severity of wildland fires may eliminate sources of forest products in some locations (e.g., for berries), but in some cases fires may encourage short- or medium-

term productivity for other products (e.g., mushrooms). Long-term changes in vegetation that reduces forest cover may reduce viability of forest product gathering in areas that have a high probability of vegetative transition to less productive vegetation types.

Recreationists engaged in forest product gathering may have the ability to select different gathering sites as the distribution and abundance of target species changes, although these sites may increase the costs of gathering. Those who engage in gathering as a secondary or tertiary activity may choose alternate activities to complement primary activities. Commercial products serve as an imperfect substitute for some forest products such as Christmas trees.

The magnitude of climate effects on forest product gathering is expected to be low. This activity is among the less-common primary recreation activities in the region, although it may be more often engaged in as a secondary or tertiary activity. Longer warm-weather seasons may expand opportunities for gathering in some locations, although these seasonal changes may not correspond with greater availability of target species. The likelihood of effects is expected to be moderate, although significant uncertainty exists regarding direct and indirect effects on forest product gathering. Vegetative changes caused by climate changes and disturbances may alter abundance and distribution of target species, although the magnitude and direction of these effects is unclear.

Water-Based Activities, Not Including Fishing

Separate from angling, water-based activities comprise a small portion of primary recreation activity participation on federal lands. Upper reaches of streams and rivers are generally not desirable for boating and floating. Lakes and reservoirs provide opportunities for both motorized and non-motorized boating and swimming, although boating may commonly be paired with fishing. Existing stressors include the occurrence of drought conditions that reduce water levels and site desirability in some years, and disturbances that can alter water quality (for example, erosion events following wildland fires).

Even if total precipitation does not change significantly under future climate scenarios (see chapter 3), the availability of suitable sites for non-angling, water-based recreation is sensitive to reductions in water levels caused by warming temperatures, increased variability in precipitation (including the possibility of

severe droughts), and decreased precipitation as snow. Reduced water levels may also have an indirect effect on the aesthetic qualities of some water-based recreation sites (e.g., exposure of “bathtub rings” at reservoirs with low water levels). Reductions in surface-water area are associated with decreases in participation in boating and swimming activities (Bowker et al. 2012; Loomis and Crespi 2004; Mendelsohn and Markowski 2004), and streamflow is positively associated with number of days spent rafting, canoeing, and kayaking (Loomis and Crespi 2004). Demand for water-based recreation is also sensitive to temperature. Warmer temperatures are generally associated with higher participation in water-based activities (Loomis and Crespi 2004; Mendelsohn and Markowski 2004), although extreme heat may dampen participation for some activities (Bowker et al. 2012).

Increasing temperatures, reduced storage of water as snowpack, and increased variability of precipitation are expected to increase the likelihood of reduced water levels and greater variation in water levels in lakes and reservoirs on federal lands (see chapter 4), which is associated with reduced site quality and suitability for certain activities (fig. 10.5). Increased demand for surface water by downstream users may exacerbate water levels in drought years. Warmer temperatures are expected to increase the demand for water-based recreation as the viable season lengthens. Extreme heat encourages some people to seek water-based activities as a climate refuge, although extreme heat also discourages participation in outdoor recreation in general (Bowker et al. 2012). Overall, projections of water-based activities in response to climate change tend to be small compared to broad population and economic shifts (Bowker et al. 2012).

Climate change is expected to have a moderate effect on water-based activities. Increasing temperatures and longer warm-weather seasons are likely to increase demand, although the incidence of extreme temperatures may dampen this effect in certain years. A higher likelihood of lower streamflows and reservoir levels and potential reductions to site aesthetic quality may also offset increased demand to some extent. Climate change effects are expected to occur with moderate likelihood. Climate model projections tend to agree on a range of warming temperatures and longer seasons, although changes in precipitation are uncertain. Changes in the timing of snowmelt may increase the likelihood of negative

effects to water-based activities (through lower summer flows and reservoir levels) that offset increases due to warmer temperatures.

Summary

Several recreation activities are considered highly sensitive to changes to climate and ecosystem characteristics. However, recreation in the Northern Rockies is diverse, and the effects of climate are likely to vary widely between different categories of activities and across geographic areas within the region. Overall, participation in climate-sensitive recreation activities is expected to increase in the region, primarily because longer warm-weather seasons will make more recreation sites available for longer periods of time.

Increased participation in warm-weather activities is likely to be offset somewhat by decreased snow-based winter activities. Receding snow-dominated areas and shorter seasons in the future are likely to reduce the opportunities (in terms of available days and sites) for winter recreation.

Beyond these general conclusions, the details of changes to recreation patterns in response to climate changes are complex. Recreation demand is governed by several economic decisions with multiple interacting dependencies on climate. For example, decisions whether to engage in winter recreation, activity type (e.g., downhill or cross-country skiing), location, frequency of participation, and duration of stay per trip depend somewhat on climate and ecological characteristics. On the supply side, site availability and quality depend on climate, but the effect may differ greatly from one location to another. Thus, climate effects on recreation depend on spatial and temporal relationships between sites, climate and ecological characteristics, and human decisions.

Uncertainty derives from unknown effects of climate on site quality and characteristics that are important for some recreation decisions (e.g., indirect effects of climate on vegetation, wildlife habitat, and species abundance and distribution). The precise effect of climate on target species or other quality characteristics may be difficult to predict or diverse across the region, yet these characteristics play a large role in recreation decisions for some activities. Another source of uncertainty is how people will adapt to changes when making recreation decisions. Inter-regional and inter-temporal substitution

behavior is not yet well understood (Shaw and Loomis 2008). This may be important for the Northern Rockies if in the future some sites exhibit relatively little effect from climate change compared with sites in other regions. For example, winter recreation sites in the Northern Rockies may experience shorter or lower-quality seasons in the future but see increased demand if the quality of sites in other regions becomes relatively worse in the future.

Substitution is likely to be an important adaptation mechanism for recreationists. Many recreation activities that are popular in the region may have several alternate sites, or timing of visits can be altered to respond to climate changes. However, substitution may represent a loss in benefits derived from recreation even if it appears that participation changes little (Loomis and Crespi 2004); the new substitute site may be slightly more costly to access, or slightly lower quality than the preferred visit prior to climate change. This represents a decrease in benefits to the person engaging in recreation.

ADAPTING RECREATION TO THE EFFECTS OF CLIMATE CHANGE

Adapting recreation management to climate change in the Northern Rockies will be critical to ensure that recreation opportunities exist in the future.

Adaptation by Recreation Participants

Increasing temperatures with changing climate will have significant negative effects on snow-based recreation, because the snow-based recreation season will likely decrease in length, and the quality of the snow during the season may also decrease (be wetter).

Water-based recreationists may adapt to climate change by choosing different sites that are less susceptible to changes in water levels (e.g., by seeking higher-elevation natural lakes) and changing the type of water-based recreation activity they engage in (e.g., from motorized boating on reservoirs to non-motorized boating on natural lakes).

Hunters may need to adapt by altering the timing and location of hunts. However, state rules on hunting season dates impose a constraint on this behavior unless states change hunting seasons based on expected climate changes. Hunters may also target different species if the abundance or distribution of preferred species changes in the future.

Like hunters, wildlife viewers may change the timing and location of viewing experiences and target different species. Since viewing is not typically governed by state-regulated seasons, wildlife viewers may have more flexibility to shift timing to coincide with appropriate weather conditions or species movements into accessible areas. However, adaptation options may be more limited if the abundance or distribution of highly valued species significantly decreases the likelihood of viewing, and limited high-quality substitute species are available.

Anglers may adapt by choosing different species to target (for example, shifting from cold-water to warm-water tolerant species) and choosing sites that are relatively less affected by climate change (for example, higher-elevation secondary-stem reaches of streams). The former is less costly than the latter, although some anglers may place a high value on certain target species and have a lower willingness to target warm-water species that may thrive in place of cold-water species.

Adaptation by Public Land Managers

Managers may need to reconsider how infrastructure investments and the provision and maintenance of facilities align with changing ecological conditions and demands for recreation settings. The Recreation Opportunity Spectrum (ROS) can be used to match changing conditions and preferences to the allocation of available recreation opportunities. Adaptation by managers may take the form of responding to changing recreation patterns, but also helping to shape the settings and experiences that are available to recreation users on public lands in the future.

For winter recreation, a general adaptation strategy may be to transition recreation management to address shorter winter recreation seasons and changing recreation use patterns (table 10.4). Specifically, opportunities may exist to expand facilities where concentrated use increases, and options for snow-based recreation can be diversified to include more snow-making, additional ski lifts, and higher-elevation runs. However, in some cases adaptations related to the supply and quality of winter recreation opportunities could result in tradeoffs with other activities, e.g. undeveloped warm-weather access to higher elevation sites or winter vs. summer streamflow effects of snowmaking.

With higher temperatures and earlier snowmelt, warm-weather activity seasons will likely lengthen. Recreation managers have options for responding to changing patterns in warm-season recreation demand in order to provide sustainable recreation opportunities. A first step will be to conduct assessments to understand the changing patterns of use (table 10.4). Then, adjustments can be made to increase the capacity of recreation sites that are showing increased use (e.g., campgrounds can be enlarged, and more fences, signs, and gates can be installed where necessary). The potential for congestion and resource damages due to increases in use for some sites may, in part, drive such adjustments. However, there may be some limitations to increasing the capacity of some recreations sites (e.g., limitations for developed recreation sites under the U.S. Fish and Wildlife Service Northern Continental Divide Ecosystem Grizzly Bear Conservation Strategy; USFWS 2013). The timing of some actions such as trail closures, food storage orders, and special use permits may also need to be adjusted within the context of providing sustainable recreation. For example, the season for whitewater rafting permits may need to be modified to adjust to shifts in timing of peakflows (table 10.4).

Increased frequency of disturbances, such as fire and flooding, will likely cause increased damage to infrastructure associated with multiple types of recreation activities. Recreation sites can be managed to decrease risks to public safety and infrastructure (table 10.4). Assessments can be used to determine which sites and infrastructure are most at risk from disturbance, and strategic investments can be made in those facilities that will likely be viable in the future and accommodate changing use patterns.

More specific details on adaptation strategies and tactics for each Northern Rockies Adaptation Partners (NRAP) subregion are in Appendix 10A.

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Chapter 11: Effects of Climate Change on Ecosystem Services

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INTRODUCTION

In this chapter, we focus on the ecosystem services provided to people who visit, live adjacent to, or otherwise benefit from natural resources on public lands. Communities in the region are highly dependent on ecosystem services from water, soil, and air that will be impacted by climate change in a variety of ways. Every community in the region will feel these impacts. We link biophysical effects associated with climate change, as described in previous chapters, with potential effects on the well-being of humans and communities, and identify strategies for adapting to climate-induced changes and prioritizing among competing interests. First, we introduce ecosystem services and how to describe and measure them. Second, we describe how people and communities currently use and benefit from public lands in the Northern Rockies, as well as existing stressors that may affect the ability of communities to adapt to a changing climate. Third, we discuss climate change effects on specific ecosystem services. Finally, we identify adaptation strategies that can help reduce negative effects on ecosystem services, and discuss the ability of public agencies and communities to respond to climate change (adaptive capacity).

Ecosystem services are benefits to people from the natural environment. These include timber for wood products, clean drinking water for downstream users, recreation opportunities, and spiritual and cultural connection to the environment and natural resources. As stated by Collins and Larry (2007), “An ecosystem services perspective encourages natural resource managers to extend the classification of multiple uses to include a broader array of services or values.”

Ecosystem services are commonly placed in the following four categories (Millenium Ecosystem Assessment 2005):

- Provisioning services—products obtained from ecosystems, including timber, fresh water, wild foods, and wild game.

• Regulating services—benefits from the regulation of ecosystem processes, including the purification of water and air, carbon sequestration, and climate regulation.

• Cultural services—nonmaterial benefits from ecosystems, including spiritual and religious values, recreation, aesthetic values, and traditional knowledge systems.

• Supporting services—long-term processes that underlie the production of all other ecosystem services, including soil formation, photosynthesis, water cycling, and nutrient cycling.

Categorizing ecosystem services in this manner helps identify the ways in which natural resources and processes benefit humans, and how changes in the natural environment will affect these benefits. Climate change will affect the quality and quantity of ecosystem services provided by public lands. Establishing the link among natural processes, ecosystem services, and human benefits helps clarify the communities or types of people most vulnerable to a changing climate.

Although ecosystem service categories help organize our understanding of the relationship between natural resources and human benefits, this simple approach may obscure complex relationships between natural and human systems. Three important caveats are relevant to discussions of ecosystem services and anticipated climate change effects. First, these categories are not exclusive, and many natural resources fall under multiple categories, depending on the context. For example, the consumption of fresh water can be considered a provisioning service, the process of purifying water a regulating service, the use of fresh water for recreation a cultural service, and the role of fresh water in the life cycle of organisms a supporting service. Second, these categories are interdependent, such that individual services would not exist without the functioning of a broad set of ecosystem services.

To address the challenges of ecosystem services falling into multiple, interdependent categories, Boyd and Krupnick (2009) use ecological production theory to describe ecosystems as “collections of commodities linked by a range of biophysical processes, delineating biophysical inputs and outputs, ecological endpoints, and processes that transform them from one to another.” In this framework, fresh water is an output from a filtration process, an ecological endpoint in itself as drinking water, and then an input for the endpoints of recreation and plant and animal populations. This framework facilitates

assessment of ecosystem service vulnerability by allowing analysts to identify ecosystem service endpoints and connect changes in inputs and processes caused by climate change to changes in ecosystem service provision.

Ecological production theory and the subsequent distinction between natural resources that are endpoints, inputs, and outputs, provides a helpful framework for measuring ecosystem services. Later in this chapter, we identify the most significant ecosystem services in the Northern Rockies and describe how they are expected to change.

ECOSYSTEM SERVICES AND PUBLIC LANDS

The evaluation of ecosystem services in this assessment is consistent with federal agency management requirements. Under the Forest Planning Rule of 2012, the Forest Service, U.S. Department of Agriculture is required to formally address ecosystem services in land management plans for national forests (Federal Register 2012). The National Park Service does not have specific mandates concerning ecosystem services, but they have incorporated ecosystem service considerations into management planning and made ecosystem services a key part of their 2014 Call to Action (NPS 2014). The Bureau of Land Management has also identified nonmarket environment values, synonymous with ecosystem services, as an increasingly important consideration for land management (Winthrop n.d.).

Although all natural systems provide some type of ecosystem services, managing for ecosystem services on public lands involves specific considerations that make it especially important to identify the endpoints, how they are used, and which ones are most susceptible to disruption from a changing climate. There are many beneficiaries from ecosystem services provided by public lands, including neighboring communities, non-local visitors, and people who may never visit or directly use the lands but gain satisfaction from knowing a resource exists and will be there for future generations (Kline and Mazzotta 2012). This is particularly true for iconic landscapes and rivers in the study area such as Yellowstone National Park, Glacier National Park, the Salmon River, and the Selway River (Borrie et al. 2002; Chouinard and Yoder 2004; Mansfield et al. 2008; O’Laughlin 2005; Pederson et al. 2006).

Mandates to manage for multiple use of natural resources can create situations in which some ecosystem services conflict with others. For example, managing lands for non-motorized recreation may conflict with managing for motorized recreation, timber, and mining, but it could complement management for biodiversity and some wildlife species. Ecosystem services from public lands are critical for neighboring communities, particularly in rural areas of the Northern Rockies where people rely on these lands for fuel, food, water, recreation, and cultural connection. Decreased quantity and quality of ecosystem services produced by public lands will affect human systems that rely on them, requiring neighboring communities to seek alternative means of providing these services or to change local economies and lifeways.

Management decisions for public lands can substantially affect ecosystem service flows, with cascading effects on numerous users. This chapter is intended to highlight potential climate change effects on ecosystem service flows, for which management decisions can help users mitigate or adapt to these effects and illustrate the tradeoffs in the decision-making process. Since the concept of ecosystem services is somewhat new, data on ecosystem services are scarce. In this chapter, we use quantitative data when possible, but we often rely on qualitative descriptions or proxy measures. Demographic and economic factors often have a significant effect on ecosystem services, providing an important context for understanding the effects of climate change.

ECOSYSTEM SERVICES IN THE NORTHERN ROCKIES

The U.S. Forest Service Northern Region Resource Information Management Board identified ecosystem services that are used by a large number of people and can also be affected by management decisions. Using the standard categories discussed above, we focused on provisioning, regulating, and cultural ecosystem services. Supporting services were not included because, although important, they are largely indirect services that are inputs to other biophysical processes, and are unlikely to be directly affected by management decisions. Note, while we have grouped ecosystem services into provisioning, regulating, and cultural services below, these categories are not definitive; many could have been

included in an alternative category. Although the Forest Service designated these ecosystem services, many of these services are also important for other public agencies in the Northern Rockies:

Provisioning ecosystem services

- Abundant fresh water for human (e.g., municipal and agricultural water supplies) and environmental (e.g., maintaining streamflows) uses

- Building materials and wood products

- Mining materials

- Forage for livestock

- Fuel from firewood and biofuels

- High air quality and scenic views

- Genetic diversity and biodiversity

Regulating ecosystem services

- Water filtration and maintenance of water quality associated with drinking, recreation, and aesthetics

- Protection from wildfire and floods

- Protection from erosion

- Carbon sequestration

Cultural ecosystem services

- Recreation opportunities

- Aesthetic values from scenery

- Protection and use of cultural sites

- Native American treaty rights

The amount of detail below for these ecosystem services varies as a function of how much information is available and can be interpreted in the context of climate change. Many of the ecosystem services are also discussed in other chapters of this assessment, including recreation (chapter 10), genetic

diversity and biodiversity (chapter 6), and protection from wildfire and floods (chapter 9). Most of the others are covered to some extent in this chapter. Ecosystem services are combined in a single section if all of them are likely to be affected by the same changes in natural resource conditions.

SOCIAL VULNERABILITY AND ADAPTIVE CAPACITY

Communities that have the social structure and resources to adapt to one environmental impact generally have the capacity to adapt to others. A growing literature on social vulnerability seeks to identify which institutions, resources, and characteristics make communities more or less resilient to environmental hazards. The sections below address the first part of social vulnerability – exposure to negative changes related to specific ecosystem services and possible adaptation strategies. The capacity to adapt to those changes often depends on factors that transcend specific resources, and are so addressed more broadly here.

The most widely used measure of social vulnerability is the Social Vulnerability Index (SoVI), managed and updated by the Hazards and Vulnerability Research Institute at the University of South Carolina (Cutter et al. 2003). The SoVI is based on 11 underlying factors identified to affect social vulnerability: personal wealth, age, density of the built environment, single-sector economic dependence, housing stock and tenancy, race, ethnicity, occupation, and infrastructure dependence. For each county in the U.S., scores based on these 11 factors are summed to form a composite vulnerability score. To highlight counties with the most “extreme” scores, composite scores are then converted to standard deviations and mapped (fig. 11.1).

Figure 11.1 shows that most counties in the region fall in the high to medium vulnerability range. A large factor in the region’s vulnerability is its rural character. Among the region’s counties, the average percentage of county populations living in rural areas is 75.3 percent, compared to a national average of 19.3 percent (all demographic data in this section is based on the 2012 Census American Community Survey). Rural counties tend to be reliant on a single industry, have older populations, and have fewer social resources (hospitals, for example) than urban areas. Loss of youth is also a primary concern among ranching communities, where the younger generation is often reluctant to take over the ranching business

and more likely to move outside the region. The oldest mean average age in the region is found in Prairie County, Montana, where the mean age is 56. The average median age among the counties is 43.4, and the low is 22 in Madison County, Idaho. Figure 11.2f shows the proportion of each county over the age of 65. An aging population and decline in youth in rural counties worries many because of the potential loss of a traditional culture in many Western communities.

The median household income of Region 1 counties is \$45,235, which is considerably lower than the national average of \$53,046. The high-income counties tend to be in the eastern part of the region, with ties to the oil and gas industry, and areas with high concentrations of recreation-based industries. Income is lowest in the counties dependent on grazing and timber.

Figures 11.2a and 11.2b show relatively widespread unemployment and poverty in the region. Theodossiou (1998) found employment is more important than income in predicting life satisfaction. The region on average had an average unemployment rate in 2012 of 5.4 percent, which was lower than the national average of 9.3. Spatially, unemployment follows median incomes closely, with counties in the east having low unemployment and counties in the west having high unemployment. A few counties have very high unemployment, particularly in the timber-dependent counties where jobs are concentrated among a few large employers.

The service industry typically pays low wages, maintains part time positions, and does not pay benefits like retirement and health insurance. Employment fluctuates with overall economic conditions. For these reasons, workers in the service industry can be vulnerable to economic fluctuations. The mean percent employed in the region's service industry is 17.8. Some counties have more than 30 percent of their labor force employed in the service industry.

Many of the factors that make individuals more vulnerable are compounded among migrants and minorities. They tend to have fewer economic resources, lack political power and sometimes struggle with communication (Aguirre 1998; Blaikie et al. 1994; Fothergill and Peek 2004; Morrow 1999; Phillips 1993; Phillips and Ephraim 1992). Such factors make minorities less likely to participate in disaster planning, be familiar with support services, and have basic resources like a vehicle for use during an

evacuation or to transport the injured and sick to hospitals (fig. 11.2c). On average, the region has very few foreign born residents, 2.7 percent compared to a national average of 12.9 percent. A few counties, however, have large concentrations of migrant agricultural workers (fig. 11.2d). Clark County, Idaho, though it only had 982 people in the 2010 Census, was home to over 350 immigrants. Minorities are also concentrated among a few counties. Between 39 and 56 percent of the populations in the Idaho counties in the region are minorities, compared to a regional average of only 15.9 percent. In comparison, many counties in eastern Montana and North Dakota have less than 5 percent minorities. The predominant minority group in the region is Native American, located in counties with more than 56 percent of their population from minorities.

Some of the regional trends in vulnerability and demographics are tied to traditional uses of the land and major industries in the counties. Table 11.1 shows mean SoVI scores by industry. Grazing communities, because they tend to be older, poorer, and more rural, score significantly higher on the SoVI than communities without grazing. Communities dependent on timber, oil and gas, and recreation have significant score significantly lower on the SoVI than other counties. Counties in the national forest economic impact zones of Region 1 have higher SoVI scores, though the difference is not significant (table 11.1).

Table 11.2 shows the number of counties significantly below or above the regional mean SoVI, by industry. Each row shows data for counties that are in the top half of counties sorted by share of employment in that industry. For example, the “Grazing” row shows results for counties for which grazing represents a larger share of total employment than half the other counties in the region. Among grazing counties, 54 counties have unemployment rates significantly below the regional average of 5.4 percent and 18 counties have unemployment rates significantly above the regional average (based on 95 percent confidence intervals). Grazing counties tend to have the lowest median incomes, the oldest populations, and the highest percentage of people living in rural settings. Timber counties tend to have the highest unemployment rates and the highest percentages of foreign-born residents and minorities. Counties with a lot of recreation-based employment are among the least vulnerable, though they do have

a lot of service industry employment. Counties with oil and gas tend to have lower unemployment rates and higher wages than most places in the U.S., much less the region.

ECOSYSTEM SERVICE: WATER QUANTITY

Water use can be broadly classified as consumptive or non-consumptive. Water allocated to a consumptive use is not available for other uses, whereas water allocated to a non-consumptive use is available for other uses. Most economic uses of water have components of both consumptive and non-consumptive uses. For example, a portion of water applied to croplands is taken up by plants and does not return to the waterways; this portion represents consumptive use of water by the crop. The portion of water applied to cropland that returns to the waterways via runoff is the non-consumptive portion. Major consumptive uses of water in the Northern Rockies include domestic and municipal water supply, industrial use of water, and water for oil and gas development (drilling and hydraulic fracturing). Non-consumptive uses of water in the region include recreational uses (e.g., boating, maintaining fish habitat) and hydroelectric power production. Most water in the Northern Rockies is already appropriated, and many uses are tied to junior water rights. Junior water rights can be exercised only during high-flow years, so they are unreliable from season to season or year to year. Any new uses of water require a transfer of water rights, increased water supply through reservoir storage, or mining of ground water.

A recent draft of the Montana State Water Plan (Montana DNRC 2014) details water use in Montana (tables 11.3, 11.4) and is representative of most of the Northern Rockies. Hydroelectric power generation (hydropower) accounts for 86 percent of total water demand in Montana, although hydropower is considered a non-consumptive use because it does not affect in-stream flow or total water available downstream. However, reservoirs needed for hydropower experience high rates of water loss to evaporation. Fort Peck Reservoir, in the Lower Missouri River Basin, annually loses 611,400 acre-feet of water to evaporation.

The largest consumptive use of water in Montana is irrigated agriculture, which accounts for 96 percent of all water diversions and 67 percent of all consumptive use (accounting for return flows). In the Yellowstone River basin, irrigation accounts for 83 percent of consumptive use.

Due to the downstream location of fish and wildlife habitat, preserving in-stream water for habitat often requires explicit water rights. Montana Fish, Wildlife, and Parks maintains 3.6 million acre-feet of in-stream flow rights downstream of Fort Peck and below the Milk River confluence with the Missouri River. They maintain 5.5 million acre-feet of in-stream flow rights for the Yellowstone River at Sidney. Although population is increasing in the Western Rockies and Greater Yellowstone Area subregions, water demand for urban uses has not increased significantly; even in the most populated regions, consumptive use by households is below 4 percent.

The share of any particular water use does not imply anything about relative values of water among uses. The marginal value of water in agriculture is routinely an order of magnitude lower than the marginal value of water for municipal uses, particularly in areas of recent population growth. Prices for municipal uses are \$290 to \$3,145 per acre-foot, whereas prices for leased agricultural water diverted for in-stream conservation are \$42 to \$3,614 per acre-foot (Montana DNRC 2014). In general, prices increase for more senior water rights and when few other options for obtaining water exist in the area. Current rates paid by agricultural users of water from Bureau of Reclamation and Montana Department of Natural Resources and Conservation facilities are \$2.32 to \$7.50 per acre-foot per year, or a capitalized value of \$76 to \$244 per acre-foot. Accounting for delivery and operating costs, the capitalized costs of agricultural water range from \$189 to \$615 per acre-foot.

Effects of Climate Change

A warming climate is expected to cause a transition in the form of precipitation from snow to rain (see chapter 3), which will affect the timing of water availability (see chapter 4). Warmer temperatures will make drought more frequent, despite small increases in precipitation shown in some climate models, increasing overall competition for water. This will amplify many of the effects of population growth and demographic changes already occurring. Agricultural and municipal users will experience major impacts, making it more difficult to allocate in-stream flows for recreation and wildlife.

Agriculture

Timing of snowmelt is a chief concern in the Columbia and Missouri Basin headwaters (see chapter 4). Earlier runoff may be out of sync with many of the water rights currently held by agriculture, even as warmer months extend the growing season. Future water quantities in North Dakota and the eastern plains of Montana are likely to be more variable.

North Dakota has already seen an increase in regional temperatures that has brought a mixture of impacts to agriculture, the largest industry in the state. Wheat production alone generates \$4.5 billion annually in economic activity (North Dakota Wheat Commission 2007). Warmer temperatures and higher commodity prices have pushed wheat and corn production into areas of the state where either they were not previously grown or where shorter-season varieties dominated.

Higher temperatures increase plant demand for water, contributing to droughts even though the Grassland subregion is expected to see a slight increase in precipitation (see chapter 3). Drier soils and more intense precipitation events may increase flood frequency, leading to increased dependence on tile drainage. In 2002, drought cost North Dakota \$223 million, and heavy rains in 2005 ruined over 1 million acres of cropland and prevented another 1 million from being planted. These heavy rains caused \$425 million in damage to North Dakota crops, and the state's livestock industry lost \$32 million, largely from the increased price of feed which was in short supply (Karetinkov et al. 2008). More droughts and intense temperatures may also make plants more susceptible to insect pests (Rosenzweig et al. 2000).

Domestic and Municipal Uses

If the frequency of drought and heavy rain events increases, they will stress municipal water supply systems and built infrastructure. Decreased permeability of soils associated with drought conditions will also lead to more flash floods, endangering lives and affecting water supply systems and infrastructure. In regions with clay soils, increased frequency of drought is already causing sidewalks, driveways, and streets to crack, and while the cost of fixing one sidewalk one time is relatively small, these persistent costs add up and have been shown to cause large financial burdens on communities.

Warmer months and growing populations will increase demand for both air conditioning and lawn watering. There will be a slight decrease in demand for heat, but net household demand for electricity is

expected to rise. Therefore, demands for water for power generation and other municipal uses are expected to increase.

Recreation and Wildlife

The effects of climate change on skiing, boating, and fishing are summarized in chapter 10, and the effects of wildfire are described in chapter 8. Beyond effects mentioned in those chapters, it may become harder to preserve in-stream flows even though demographic changes will increase demand for such preservation. Particularly vulnerable habitats include small streams in the mountains and highly valued fisheries throughout the Northern Rockies.

Climate models suggest a drier climate will shift some of the most productive waterfowl breeding grounds of the northern prairie wetlands and pothole region (which produces 50 to 80 percent of North America's ducks) to the wetter eastern and northern fringes of the Northern Rockies, an area where many wetlands have been drained. Unless these wetlands are restored, bird populations will be significantly affected (Johnson et al. 2005). Some estimates show that the north-central duck population in the United States could be reduced by 50 percent (Sorenson et al. 1998).

Adaptive Capacity

As noted above, adaptive capacity refers to institutional capability to modify management, decision-making, and policy to ensure sustainable production of ecosystem services. Objectively assessing the region's capacity to respond to changes in ecosystem services is difficult, with little guidance in general from science and no guidance specific to the region. This section, therefore, mostly focuses on adaptation strategies.

Transfer of water rights from one use to another is legally possible within the Northern Rockies but realistically constrained by the ability to transport water. Transfers between agricultural and municipal uses, for example, can only occur between users in the same watershed. Since municipal values of water are usually higher than those of agriculture, these transfers are likely to occur should the need be dire enough.

Reuse of effluent and other conservation methods will be important tools for adaptation. Ground water pumping is also available as a short-term solution, but is not sustainable in the long run. These methods are expensive and will be cost prohibitive for most rural communities in the Northern Rockies. New municipal demands are more likely to be met by purchasing or leasing reliable senior water rights (Montana DNRC 2014). Water rights are still available in some water basins, but these new appropriations are junior in priority and not likely to be reliable enough for municipal uses.

A drier climate in the central and western prairie pothole habitats of the Grassland subregion will diminish the benefits of preserving waterfowl habitat in that area and increase the importance of restoring wetlands along the wetter fringes (Johnson et al. 2005).

Risk Assessment

Compared to more arid regions of the western United States, changes in water yield in the northern Rockies are expected to be modest, although they may be disproportionately large for local residents who experience them (Foti et al. 2012). Changes in timing of runoff will be significant. Climate and hydrological models consistently project changes in temperature and timing of runoff, making the likelihood of these effects high.

ECOSYSTEM SERVICE: WATER QUALITY, AQUATIC HABITATS, AND FISH FOR FOOD

Compared to many areas of the United States, the Northern Rockies have excellent water quality. The headwater streams of the region generally provide safe, clean drinking water to downstream communities (fig. 11.3) and provide habitat for some of the country's premier recreational and commercial fisheries (see chapter 10). Fresh water is important to the cultural practices of area tribes, including ability to exercise their indigenous fishing rights. Nonetheless, many of the region's streams and lakes are already threatened or impaired according to U.S. Environmental Protection Agency standards (tables 11.5, 11.6, 11.7). In all Northern Rockies states, agriculture is the primary source of impairment in rivers and streams, caused by grazing in riparian and shoreline zones and by fertilizer sediment in runoff. In Montana, grazing leads to loss of streamside vegetation and increased sedimentation. Idaho sees similar disturbances, but with increased water temperatures as the primary reason for impairment. In North

Dakota, animal feeding operations add to riparian grazing, causing unsafe levels of fecal coliform and habitat alterations.

Major causes of impairment for lakes, reservoirs, and ponds differ between states. Runoff from roads and bridges are a problem in Idaho, leading to high levels of phosphorous and mercury. In Montana, abandoned mines can cause accumulation of mercury and lead. In North Dakota, grazing and animal feeding operations can produce levels of fecal coliform that can contaminate water bodies.

For municipal water supplies, disturbances such as wildfires and mudslides are a major concern (see chapter 8) (fig. 11.4). Due to the generally high water quality in the region, water treatment plants are able to operate with lower capital investments. When there are sudden increases in sediment or other pollutants, such as often occurs after a wildfire, treatment plants need to shut down or incur high costs to treat the water and remove sediment from reservoirs.

Some Northern Rockies residents worry about the effects of increased oil and gas extraction activities on watershed health. Groundwater contamination in northeastern Montana near the Fort Peck Indian Reservation has been linked to development of the East Poplar oil field (Thamke and Smith 2014). Groundwater is the only source of drinking water in the area, and contamination has affected drinking water quality. Oil spills in the Yellowstone River (2011, 2015), a pipeline leak near Tioga, North Dakota (2014), and train derailments in Lac Megantic, Canada (2013) and near Lynchburg, Virginia (2014) highlight the dangers to watersheds surrounding oil and gas fields, even if the activity that caused contamination does not occur in the watershed.

Effects of Climate Change

Climate change will impact water quality in ways that affect fishing, water-based recreation, and drinking water. Climate change will amplify the effects of development on water quality already occurring in the region. Increased number and severity of wildfires will deposit more sediment in streams, lakes, and reservoirs. Increased air temperature and loss of vegetation along stream banks will raise the temperature of streams, and altered vegetation may affect water filtration and flow rate. Lower water

quality may affect municipal water supplies, water-based recreation, and ecosystem services tied to the health of fish and wildlife and associated aquatic systems.

Warming air temperature due to climate change and loss of streamside vegetation due to development, grazing, and agriculture in the riparian zone will cause water temperatures to increase. Since most aquatic organisms are ectothermic, temperature is a significant abiotic factor influencing physiology, bioenergetics, behavior, and biogeography (Rahel 2002; Sweeney et al. 1992). Some native fish species, such as bull trout (*Salvelinus confluentus*), are extremely sensitive to warm water, whereas some nonnative species can tolerate higher temperatures (see chapter 5). Fish habitats at lower elevations are likely to experience the biggest and soonest temperature increases, making them the most vulnerable to shifts in species composition and distribution. The response of microbial and aquatic invertebrate communities to a warming climate and altered hydrologic patterns is poorly understood. Native fish species with high ecological plasticity will be able to withstand some environmental change by altering life history timing or distribution patterns, but the magnitude and rate of change will overwhelm species with narrow ecological niches or limited ability to withstand competition from nonnatives. In the Northern Rockies, this includes bull trout and cutthroat trout (*Oncorhynchus clarkii*).

Effects of climate change on fish are summarized in chapter 5, and effects on recreational fishing are summarized in chapter 10. Additional effects are likely to occur to culturally important fisheries. For example, the Nez Perce tribe maintains fishing rights within the boundaries of their reservation and traditional fishing grounds, which include the mainstem of the Columbia River. Hydropower and stream modification have already significantly affected salmon and steelhead (*O. mykiss*) fisheries (Smith et al. 2002; Wagner et al. 2004; Williams et al. 2001). Climate change is expected to amplify these impacts, leading to decreased fish abundance and increased emphasis on conservation programs.

Threats to municipal watersheds from wildfire and insects are expected to increase considerably (see chapter 8). Climate models project higher precipitation for the region and more frequent occurrence of storm events (see chapter 3). These changes will potentially increase sedimentation in rivers and

reservoirs, increase water treatment costs, and require expensive dredging in reservoirs to maintain water storage.

Warming has already led to expansion of agriculture in some areas of the western United States, including the Northern Rockies. Higher precipitation could lead to increased dependence on tile drainage and increased levels of pollutants in waterways. Increased occurrence of drought would have the exact opposite effect. Expansion of agriculture would generally cause reduced water quality, but the net effects of both more flooding and more drought are uncertain (Warziniack 2014).

Many of the effects on water quality will be magnified if water quantity also falls substantially. Lower flows have been linked to increases in water temperature, eutrophication, and increases in nutrients and metals. Lower flows imply less water to dissipate solar radiation and dilute pollutants already in the water (Allan and Castillo 2007; Murdoch et al. 2000; Poole and Berman 2001; van Vliet et al. 2011). Low flows also increase the likelihood of eutrophication in nutrient-rich bodies of water (Conley et al. 2009; Schindler et al. 2008; Vollenweider 1968).

Adaptive Capacity

Restoration of streams, wetlands, and riparian areas may help stabilize temperatures in some locations, but in the long term, investments in water treatment infrastructure will be needed if sediment increases substantially or if large disturbances become more frequent. Enhancing fish populations through hatcheries is already occurring, and such human intervention may become more important in the face of climate change. Other adaptation strategies for aquatic species and water-based recreation are described in chapters 5 and 10.

Risk Assessment

The effects of increased fire frequency on municipal water supplies will be large, and are likely to be amplified by an increasing population reliant on surface water. Altered timing of precipitation and frequency of flooding may affect erosion rates (Sham et al. 2013). Given current knowledge gaps regarding species response to climate change, it is difficult to provide a quantitative risk assessment. For example, 20-90 percent of currently suitable habitat for native trout species could disappear in the

Northern Rockies by 2100 (Isaak 2012). This would be an example of a high magnitude effect for ecosystem services and aquatic species.

The likelihood of effects on municipal water supplies is high, and is already occurring in some regions of the western United States. Sedimentation from severe wildfires in areas where fire has been excluded for many decades may cause more impacts than climate change. Nonetheless, climate change is expected to exacerbate these effects. Given the high levels of diversity and variability in how aquatic habitats will respond to a changing climate, it is difficult to quantify the likelihood of effects for these ecosystem services. Low-elevation habitats are expected to be affected the most and soonest, resulting in a high likelihood for a shift in ecosystem services in aquatic systems. High-elevation aquatic environments may be buffered by the influence of altitude on temperature, resulting in a lower likelihood of effects, at least in the near term.

ECOSYSTEM SERVICE: BUILDING MATERIALS AND WOODS PRODUCTS

Timber used for wood products is a provisioning ecosystem service. Since much of the timber is exported from the region, the most important aspect of timber is its ability to provide jobs, particularly in rural communities. The timber industry also helps maintain a labor force capable of doing forest restoration work.

A timber processing area for the U.S. Forest Service Northern Region is defined by counties with processing facilities that receive timber from counties containing non-reserve timberland in the region (primarily located in Idaho north of the Salmon River and in Montana) (McIver et al. 2013). Timber processing spans 12 Idaho counties, 26 Montana counties, and four Washington counties (fig. 11.5). Over 95 percent of timber harvested from regional forests is processed by mills in northern Idaho and Montana. In 2011, Idaho and Montana contained 160 timber processing facilities including saw mills (73), house log/log home facilities (42), manufacturers of log furniture (18), post and small pole producers (18), cedar products producers (4), plywood and veneer plants (4), and a utility pole producer. Over 97 percent of timber is processed in sawmills, and 91 percent of timber processed is from trees with diameters greater

than 10 inches. The percent of timber processed in sawmills is up from 80 percent reported in Keegan et al. (2005).

Timber and forest products are dominant economic forces in the Northern Rockies, with forest products (as defined by U.S. Department of Labor, Bureau of Labor Statistics) comprising 23 percent of direct manufacturing employment in Montana (McIver et al. 2013) (table 11.8). Historically, much of the timber harvested in the area has come from national forests, although that share has decreased greatly. In 1979, 46 percent of timber harvested in Idaho came from national forests, declining to only 7 percent by 2006 (Brandt et al. 2012). Table 11.8 shows the sold volume for the Northern Rockies for the past two decades. Timber removal has varied over time in response to changing market and policy conditions, but the past decade has been particularly difficult for the timber industry.

Timber harvests have decreased since the late 1980's on national forests throughout the nation due to changing economic conditions, environmental policies, and litigation against public agencies. The easily accessible larger tree stock has mostly been cut, increasing timber costs and decreasing profits. Increased housing starts spurred a slight recovery in 2003-2005, but the recession that followed led to the worst wood products markets since the Great Depression (Keegan et al. 2012). Between 2005 and 2009, employment in the wood products industry declined 29 and 24 percent in Idaho and Montana, respectively. Most of these losses were in the forestry and logging industries, for which employment declined 33 and 37 percent in Idaho and Montana, respectively (Bureau of Economic Analysis data, from Keegan et al. 2012).

Mills in the region are the major employer for some small communities, making the effects particularly pronounced in a few places. At the height of the downturn in 2008, initial unemployment claims in the woods products industry were over 3,400 in 39 mass layoffs. Across the West, there were 30 percent fewer mills operating in 2009-2010 than in 2004-2005, a 27 percent decrease in timber-processing capacity (Keegan et al. 2012).

Timber jobs have generally been declining in the Northern Rockies, whereas non-timber jobs have generally been increasing (fig. 11.6). These data include jobs in growing and harvesting, sawmills and

paper mills, and wood products manufacturing. In 1998, there were 17,076 jobs in the timber industry, but in 2012, there were only 9,531 jobs, a 44.2 percent decrease. At the same time, non-timber employment increased from 287,163 to 350,929 jobs, a 22.2 percent increase. Since the absolute number of timber jobs has declined while the number of non-timber jobs has increased, the proportion of employment in timber has decreased substantially, from 5.6 percent in 1998 to 2.6 percent in 2012.

However, regional trends in timber employment differ within the Northern Rockies (table 11.9). The Western Rockies subregion, which includes the Idaho Panhandle, Kootenai, and Nez Perce-Clearwater National Forests, has the highest proportion of employment in the timber industry, accounting for 5.2 percent of private employment in 2012. Benewah County, Idaho has 31.8 percent of private employment in timber, the highest in the subregion. Employment in the timber industry has decreased most in the Western Rockies subregion, with 7 of 15 counties (Asotin, WA; Bonner, ID; Clearwater, ID; Kootenai, ID; Lincoln, MT; Pend Oreille, WA; and Sanders, MT) losing over half of their timber-related jobs between 1998 and 2012. Only one county in the subregion (Idaho County, ID) increased employment in the timber industry (18 percent). Some counties in the Central Rockies and Eastern Rockies subregions have increased employment, but these are counties with a low proportion of jobs in the timber sector, so a small number of new jobs have a disproportionate effect.

Effects of Climate Change

Although temperature and precipitation may affect vegetation in the Northern Rockies, the direct effect of climate on timber production is expected to be small. More important to the timber industry are the economic and policy changes that affect demand for forest products and timber quotas for national forests. The primary effects of climate change on timber will occur through the effects of temperature on disturbance and to a lesser extent on growth and productivity (see chapters 7 and 8).

The primary sensitivities of timber resources associated with climate change are wildfire, insects, and disease. Forest growth is expected to be lower in areas that experience higher temperature and decreased precipitation (Ryan et al. 2008) (see chapter 7). In addition, warmer winters and associated freezing and thawing may increase forest road erosion and landslides, making winter harvest more difficult and

expensive, and potentially reducing the timber supply (Karl et al. 2009). Reduced snowpack may promote insect or disease outbreaks, although harvests could increase in the short term through salvage of dead and dying trees. Climate change will result in larger, more frequent fires and a longer fire season. Increased fires may increase demand for fuel treatments, either through timber harvests or through mechanical and manual thinning that uses the timber labor force and infrastructure. Although this may affect the availability of harvestable wood products, the overall effect on timber-related jobs would be relatively small.

Forest Products (Commercial Use)

The provision of commercial timber from national forests could be affected by altered temperature and precipitation. Effects on the distribution and abundance of vegetation are expected to vary widely by species and location (see chapter 6). Although overall wood production is projected to increase, the proportion of saw timber (combining both softwoods and hardwoods) is somewhat larger with climate change in all scenarios, species, and regions. This shift in product mix reflects the effects of accelerated growth on rotation age, which is lengthened in the long term for all regions and species. With longer rotations come larger volumes of saw timber relative to pulpwood (Irland et al. 2001).

Although direct effects of elevated temperature on tree growth rates can be positive (e.g., through lengthening the growing season), associated soil water deficits will probably occur in most locations except in the high elevations. Tree responses to soil water deficits vary among species as a result of differences in tree physiology and morphology. Within species, drought sensitivity of trees is usually largest in seedlings. Mortality can result directly from water stress or indirectly from insects and pathogens, and vulnerability of trees to increase outbreaks may increase during periods of water deficit (Kardol et al. 2010). Climate-driven changes in in-stream flow are likely to reduce abundance of early-successional tree species, favor herbaceous species and drought-tolerant and late-successional woody species (including introduced species) reduce habitat quality for some riparian animals, and slow litter decomposition and nutrient cycling (Perry et al. 2012).

Although direct effects on tree growth will vary by species and climate change scenario, one study observed that productivity and timber inventories will increase while timber prices decrease (Irland et al. 2001), the result of an adaptive timber market. Adaptation in U.S. timber and wood product markets are expected to offset some potentially negative effects of climate change. In the United States, lumber and plywood production increases under all scenarios, and pulpwood production decreases under some scenarios. Overall, consumers and mill owners would benefit from climate change, whereas landowners may have reduced economic benefits (Irland et al. 2001).

Markets generally adapt to short-term increases in mortality by reducing prices, salvaging dead and dying timber, and replanting new species that are favorably adapted to the new climate. Salvage during dieback ranges from 50 to 75 percent, depending on management intensity. Total benefits to producers plus consumers rise in all scenarios considered. Market adaptation can reduce or reverse potential forest carbon fluxes in the United States (Irland et al. 2001). New technologies represent another method of adapting to climate change. For example, new adhesives have led to new classes of wood panels and composites, which have displaced older products. These new products often enable the industry to draw on more abundant species of trees that are also closer to end-use markets. New technologies have also helped mills produce more product value from a given tree. If this trend continues, the forest-based economy will be more resilient if forest dieback occurs in the future (Irland et al. 2001).

Adaptive Capacity

Adaptive capacity will depend on the ability to manage both the natural resources (maintaining healthy forests) and adapting to economic forces. Management actions may be able to mitigate drought stress and soil water deficits, mitigating some of the effects of climate change. Land managers also have the option to conduct fuel treatments, which help decrease the probability of large, severe wildfires and to salvage burned or insect-killed timber before it loses market value. Timber management can improve forest resistance and resilience to stressors in areas identified for treatment, usually in the portions of the forest that contain roads. Timber management is a relatively slow process, requiring 50 or more years from regeneration to harvest. Therefore, timber management cannot respond quickly to potential threats,

serving more as a long-term modification of forest composition and structure by helping the landscape gradually become more resistant and resilient. The wood products industry may also be able to adapt to changing conditions by using alternative species, changing the nature or location of capital and machinery, changing reliance on imports or exports, and adopting new technologies (Irland et al. 2001). Developing capacity within the industry to take advantage of emerging products will be important, though the most resilient communities will be those that diversify their economic bases, effectively reducing their exposure to adverse impacts to the timber industry.

Risk Assessment

In summary, the magnitude of effects for wood products is expected to be large, but mostly from non-climate forces. The likelihood of effects is moderate, again from non-climate forces, but it is uncertain how climate will affect forest disturbances that could have a more dominant influence on timber supply.

ECOSYSTEM SERVICE: MINING MATERIALS

Minerals are provisioning ecosystem services, but their primary role in the region is as an economic driver, providing jobs and incomes. Mineral development is important throughout the Northern Rockies, but particularly in northeastern Montana and northwestern North Dakota. In some counties, oil and gas development represents a third of total income to residents. According to 2012 IMPLAN data (MIG 2012), the percentage of total county income directly from the oil and gas sector are: Fallon County, MT (33 percent), Williams County, ND (32 percent), Slope County, ND (29 percent), Dunn County, ND (26 percent), Stark County, ND (23 percent), Mountrail, ND (22 percent), McKenzie, ND (21 percent). Most of this income comes from the Bakken Formation, which lies under parts of North Dakota, Montana, and Saskatchewan. At full development (about four wells per square mile), the formation is expected to be the nation's largest oil field (Mason 2012).

The main stressors from oil and gas development are effects on other ecosystem services, such as water quality (discussed above). Traffic from trucks and heavy machinery also increase the risk of introducing nonnative species to surrounding rangelands (see chapter 7).

Effects of Climate Change

Climate is not likely to directly affect minerals, but it is included in this assessment due to its prominence in the region and because of its potential to conflict with other ecosystem services. Power generation, oil and gas development, and mineral extraction are major users of water. Increased mudslides and fires may threaten oil and gas infrastructure, which would in turn threaten the ecosystem services that are co-located with mineral development.

Regional centers of oil and gas draw people from all over the country looking for high-paying jobs. Competition for workers in the oil fields causes wages in all other sectors of regional economics, including traditionally low-wage jobs in the service industry, to rise. If climate adversely affects other economic sectors, job opportunities in mining and energy will become more important. Climate change could affect the oil and gas infrastructure, but non-climatic drivers will be more important, including international prices for oil and gas, national climate policy, and regional concerns about threats to watersheds.

Adaptive Capacity

Global economic forces primarily drive the oil and gas industry. Oil and gas development potential determines where drilling activity takes place, and regional growth occurs so quickly that communities respond to rather than plan for such development. Adaptive capacity is either not applicable to this ecosystem service or limited from an economic development perspective. The most successful mineral-based economies are those that are able to collect some of the resource rents from drilling and invest them back into the community, extending prospects for long-term economic growth (Kunce and Shogren 2005). Oil and gas development is subject to booms and busts, and the most resilient communities are those that invest resource rents into efforts to diversify the economy.

Risk Assessment

Climate change is not expected to have significant effects on industries based on extraction of minerals and energy. The magnitude of effects is expected to be large from non-climate forces, and the likelihood of effects is expected to be moderate from non-climate forces.

ECOSYSTEM SERVICE: FORAGE FOR LIVESTOCK

The area contained within the Northern Rockies Adaptation Partnership contains 158 million acres of rangeland. Over 85 percent of these rangelands are privately held; 43 percent of rangeland in the Northern Region economic impact area is in Montana, which ranks third in the nation, behind Texas and New Mexico, in non-federal rangeland area. Of the federal rangeland, 8.5 million acres are Bureau of Land Management lands, of which 8 million acres are in Montana (USDI BLM n.d.). A variety of economic uses for rangeland exist in the Northern Rockies, but grazing cattle is by far the largest. Almost all counties in the region have shares of total income derived from cattle above the national average, with some counties in Montana and the Dakotas having more than 100 times the national average (MIG 2012 IMPLAN data).

Cheatgrass (*Bromus tectorum*), and other nonnative plants have become a major nuisance throughout Western rangelands, significantly reducing usable forage. The Nez Perce-Clearwater National Forest assessment (June 2014 review draft) states that forage has decreased in some places from 250 pounds per acre to as low as 25 pounds per acre (table 11.10). Human modification has also converted rangeland to other uses (Reeves and Mitchell 2012). Between 1982 and 2007, Montana lost about 900 acres of rangeland, 3100 acres of Conservation Reserve Program land, and 30 acres of cropland. This pattern of loss is consistent across the region, with the exception of small gains in pasture in Montana and Idaho (table 11.11). Historic rangeland losses in the West have been caused by agricultural development (17 percent), resource extraction (7.4 percent), and residential development (5.8 percent) with much smaller losses to mixed use, recreation, and transportation (Reeves and Mitchell 2012).

Rates of land conversion exceed population growth. Nationally, between 1945 and 1992, one additional person led to about half an acre converted to urban use; between 1992 and 1997, the rate reached 1.2 acres per additional person (DeCoster 2000). Human modification and fragmentation of rangelands have potential consequences for the socio-economic sustainability of rural communities, including loss of rural character, loss of biodiversity, difficulty in managing interconnected lands for

grazing, threats to watershed health, limited outdoor opportunities, compromised views, loss of native species, changes in disturbance regimes, and increased spread of nonnative species.

Effects of Climate Change

Warmer temperatures and increased precipitation are expected to increase productivity of rangelands (Reeves and Mitchell 2012) (see chapter 7), and increased regional population will lead to fragmentation of rangelands. Arid grasslands are likely to experience short-term response in species richness to altered precipitation due to the prevalence of annual species (Cleland et al. 2013). Carbon dioxide (CO₂) enrichment may alter the relative abundance of grassland plant species by increasing the production of one or more species without affecting biomass of other dominant and co-dominant species. This favored-species pathway to species change is the most frequently reported mechanism by which CO₂ affects grassland communities (Polley et al. 2012).

Cattle stocking rates in the Northern Rockies remain at or below current capacity of the land to support livestock (Reeves and Mitchell 2012), with few counties experiencing forage demand above current forage supply. In the long term, longer and wetter growing seasons would likely make rangeland more productive. The greatest threat to grazing from climate change may be increasing rates of spread of nonnative weeds and changes in fire regime (Maher 2007). Fire, itself, makes ranch planning difficult. Loss of access to grazing areas, on both private and public lands, requires emergency measures like the use of hay, which can devastate ranchers already operating with thin margins. Across all rangelands, increased fire in the future has the general effect of converting more lands to invasive mono-cultures (*B. rubens*, *B. tectorum*, etc.). Fire also kills shrubs, increasing the prevalence of grasses and herbs, which can reduce structural and floristic diversity. The net effect is a narrowing of options for ranch income diversification (e.g., loss of quail habitat and loss of mule deer winter range).

Adaptive Capacity

Human modification of rangelands and associated fragmentation are driven by opportunities for economic growth, as land is converted to higher-value uses. Rangeland conversion to residential development has brought new populations, higher incomes, and higher tax bases to rural communities,

creating what has been called the “New West” (Riebsame et al. 1997). During the 1990s, 67 percent of counties in the Rocky Mountains grew faster than the national average (Beyers and Nelson 2000). Natural amenities in the Northern Rockies are often touted as an economic asset (Power 1998; Rasker 1993). Economic growth without preservation of these assets is not likely to be sustainable.

Risk Assessment

The magnitude of effects on rangeland reflected in potentially large increases in productivity will be high, but given that forage supply exceeds demand, the effect on grazing will be small. Effects of invasive species and development may be large. The likelihood of effects is high, given that change is already being observed and that these trends are likely to persist. Loss of rural character is a concern, but it is not likely that the region will become heavily urbanized in the foreseeable future.

ECOSYSTEM SERVICE: VIEWSHEDS AND CLEAN AIR

Air quality is an important ecosystem service that can be altered by changes in vegetation composition and tree responses to climate change. For example, tropospheric ozone (O₃), air pollution episodes, plant sensitivity to air pollutants, and release of pollen all affect the provision of air quality by forests.

The Northern Rockies generally have exceptional air quality, although a few counties in the region regularly have days with poor air quality (American Lung Association 2015), and some areas are subject to wintertime inversions that trap air pollutants. During these inversions, wood-burning stoves used to heat homes become a major source of air pollution. In the summer, smoke from wildfires settles in valleys, leading to poor air quality. Counties in Idaho are often affected by burning of crop residues, and smoke can get trapped or settle into valleys where it persists until strong winds clear the air. Major sources of air pollution in North Dakota include coal-fired power plants, oil-field emissions, and vehicle traffic in the mineral-rich areas of the state. However, the North Dakota topography does not contain any features that would trap pollutants, so air quality is generally good throughout the state.

A large percentage of Northern Rockies residents are in demographic groups (e.g., elderly, poor) that are sensitive to poor air quality. Almost 1 in 10 adults in the region have asthma (Center for Disease

Control 2009). As more and more young people leave rural communities for more urban settings, sensitive populations are left isolated in rural areas that often lack the health facilities needed to accommodate an aging, ailing population.

Effects of Climate Change

Air quality can decline rapidly during a wildfire, and increased frequency of wildfires will affect viewsheds and air quality. Extended fire seasons will affect both scenery and air quality, with detrimental effects to human health. Analyses of the effects of climate change on air pollution in general have shown that climate change will increase the severity and duration of air pollution episodes (Bedsworth 2011). Climate change may affect distribution patterns and mixtures of air pollutants through altered wind patterns and amount and intensity of precipitation. The intensity of precipitation determines atmospheric concentration and deposition of acidifying compounds, potentially altering frequency and extent of pollution episodes (e.g., O₃) (Bytnerowicz et al. 2007). By 2050, summertime organic aerosol concentration over the western United States is projected to increase by 40 percent and elemental carbon by 20 percent. Higher temperatures accelerate chemical reactions that synthesize O₃ and secondary particle formation. Higher temperatures, and perhaps elevated CO₂ concentrations, also lead to increased emissions by vegetation of volatile organic compound precursors to O₃ (Kinney 2008). In addition to earlier onset of the pollen season and possibly enhanced seasonal pollen loads in response to higher temperatures and longer growing seasons, elevated CO₂ itself may increase pollen levels in some plant species (Kinney 2008).

Adaptive Capacity

A number of systems are already in place to alert residents when air quality deteriorates. These systems may become more common, as will days with poor air quality and associated alerts. Adaptation options include limiting physical activity outdoors, using air conditioning, and taking medications to mitigate health impacts. Tighter restrictions on use of wood for heating homes and on agricultural burning can reduce pollutants, and fuels treatments can reduce wildfire risk and smoke intensity. These strategies reduce exposure and mitigate damages. Many may be possible in the long run, but the geographic

diversity and rural character of the region makes quick adaptation unlikely. Unfortunately, the effects of poor air quality also fall heaviest on the most vulnerable populations like the elderly, young, and poor – groups that make up much of the rural populations of the region where shortages of health care already exist. These groups have little capacity to adapt.

Risk Assessment

The magnitude of effects is expected to be high, since a large percentage of the population (rural poor and elderly) is at risk for health impacts from poor air quality. This percentage will increase as the population ages, and young people move to urban areas. The likelihood of effects is expected to be high because many areas are already seeing diminished air quality from increased fires and longer pollen seasons.

ECOSYSTEM SERVICE: SOIL EROSION REGULATION

A U.S. Forest Service soil management directive (USDA FS 2009) identifies six soil functions: soil biology, soil hydrology, nutrient cycling, carbon storage, soil stability and support, and filtering and buffering. Steep slopes are the key element associated with erosion and landslides in mountain landscapes, and open rangeland is susceptible to topsoil loss. Erosion and landslides threaten infrastructure, water quality, and important cultural sites.

General resource management practices are designed to limit erosion and soil impaction, but landslides and erosion are still a common problem. Roads and other human activities are the largest source of sediment in most watersheds. Landslide-prone areas are generally on slopes greater than 60 percent with geomorphology and surficial geology sensitive to earth movement. Individual management units in public lands may experience hundreds of landslides each year.

Loss of soil from farm fields is a problem in the eastern part of the Northern Rockies (Kellogg et al. 1997) (fig. 11.7), but best practices in agriculture and range management have begun to slow the loss. Soil loss rates still exceed natural regeneration of soil in much of the eastern part of the Northern Rockies, and recent expansion of agriculture is likely to make the problem worse.

Effects of Climate Change

Soil erosion is tied to many forces on the landscape that are affected by climate change. In mountainous areas, wildfire and precipitation interact to affect erosion rates. Frequency of wildfire, precipitation in the form of rain rather than snow, and intense precipitation events are expected to increase (see chapters 3, 4, and 8), a combination that will lead to greater erosion and more landslides.

In the eastern rangelands, increased precipitation and warmer temperatures may benefit grass productivity and limit erosion. However, the same changes that make rangelands more productive also make land more valuable for agriculture. Expansion of agriculture is already occurring and will increase soil erosion in some areas. A combination of increased drought and increased flooding will add to already high erosion rates. Erosion rates on rangelands are also likely to increase with increased fire prevalence and spread of nonnative species.

Erosion is a significant concern for cultural sites, and is discussed in more detail in chapter 12.

Adaptive Capacity

One of the key impacts of soil erosion in mountains is its effect on water quality and drinking water treatment costs. Without expensive dredging, the usable life of dams and reservoirs will shorten, and capital investments will be necessary to remove added sediment from drinking water sources (Sham et al. 2013). Limiting erosion on rangelands can be done with best management practices for agriculture, including the use of buffers and limiting activity in sensitive riparian areas. In all areas, more resilient vegetation can be used to stabilize soils and support soil formation and nutrient cycling.

Risk Assessment

Landslides and flooding in mountainous areas have the potential for large, sudden damages to homes, infrastructure, and watersheds. Costs of soil erosion on the plains are high, but occur over extended periods of time. The likelihood of increased erosion in the mountains is high, because it depends on natural processes (e.g., fire, flooding) that are already changing. If agricultural practices do not change, erosion on the plains is also fairly certain. Likelihood of effects on the plains could be low if best practices become more common in agriculture.

ECOSYSTEM SERVICE: CARBON SEQUESTRATION

Forests provide an important ecosystem service in the form of carbon sequestration, or the uptake and storage of carbon in forests and wood products. Carbon sequestration is often referred to as a regulating ecosystem services because it mitigates greenhouse gas emissions by offsetting losses through removal and storage of carbon. As such, carbon storage in forests is “...becoming more valuable as the impacts of greenhouse gas emissions are becoming more fully understood and experienced” (USDA FS 2015).

The National Forest System (NFS) constitutes one-fifth (22 percent) of the Nation’s total forestland area and contains one-fourth (24 percent) of the total carbon stored in all U.S. forests, excluding interior Alaska. The management of these lands and disturbances such as fire, insect, and disease influence carbon sequestration rates. Rates of sequestration may be enhanced through management strategies that retain and protect forest land from conversion to nonforest uses, restore and maintain resilient forests that are better adapted to a changing climate and other stressors, and reforest lands disturbed by catastrophic wildfires and other natural events (e.g., mortality following windthrow).

The Forest Service champions the principles of considering carbon and other benefits together, integrating climate adaptation and mitigation, and balancing carbon uptake and storage in a wide range of ecosystem services, some of which have tradeoffs. The goal is to maintain and enhance net sequestration on federal forests across all pools and age classes through protection of existing stocks and building resilience in stocks through adaptation, restoration and reforestation. Carbon stewardship is an aspect of sustainable land management. It is also important to consider that carbon estimates are most useful at larger spatial scales; typically, baseline carbon estimates at the forest scale are not useful for project-specific applications.

Forests are highly dynamic systems that are continuously repeating the natural progression of establishment, growth, death, and recovery, while cycling carbon throughout the ecosystem and the atmosphere. This cycle, which drives overall forest carbon dynamics, varies geographically and by forest type, but also depends on the frequency, magnitude, and type of disturbance events. Natural and anthropogenic disturbances can cause both immediate and gradual changes in forest structure, which in

turn affect forest carbon dynamics. For instance, a severe wildfire may initially release carbon dioxide to the atmosphere and cause tree mortality, shifting carbon from living trees to dead wood and the soil. However, as the forest recovers, new trees establish and grow, absorbing carbon dioxide from the atmosphere. While disturbances may be the predominant drivers of forest carbon dynamics (Pan et al. 2011), environmental factors, such as the availability of key forest nutrients like CO₂ and nitrogen, as well as climatic variability, influence forest growth rates and consequently the cycling of carbon through a forest ecosystem (Pan et al. 2009).

Changes in carbon stocks and resulting net emissions may be influenced through vegetation management strategies. Land management and restoration strategies, plans, and actions, such as fire and fuels management, timber harvesting, reforestation, and other forest stand treatments, can be designed to integrate carbon sequestration capacity across broad landscapes and over the long-term, while meeting other resource management objectives.

Wood uses for products can also complement land management by extending the storage of carbon in useful products and reducing emissions as wood products substitute for those that emit more carbon dioxide and other greenhouse gasses. Harvested wood products (HWP), such as lumber, panels, and paper, can account for a significant amount of off-site carbon storage and estimates of this addition are important for both national level accounting and regional reporting (Skog 2008). Products derived from the harvest of timber from the national forests extend the storage of carbon and/or substitute for fossil fuel use, which is part of the overall carbon cycle.

Baseline Estimates

The Forest Service's 2012 Planning Rule and Climate Change Performance Scorecard Element 9 (Carbon Assessment and Stewardship) both require NFS units to identify baseline carbon stocks and to consider that information in planning and management. The Climate Change Advisor's Office (now the Office of Sustainability and Climate Change) facilitated work by Forest Service Research & Development to develop a nationally-consistent carbon assessment framework and to deliver forest information for every NFS unit. Estimates of total ecosystem carbon and stock change (flux) have been produced at the

forest level across the entire country, relying on consistent methodology and plot-level data from the Forest Inventory and Analysis (FIA) program (USDA FS 2015).

Carbon stocks reflect the amount of carbon stored in seven ecosystem carbon pools – above-ground live tree, below-ground live tree, understory, standing dead trees, down dead wood, forest floor, and soil organic carbon – for the period 1990 to 2013. Carbon stock change (flux) reflects the year-to-year balance of carbon going into or being pulled from the atmosphere (Woodall et al. 2013). Carbon stock change measures the inter-annual change in carbon stock caused by tree growth, disturbance, management, etc. Negative stock change values indicate that carbon is being pulled from the atmosphere (i.e., net carbon sink), while positive values mean carbon is being released (i.e., net carbon source).

Figure 11.8 displays carbon stock trends for each of the national forests in the Northern Region between the years 1990 and 2013, where the Idaho Panhandle National Forest stored the largest amount of carbon in the region, approximately 207 million short tons in 1990 and 202 million short tons in 2013. During this period, the Beaverhead-Deerlodge, Kootenai, Nez Perce, Flathead, Lolo, Clearwater, Gallatin and Custer national forests all increased in ecosystem forest carbon stocks, while the Lewis and Clark, Helena, Bitterroot national forests and Dakota Prairie Grassland decreased.

The cumulative carbon stored in the Northern Region HWP experienced a jump in 1955 and began to continually increase at a steady rate, peaking in 1995 with approximately 37 million short tons in storage (fig. 11.9). The HWP pool since then has decreased to 35 million short tons. This illustrates the influence of timber harvest on the HWP pool. Since the amount of HWP carbon entering that pool is less than the amount of carbon exiting it through various pathways, HWP stocks are decreasing.

Effects of Climate Change

Many factors affect the sensitivity of forests to sequester carbon, and the net effect of climate change on carbon storage in forests is uncertain. The greatest vulnerability to forest distribution and health as a result of climate change is increased risk of fire, insects, and disease (mostly fungal pathogens). Preliminary results from the Forest Carbon Management Framework (Healey et al. 2014; Raymond et al. 2015), show for example, that fire had the largest impact of carbon storage on the Flathead National

Forest between 1990 and 2012, followed by harvest. The largest impact on carbon storage on the Idaho Panhandle National Forest was disease, followed by harvest.

Since nitrogen often is a limiting nutrient in forests, nitrogen deposition may increase wood production and accumulation of soil organic matter, thus increasing carbon sequestration. When carbon uptake is caused by increased growth, it is likely a transitory phenomenon. When soil accumulation is the main cause, forests could be a long-term carbon sink, because belowground carbon has longer turnover times than aboveground carbon (Bytnerowicz et al. 2007).

Tropospheric O₃ damage in sensitive plant species may offset some productivity gains from elevated atmospheric CO₂, thus reducing carbon storage on land and possibly contributing further to climate change. Increasing O₃ will negatively affect plant productivity, reducing the ability of ecosystems to sequester carbon, indirectly providing feedback to atmospheric CO₂ (Sitch et al. 2007). Over the course of the 21st century, net carbon uptake by terrestrial ecosystems is likely to peak before mid-century and then weaken or even reverse, thus amplifying climate change (IPCC 2007).

Fungal pathogens, especially various types of root rot, are another key concern for forests and may affect the ability of forests to sequester carbon (Hicke et al. 2012). Increased temperature and humidity coupled with decreased snow and cold weather facilitate the spread of root rot. As more trees die and decompose, forests could switch from carbon sinks to carbon sources.

Adaptive Capacity

Adaptive capacity for sequestering carbon depends on the spatial and temporal scales at which an ecosystem service is defined. Carbon storage in any particular forest location may go up or down over time, but analysis of storage should occur at very large spatial scales. Adaptive capacity for this particular ecosystem service is likely low, since most of the factors affecting carbon sequestration are external, including development pressures and wildfire. The Climate Change Scorecard and Carbon Management Principles highlight the role National Forests can play in managing forest carbon.

Risk Assessment

Although increased temperature and drought will reduce forest growth, the most detrimental effects to carbon sequestration will be indirect, through increased risk and frequency of wildfires and insect outbreaks. Some deterioration in forest health is highly likely, so some change in the ability of forests to sequester carbon is also likely. However, the net effects on forest health and carbon sequestration are difficult to project, primarily due to the uncertainty in the magnitude of future occurrence of wildfire and insect outbreaks.

ECOSYSTEM SERVICE: CULTURAL AND HERITAGE VALUES

The goods and services that ecosystems provide have spiritual, cultural, and historical value to many people. The effects of climate change will affect the provision of these services for individual locations, plant and animal species, and landscape characteristics. The majority of research on this topic pertains to forest resource values realized by Native American tribes and the effect of climate change on sense of place (see Adger et al. 2013 for a review).

Availability of resources (e.g., for food) and adequate habitat limit traditional lifeways, especially if the distribution and abundance of plants and animals change in response to increased temperature and disturbance (especially wildfire). In general, cultural and heritage values are high in the Northern Rockies, and mostly threatened by changes in culture and the way humans interact with the landscape. Tribal values face ongoing stresses as Native American people attempt to preserve both culture and places on the land, including legal struggles with federal agencies (for example, the ongoing disagreement between the Blackfeet and Glacier National Park regarding access to resources on the park) and effects of recreation on sacred places. Educational programs and law enforcement on federal lands protect many cultural sites, but funding is insufficient to protect all of them (see chapter 12).

A large part of one's culture is his or her connection with physical places, often including an image of "home." Such senses of place may be at risk by climate change if those connections and images change. People may identify with livelihoods and activities that are no longer sustainable in a changing climate (Adger et al. 2011; Agyeman et al. 2009; Igor 2005). People that are tied to their communities are more

reluctant to leave during economic and social hard times, which makes them more vulnerable to the effects of climate change (Field and Burch 1988).

Effects of Climate Change

Increased frequency of wildfire, floods, nonnative species establishment, and erosion all put cultural values, cultural sites, and historic sites at risk. Changes in climate that affect ranges of species that are traditionally harvested by Native Americans affect the ability of tribes to exercise their treaty rights. Impacts can be amplified or mitigated by management decisions and societal forces.

The economies of resource-dependent communities and indigenous communities in the region are particularly sensitive to climate change, with likely winners and losers controlled by effects on important local resources (Maldonado et al. 2013). Residents of high-elevation and northern-latitude communities are likely to experience the most disruptive impacts of climate change, including shifts in the range or abundance of wild species crucial to the livelihoods and well-being of indigenous people (Field et al. 2007). As traditional foods are affected by climate change through habitat alterations and changes in the abundance and distribution of species, traditional practices and knowledge tend to erode (Cordalis and Suagee 2008; Lynn et al. 2013). Tribal rights to harvest culturally important plants, animals, and fish are based on historic harvest areas, so tribes may lose their ability to exercise these rights if species leave their historic ranges.

Adaptive Capacity

Since this ecosystem service relates to preserving the past and maintaining access to current sites, adaptive capacity is low. Increased resources for law enforcement and preservation of cultural sites can mitigate some of the expected damages, and Traditional Ecological Knowledge has helped Tribes adapt to past social and ecological periods of change. Fish hatcheries and other human assistance to survival of plant and animal species will become more important. Vegetation management can potentially be implemented near high-risk cultural and historic sites that are prone to fire, floods, nonnative species establishment, and erosion.

Risk Assessment

Loss of sacred places and heritage is largely irreversible, and many argue that the damage associated with such losses cannot be quantified. The overall magnitude of climate-induced changes may be moderate to high. Increased rates of erosion are already being observed at some cultural sites, and vandalism rates are increasing as human population increases. Culturally important fish populations are declining and in some cases rely on human assistance for migration and survival. Therefore, the likelihood of climate change effects is high.

SUMMARY

Ecosystem services are the benefits people derive from landscapes and encompass the values that motivate people to live in the Northern Rockies. Ecosystem services are the core of our sense of place and are important to protect in the face of a growing number of threats. Some of these threats are social (demographic changes, economics, policy) and some are environmental (e.g., climate change). In many cases, social and environmental forces will act to amplify the effects of the other, but opportunities exist for adaptation in some cases. Below are key findings from the ecosystem services vulnerability assessment.

- Total annual **water yield** is not expected to change significantly. However, timing of water availability will likely shift, and summer flows may decline. These changes may result in some communities experiencing summer water shortages, although reservoir storage can provide some capacity. Snowmelt is already occurring earlier, and both floods and drought may become more common. Agriculture is currently the largest consumer of water and one of the largest economic forces in the region, and rural agricultural communities will be disproportionately affected by climate change.
- **Water quality** is closely tied to water yield. Increased occurrence of wildfires and floods will add sediment to rivers and reservoirs, affecting in-stream water quality and making water treatment more expensive. Agriculture is currently the major source of impairment, leading to loss in streamside vegetation, loss of aquatic habitat, increased water temperatures, and high levels of fecal coliform. Climate change is expected to amplify these effects.

14975 • **Wood products** provide jobs in the region. Climate changes will lead to more wildfires
14976 and insect outbreaks, but in general effects will be small. The largest effects on wood products are
14977 likely to be from economic forces and policies. Timber production has been in steady decline, and
14978 that trend is likely to continue. Timber is a major employer in some small towns that have already
14979 seen an economic downturn, a trend that may continue as a function of economic factors at the
14980 national to local levels.

14981 • The Northern Rockies contain one of the largest oil fields in the United States. Near the
14982 Bakken formation, about a third of regional income comes directly from oil and gas. **Minerals**
14983 and mineral extraction are not likely to be affected by climate change, making mining and energy
14984 development important economic drivers. The greatest effect on mineral and energy extraction is
14985 likely to be how it connects to other ecosystem services, particularly water quality. Wildfires,
14986 floods, and mudslides all put mineral extraction infrastructure in danger, which in turn increases
14987 risk to watersheds.

14988 • Climate change is expected to increase the potential of rangeland to provide **forage for**
14989 **livestock**. Ranching and grazing, all else equal, may benefit from climate change. Major threats
14990 to grazing are human induced, including loss of rural population, spread of nonnative grasses, and
14991 fragmentation of rangelands.

14992 • **Viewsheds** and **air quality** will be affected by increasing wildfires and longer pollen
14993 seasons. A growing percentage of the region's population will be in at-risk demographic groups
14994 who will suffer respiratory and other medical problems on days with poor air quality.

14995 • The ability to **regulate soil erosion** will be diminished by both agricultural expansion,
14996 spread of invasive plants, and increased frequency of wildfire and floods. Increased capital
14997 investments may be needed for water treatment plants if water quality degrades significantly. Best
14998 practices in agriculture and construction of roads can mitigate some of these effects.

• The ability of forests to **sequester carbon** may be affected by wildfires, insect outbreaks, and plant disease, and carbon sequestration in the western part of the Northern Rockies, will be affected by more frequent disturbance and stress. Managing forests for carbon sequestration is likely to become more important in response to national climate policies.

• Disturbances such as wildfires, floods, and soil erosion place **cultural and heritage values** at risk. Damage to cultural and historic sites are irreversible, making protection a key management focus. Climate-induced changes in terrestrial habitats and human modification of streamflow affect abundance of culturally plants and animals (especially native fish), affecting the ability of Native American tribes to exercise their treaty rights. Effects on this ecosystem service are amplified by social forces that include a growing regional population, vandalism, and loss of traditional practices in a globalizing culture.

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Chapter 12: Effects of Climate Change on Cultural Resources

Carl M. Davis

BACKGROUND AND CULTURAL CONTEXT IN THE NORTHERN ROCKIES

People have inhabited the Northern Rocky Mountains of the United States since the close of the last Pleistocene glacial period, some 14,000 B.P. (Fagan 1990; Meltzer 2009). Across this region (15 national forests, 3 national parks; northern Idaho, Montana, northwest Wyoming, North Dakota, and northern South Dakota), evidence of this distant and more recent human occupation is found throughout all of the subregions within the Northern Rockies Adaptation Partnership area. Each of these subregions, and the public and private lands they now encompass, contain thousands of years of human history.

The Northern Rockies are the ancestral homeland or aboriginal territory of the Arikara, Assiniboine, Bannock, Blackfeet, Chippewa-Cree, Coeur d'Alene, Crow, Hidatsa, Kiowa, Kutenai, Mandan, Nez Perce, Northern Cheyenne, Pend d'Oreille, Salish, Shoshone, Sioux and other Plains, Intermountain, and Columbia Plateau American Indian tribes (DeMallie 2001; Schleiser 1994; Walker 1988). Beginning in the 18th century, the region was explored and then settled by people of French, British, Irish, Scottish, Chinese, German, Scandinavian and other ancestries (White 1993). The region then, as today, was a diverse blend of cultural backgrounds and lifeways.

The archaeological and historical evidence of these past cultural groups, interactions, and events—collectively called “cultural resources”—is extensive and varied across the Northern Rockies. Cultural resources here include (1) ancient Indian camps and villages, rock art, tool stone quarries, and travel routes, (2) historic military forts and battlefields, mining and logging ruins, and homesteads, and (3) ranger stations, fire lookouts, and recreation sites built by the Civilian Conservation Corps. Currently, some 20,000 cultural resources have been documented, which represents a small fraction of what likely exist in the Northern Rockies.

Protection of cultural resources has been formally recognized since 1906 when the Antiquities Act was signed into law. This law requires federal land management agencies to preserve historic, scientific, commemorative, and cultural values of archaeological and historic sites and structures of public lands for present and future generations (NPS 2015a), and gives the President of the United States authority to designate national monuments as a means to protect landmarks, structures, and objects of historical or scientific significance. The importance of cultural resources has been reaffirmed through the Historic Sites Act of 1935, the National Historic Preservation Act of 1966, the Archaeological Resources Protection Act of 1979 and the Native American Graves Protection and Repatriation Act of 1990. Although the focus of these laws differs, together they mandate the protection and management of cultural resources in federal lands. The National Park Service has a particularly strong emphasis on protection of cultural resources (box 12.1).

Beyond physical sites, structures, and artifacts associated with past human use or events, protection of cultural resources involves the ongoing use of resources and associated activities relevant to the continuation of specified extant cultures. Many cultural resources are currently vulnerable to natural biophysical phenomena and human activities. Wildfire and biological processes degrade and destroy cultural resources, particularly those made of wood or located in erosion-prone environments. Vandalism, illegal artifact digging, arson, and other depreciative human behaviors also damage cultural resources. Agency land management actions can affect cultural sites and landscapes, and although federal land managers protect and mitigate adverse effects to cultural resources, the enormity of this task often outstrips agency resources and capacity.

BROAD-SCALE CLIMATE CHANGE EFFECTS ON CULTURAL RESOURCES

This assessment of the potential effects of climate change on cultural resources in the Northern Rockies is fairly general, because so little information has been generated on this topic, compared to the effects of climate change on natural resources. A broad diversity of cultural resources and locations where they are found make it difficult to infer the spatial extent and timing of specific effects. Therefore, we have synthesized the relevant literature from diverse disciplines to cautiously

project how an altered climate, both directly and indirectly (through increased disturbance) will create conditions that modify the condition of and access to cultural resource sites and their contents.

Climate change has the potential to exacerbate and accelerate existing effects to cultural resources (table 12.1). A warmer climate will alter the scale of wildfires across western North America (Schoennagel et al. 2004; Westerling et al. 2006) (see chapter 8), thus having at least three general effects on cultural resources. First, wildfires readily burn cultural resources made of wood and combustible materials, such as ancient aboriginal wood shelters and game drives, or historic homesteads, mining ruins, and buildings. Second, emergency wildfire suppression tactics, including fireline construction using heavy equipment, affect both standing structures and archaeological sites buried in forest soils. Third, post-wildfire flooding and debris flows threaten cultural resources exposed atop fire-charred landforms and soils. Alternatively, fire can expose cultural sites that might not have been otherwise visible (fig. 12.1).

Currently, federal agencies implement various actions to reduce the effects of wildfire on cultural resources, such as encasing historic structures in fireproof wrap, routing of fireline away from sites, and armoring cultural resources vulnerable to postfire flooding events. However, these actions are often not commensurate with the scale of large wildfires or the ensuing cultural resource loss. Thus, damage is expected to continue as climate change amplifies amount of area burned, if not severity, across the Northern Rockies.

Seasonal aridity and prolonged drought accelerate soil deflation and erosion, and thus expose archaeological sites once buried in plains and mountain soils. Wind and water roil across archaeological sites, blowing or washing away ground cover, revealing ancient artifacts and features such as cooking hearths and tool-making areas (fig. 12.2). This new ground exposure leaves artifacts vulnerable to artifact collecting and illegal digging, effects that are intensified in areas where livestock grazing, recreation, and mining occur and the ground is already impacted. For example, livestock in grazing allotments typically converge around creeks and natural springs where ancient hunter-gatherer archaeological sites are commonly located.

Periods of dry climate and drought have occurred throughout the Holocene in the intermountain West, with corresponding episodes of soil deflation, erosion, and down cutting (Meltzer 1990; Ruddiman 2007). However, increasing temperatures outside of the Holocene norm (IPCC 2014; Mayewski and White 2002) (see chapter 3) will create additional potential for cultural resource loss through drought and erosion, particularly in drier areas such as southeastern Montana.

In addition, if winter precipitation increases (see chapter 3) and reduced snowpack leads to higher winter streamflows (see chapter 4), archaeological and historic sites will be increasingly vulnerable to flooding, debris flows, down cutting, and mass wasting of underlying landforms. This scenario is now common in the aftermath of large-scale wildfires, especially in the dry mountain ranges of central and eastern Montana (fig. 12.3). These severe events are likely to accelerate hydrological impacts to cultural resources (National Research Council 2002).

Perennial, high-elevation snowfields contain ancient artifacts, the result of hunting and gathering excursions to mountain environments (Lee 2012) (fig. 12.4). Melting ice caused by a warmer climate poses a risk to previously ice-encased and well-preserved cultural resources. For example, melting ice patches in the Beartooth Mountains of south-central Montana have yielded ancient bone, wood, and fiber artifacts. Although melting ice patches provide research opportunities, the rapid rate of melting ice may preclude timely inspection of by archaeologists, and newly exposed artifacts may decay or be stolen without adequate archaeological documentation.

Climate change also affects larger cultural landscapes whose integrity is derived from both cultural resources and environmental context (NPS 1994). Historical sites from the 1800s (e.g., Euro-American settlements, battlefields) are also valued historical resources, especially in some National Park Service units. Major shifts in dominant vegetation could potentially affect the physical and visual integrity of these landscapes (Melnick 2009). For example, whitebark pine (*Pinus albicaulis*) is an important historical component of the Alice Creek-Lewis and Clark Pass cultural landscape on the Continental Divide near Helena, Montana (fig. 12.5). Whitebark pine is currently in decline, because warmer winter temperatures have accelerated the rate of mountain pine beetle outbreaks

(*Dendroctonus ponderosae*) in addition to the effects of white pine blister rust (*Cronartium ribicola*), a nonnative fungal pathogen (Tomback and Kendall 2001) (see chapter 8).

Cultural sites and landscapes are also recognized for their traditional importance to descendant communities, particularly American Indian tribes in the intermountain West. Some traditional use areas provide foods, medicinal and sacred plants, paints, and other resources, as well as ceremonial-religious places. Significant climate-induced effects in these landscapes, particularly altered distribution and abundance of vegetation, may curtail and even sever the continuous cultural connectivity and traditional use of these areas by indigenous peoples and local communities.

Climate change also poses risks to historic buildings and structures, including wildfire, flooding, debris flow, and extreme weather events (fig. 12.6). In addition to these direct threats, period furniture, interpretive media, and artifact collections inside historic (and non-historic) buildings may likewise be affected by those events. More nuanced stressors include increased heat, moisture, humidity, freeze-thaw events, insect infestation, and micro-organisms (mold), all of which accelerate weathering, deterioration, corrosion, and decay of buildings, structures and ruins made of wood, stone, and other organic materials (UNESCO 2007).

Finally, climate change may diminish the appeal of cultural sites and landscapes for public visitation and interpretation. Extensive outbreaks of mountain pine beetle and other insects, which have been facilitated by higher temperature, have turned some historic landscapes in southwestern Montana from green to brown to gray (e.g., Logan and Powell 2001). In addition to visual impacts, dead and dying forests present hazards to hikers, sightseers, and other forest users (see chapter 10). Over time, altered ecological conditions in cultural landscapes of the Northern Rockies may reduce their attractiveness and value for tourism, recreation and other purposes, thus affecting local communities and economies (see chapters 10, 11).

Likelihood and Magnitude of Climate Change Effects

Climate change effects on cultural resources are likely to be highly variable across the Northern Rockies by the end of the 21st century, depending on the particular stressor and geographic location.

Wildfire is expected to create the highest risk for cultural resources and is expected to broadly, though unevenly, affect cultural resources and on all national forests, national grasslands, and national parks, including locations that have already burned since the 1990s.

The prospect of prolonged aridity and drought caused by projected temperature increase may be partly offset if winter precipitation increases in the future (see chapter 3). Thus, it is difficult to quantify the long-term effects of drought, floods, and extreme weather events on cultural resources. In general, these natural processes, enhanced by climate change, are likely to pose a significant risk to cultural resources. Resource loss will be greatest in those areas prone to major hydrological events, such as at canyon mouths and in river bottoms where cultural sites are often concentrated. Cultural sites located here are difficult to armor and protect in the face of significant flooding and debris flows. Furthermore, artifact collectors may eventually target these areas because newly exposed cultural materials are often strewn over a wide area in the aftermath of a flood or debris flow, invoking the need for active law enforcement.

Other potential climate change-related effects on cultural resources will be more subtle and moderate. Shifting or changing vegetation regimes are likely to affect the visual integrity of some cultural landscapes. Climate change effects to historic buildings or structures will be both gradual and cumulative (i.e., decay and degradation) and sudden and direct (i.e., structural collapse caused by moisture and snow loading). Certain natural resources associated with traditional cultural landscapes, which continue to be used by tribal peoples today, may be diminished or entirely disappear. However, increased wildfire may increase the abundance of some culturally valuable species, such as huckleberry (*Vaccinium* spp.) common camas (*Camassia quamash*), and nodding onion (*Allium cernuum*).

Agency proposals and efforts to control, abate, or mitigate the projected effects of climate change may also affect cultural resources. For example, in anticipation of significant flooding events in the future, historical culverts and bridge abutments made of stone may be replaced with larger metal ones. Although project design and mitigation measures would reduce many adverse effects to cultural

resources, landscape restoration projects designed to increase resilience to climate stressors could diminish the cultural resource base in some locations.

The effects of climate change on cultural resource tourism are difficult to estimate because this is contingent on social and economic factors. Visiting historical sites is popular throughout the Northern Rockies (Nickerson 2014), and tourism is an important economic contributor to many local communities (see chapter 10). Hot, dry summer weather could reduce public interest in visiting cultural resources, cultural landscapes, and interpretive sites located in federal lands, particularly in areas recently affected by severe wildfires or floods. This potential effect on forest tourism could, in turn, affect local communities to some extent.

ADAPTING TO THE EFFECTS OF CLIMATE CHANGE

Federal agencies in the Northern Rockies have the capacity to address some of the projected effects of climate change on cultural resources. Fuels reduction around significant cultural resources is already in place in some locations, thus reducing the intensity and severity of future wildfires. Forest Service, U.S. Department of Agriculture heritage personnel are engaged in all aspects of wildfire suppression and recovery, which facilitates protection of cultural resources threatened by wildfires. However, fire vulnerability assessment and abatement programs for cultural resources may need further emphasis to address a potential for more wildfires in the future.

Less progress has been made in completing vulnerability assessments or implementing protection strategies for cultural resources located in areas prone to large-scale hydrological events, and the full scope of this risk is unknown in the Northern Rockies. Hydrological events are unpredictable, and protection measures such as stabilization and armoring are expensive. Viable protection measures often require hydrological, engineering, and other resource expertise. Nonetheless, federal agencies have a strong mandate to implement measures to protect cultural sites threatened by such natural processes and emergency events.

Survey and evaluation in areas where cultural resources are concentrated or likely is ongoing, although intermittent, in the Northern Rockies. It will be possible to locate and monitor cultural

resources potentially only if these efforts are significantly expanded. High-elevation melting ice patches are a particular priority, but surveys are critical in other locations where cultural resources are likely to be affected by flooding and debris flows in mountain canyon and foothills areas. Correlating areas where cultural resources are common with areas where flooding and ice melt are expected will help to focus attention in landscapes at greatest risk.

Some climate-induced vegetation shifts in designated cultural landscapes could be partly mitigated through silvicultural treatments and prescribed burning, although the effectiveness of proposed treatments relative to the scope and scale of the cultural landscape is difficult to evaluate. Careful monitoring and tracking of vegetation stability and change in cultural landscapes will become increasingly important in future decades.

To date, the potential effects of climate change on the historic built environment in the Northern Rockies has received relatively little attention. However, a variety of actions may eventually be necessary to abate or mitigate the projected effects of climate change on historic buildings and structures. Vulnerability assessments by qualified experts are necessary precursors to initiating any remediation work such as stabilization, armoring, and other interventions. In this context, historic preservation teams, volunteers, and partners will be important contributors to climate-related preservation work in the future.

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Chapter 13: Conclusions

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The Northern Rockies Adaptation Partnership (NRAP) provided significant contributions to assist climate change response in national forests and national parks of the region. The effort synthesized the best available scientific information to assess climate change vulnerability, develop adaptation options, and catalyze a collaboration of land management agencies and stakeholders seeking to address climate change in the Northern Rockies. The vulnerability assessment and corresponding adaptation options provided information to support national forests and national parks in implementing respective agency climate change strategies described in the National Roadmap for Responding to Climate Change (USDA FS 2010), Climate Change Performance Scorecard (USDA FS 2012) (see chapter 1), and National Park Service Climate Change Response Strategy (USDI NPS 2010). The NRAP process allowed all forests in the USFS Northern Region to respond with “yes” to scorecard questions in the organizational capacity, engagement, and adaptation dimensions. Also, the NRAP process enabled participating national parks to make progress towards implementing several components (communication, science, and adaptation goals) of the National Park Service (NPS) Climate Change Response Strategy (USDI NPS 2010).

RELEVANCE TO AGENCY CLIMATE CHANGE RESPONSE STRATEGIES

In this section, we summarize the relevance of the NRAP process to the climate change strategy of federal agencies and the accomplishments of participating national forests, national grasslands and national parks. Information presented in this report is also relevant for other land management agencies and stakeholders in the Northern Rockies. This process can be replicated and implemented by any organization, and the adaptation options are applicable in the Northern Rockies and beyond. Like previous adaptation efforts (e.g., Halofsky et al. 2011; Raymond et al. 2014), a science-management partnership was critical to the success of the NRAP. For others interested in emulating this approach, we

encourage them to pursue this type of partnership as the foundation for increasing climate change awareness, assessing vulnerability, and developing adaptation plans.

Communication, Education, and Organizational Capacity

Organizational capacity to address climate change, as outlined in the Forest Service, U.S. Department of Agriculture (USFS) Climate Change Performance Scorecard requires building institutional capacity in management units through training and education for employees. Training and education were built into the NRAP process through workshops and webinars that provided information about the effects of climate change on water resources, fisheries, forested vegetation, non-forested vegetation, disturbance, wildlife, recreation, ecosystem services, and cultural resources). The workshops introduced climate tools and processes for assessing vulnerability and planning for adaptation.

The NPS Climate Change Response Strategy challenges NPS staff to increase climate change knowledge among employees and to communicate this information to the public, in addition to the actions taken by the agency to respond to climate change. Although communication about climate change with the public was beyond the scope of the NRAP, knowledge generated through this process can be used for outreach and interpretive materials.

Partnerships and Engagement

The NRAP science-management partnership and process were as important as the products that were developed, because these partnerships are the cornerstone for successful agency responses to climate change. We built a partnership that included several federal agencies as well as other organizations (e.g., EcoAdapt, Headwater Economics) and universities (Oregon State University, University of Washington).

Elements 4 and 5 of the USFS Climate Change Performance Scorecard require units to engage with scientists and scientific organizations to respond to climate change (element 4) and work with partners at various scales across all boundaries (element 5). Similarly, the NPS Climate Change Response Strategy emphasizes the importance of collaboration and building relationships, in addition to products that support decision-making and a shared vision. The NRAP process therefore allowed both agencies to achieve unit-level compliance in their agency-specific climate responses.

The NRAP process encouraged collaboration between Forest Service, U.S. Department of Agriculture (USFS) and NPS, supporting a foundation for a coordinated regional response to climate change. By working with partners (federal and non-governmental), we increased our capability to respond to climate change. Responding to such a challenge requires using an all lands approach, which this partnership fostered.

Assessing Vulnerability and Adaptation

Elements 6 and 7 of the USFS Climate Change Performance Scorecard require units to assess the expected effects of climate change and which resources as a result will be most vulnerable, and identify management strategies to improve the adaptive capacity of the national forest lands. The NRAP vulnerability assessment used the best available science to identify sensitivity and vulnerability of multiple resources in the Northern Rockies (table 13.1). Adaptation options were then developed for each of the resource areas that can be incorporated into resource specific programs and plans.

The science-management dialogue identified management practices that are useful for increasing resilience and reducing stressors and threats. Although implementing all options developed in the NRAP process may not be feasible, resource managers can still draw from the menu of options as needed. Some adaptation strategies and tactics can be implemented on the ground now, whereas others may require changes in policies and practices or can be implemented when management plans are revised or as threats become more apparent.

The NRAP process used many of the principles and goals for assessing vulnerability and planning for adaptation, as identified in the NPS Climate Change Response Strategy, which calls for units to implement adaptation in all levels of planning to promote ecosystem resilience and enhance restoration, conservation, and preservation of resources (USDNPS 2010). It specifically requires developing and implementing adaptation to increase the sustainability of facilities and infrastructure, and preserve cultural resources.

Science and Monitoring

Monitoring is addressed in Element 8 of the USFS Climate Change Performance Scorecard and in the NPS Climate Change Response Strategy. Where applicable, the NRAP products identified information gaps or uncertainties important to understanding climate change vulnerabilities to resources and management influences on vulnerabilities. These identified information gaps could drive where important monitoring and research would decrease uncertainties inherent to management decisions. In addition, current monitoring programs that provide information for detecting climate change effects, and new indicators, species and ecosystems that require additional monitoring, were identified for some resource chapters. Working across multiple jurisdictions and boundaries will allow NRAP participants to increase collaborative monitoring and research of climate change effects and effectiveness of implementing adaptation strategies and tactics that increase resilience or reduce stressors and threats.

Throughout the NRAP process, the best available science was used to understand projected changes in climate and effects on natural resources. This science can be incorporated into large landscape assessments such as forest/grassland planning assessments, environmental analysis for National Environmental Policy Act (NEPA) projects, or project design and mitigations.

NEXT STEPS

The NRAP built on previous science-management partnerships by creating an inclusive forum for local and regional stakeholders to address issues related to climate change vulnerability and adaptation. Although this partnership was conducted at the regional scale, more work is needed to truly achieve an “all lands” approach to adaptation. The federal agencies involved have different missions and goals, and are at different stages in integrating climate change in resource management and planning. Although the differences allowed agencies to share approaches and experiences, it presented challenges in terms of creating a collaborative adaptation plan.

In the future, it may be valuable to develop partnerships around specific resource issues and implement adaptation options accordingly. Similarly, working at sub-regional scales would enable the assessment to target specific management concerns. Finally, engaging managers early through a query

regarding priority information needs to support adaptation planning would help to generate “buy in” and ensure that products target important management needs.

The goal of this vulnerability assessment was to cover a range of natural resources that are critical to the region. By exploring several resources in detail, participants identified species and ecosystems that are sensitive to climate change. More detailed quantitative and spatially-explicit vulnerability assessments would improve the scientific basis for detecting the effects of climate change and developing site-specific management responses and plans. It would also allow resource managers to prioritize locations for implementation. The vulnerability assessment could also be expanded to include other systems and issues such as social and economic effects.

Implementing Adaptation Strategies and Tactics

Implementing adaptation strategies and tactics is the most challenging next step. This will gradually occur with time, changes in policies, plan and program revisions, and major disturbances or extreme weather events. As previously noted, collaboration among landowners and management agencies will produce more successful adaptation outcomes than operating independently.

With the formation of the science-management partnership, two products were produced through the NRAP partnership: the vulnerability assessment and the adaptation strategies and tactics. Prior to applying any of the adaptation strategies or tactics, land managers require a process to consider which actions are most important and the locations that are most important to implement those actions. Landscape management strategies provide context for decision making in which managers can be transparent in decisions to apply any given strategy or tactic. Determinations of which adaptation options are most appropriate must consider the condition and context of the resource, social and ecological values, time scales for management, and feasible goals for treatment given changing climate (Peterson et al. 2011). Depending on the context and conditions, landscape management strategies can have various objectives, such as increasing resilience, resisting climate influences, facilitating transitions, or realigning/restoring systems to be more resilient (Peterson et al. 2011).

Developing critical questions based on the vulnerability assessment, other factors important for resources, and site-specific ecological and social situations in the context of larger landscapes would assist land managers in making reasoned and transparent decisions in applying adaptation strategies and tactics. Workshops with large and small planning teams to develop resource specific critical questions and their response to those questions could result in the development of broadly applicable management strategies (see fig. 13.1 for general framework and fig. 13.2 for example). A process similar to the Climate Project Screening Tool (Morelli et al. 2012) could be adapted to landscape management.

In many cases, similar adaptation options were identified for more than one resource sector, suggesting a need to integrate adaptation planning across multiple disciplines. Adaptation options that yield benefits to more than one resource are likely to have the greatest benefit (Halofsky et al. 2011; Peterson et al. 2011; Raymond et al. 2014). However, some adaptation options involve tradeoffs and uncertainties that need further exploration. Assembling an interdisciplinary team to tackle this issue will be critical for assessing risks and developing risk management options.

Applications

The climate change vulnerability assessment and adaptation approach developed by the NRAP can be used by the USFS, NPS, and other organizations in many ways (fig. 13.3, table 13.2). From the perspective of federal land management, this information can integrate within the following aspects of agency operations:

- *Landscape management assessments/planning:* The vulnerability assessment provides information on departure from desired conditions and best science on effects of climate change on resources for inclusion in planning assessments. The adaptation strategies and tactics provide desired forest/grassland conditions, objectives, standards, and guidelines for land management plans and general management assessments.
- *Resource management strategies:* The vulnerability assessment and adaptation strategies and tactics can be used to incorporate NRAP best science into conservation strategies, fire management plans, infrastructure planning, and State Wildlife Action Plans.

15782 • *Project NEPA analysis:* The vulnerability assessment provides best available science for
15783 documentation of resource conditions, effects analysis, and alternatives development. Adaptation
15784 strategies and tactics provide mitigation and design tactics at specific locations.

15785 • *Monitoring plans:* The vulnerability assessment can help identify knowledge gaps that
15786 can be addressed by monitoring in broad-scale strategies, plan-level programs, and project-level
15787 data collection.

15788 We are optimistic that climate change awareness, climate-smart management and planning, and
15789 implementation of adaptation in the Northern Rockies will continue to evolve. We anticipate that by the
15790 end of the decade:

- 15791 • Climate change will become an integral component of business operations.
- 15792 • The effects of climate change will be continually assessed on natural and human systems.
- 15793 • Monitoring activities will include indicators to detect the effects of climate change on
15794 species and ecosystems.
- 15795 • Agency planning processes will provide opportunities to manage across boundaries.
- 15796 • Restoration activities will be implemented in the context of the influence of a changing
15797 climate.
- 15798 • Management of carbon will be included in adaptation planning.
- 15799 • Institutional capacity to manage for climate change will increase within federal agencies
15800 and local stakeholders.
- 15801 • Managers will implement climate-informed practices in long-term planning and
15802 management.

15803 This assessment provides the foundation for implementing adaptation options that help reduce the
15804 negative effects of climate change and transition resources to a warmer climate. We hope that building on
15805 existing partnerships, the assessment will foster collaborative climate change adaptation in resource
15806 management and planning throughout the Northern Rockies.

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Tables

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Table 1.1—U.S. Forest Service policies related to climate change.

Policy	Description
Forest Service Strategic Framework for Responding to Climate Change (USDA FS 2008)	Developed in 2008, the <i>Strategic Framework</i> is based on seven strategic goals in three broad categories: foundational, structural, and action. The seven goals are science, education, policy, alliances, adaptation, mitigation, and sustainable operations. Like the challenges themselves, the goals are interconnected; actions that achieve one goal tend to help meet other goals. The key is to coordinate approaches to each goal as complementary parts of a coherent response to climate change. All seven goals are ultimately designed to achieve the same end (the USFS mission): to ensure that Americans continue to benefit from ecosystem services from national forests and grasslands.
USDA 2010-2015 Strategic Plan (USDA FS 2010d)	In June 2010, the U.S. Department of Agriculture released the <i>Strategic Plan</i> that guides its agencies toward achieving several goals including Strategic Goal 2—Ensure our national forests and private working lands are conserved, restored, and made more resilient to climate change, while enhancing our water resources. This goal has several objectives. Objective 2.2 is to lead efforts to mitigate and adapt to climate change. The performance measures under this objective seek to reduce greenhouse gas emissions by the U.S. agricultural sector, increase the amount of carbon sequestered on U.S. lands, and bring all national forests into compliance with a climate change adaptation and mitigation strategy. The USFS response to this goal includes the <i>National Roadmap for Responding to Climate Change</i> and <i>Performance Scorecard</i> .
National Roadmap for Responding to Climate Change (USDA FS 2010c)	Developed in 2011, the <i>Roadmap</i> integrates land management, outreach, and sustainable operations accounting. It focuses on three kinds of activities: assessing current risks, vulnerabilities, policies, and gaps in knowledge; engaging partners in seeking solutions and learning from as well as educating the public and employees on climate change issues; and managing for resilience in ecosystems and human communities through adaptation, mitigation, and sustainable consumption strategies.
Climate Change Performance Scorecard (USDA FS 2010a)	To implement the <i>Roadmap</i> , starting in 2011, each national forest and grassland began using a 10-point scorecard to report accomplishments and plans for improvement on 10 questions in four dimensions: organizational capacity, engagement, adaptation, and mitigation. By 2015, each is expected to answer “yes” to at least seven of the scorecard questions, with at least one “yes” in each dimension. The goal is to create a balanced approach to climate change that includes managing forests and grasslands to adapt to changing conditions, mitigating climate change, building partnerships across boundaries, and preparing employees to understand and apply emerging science.
2012 Planning Rule (USDA FS 2012)	The <i>2012 Planning Rule</i> is based on a planning framework that will facilitate adaptation to changing conditions and improvement in management based on new information and monitoring. There are specific requirements for addressing climate change in each phase of the planning framework, including in the assessment and monitoring phases, and in developing, revising, or amending plans. The <i>2012 Planning Rule</i> emphasizes restoring the function, structure, composition, and connectivity of ecosystems and watersheds to adapt to the effects of a changing climate and other ecosystem drivers and stressors, such as wildfire and insect outbreaks. A baseline assessment of carbon stocks required in assessment and monitoring will check for measureable changes in the plan area related to climate change and other stressors. Requirements of the <i>Roadmap</i> and <i>Scorecard</i> and requirements of the <i>2012 Planning Rule</i> are mutually supportive and provide a framework for responding to changing conditions over time.

Table 1.2—National Park Service policies related to climate change.

Policy	Description
National Park Service Climate Change Response Strategy (NPS 2010)	Developed in 2010, the <i>Climate Change Response Strategy</i> is designed to guide management actions and collaboration, from the national to park levels, to address the effects of climate change. The <i>Response Strategy</i> is based on four components: science, mitigation, adaptation, and communication. These components provide a framework for consistent, legal, and appropriate management decisions. The <i>Response Strategy</i> calls for a scientific approach to updating interpretations of previous policy and mandates in order to uphold the mission of the NPS in the face of new conditions created by climate change.
A Call to Action: Preparing for a Second Century of Stewardship and Engagement (NPS 2011)	The <i>Call to Action</i> outlines themes and goals for the second century of stewardship and engagement of the NPS. The plan provides actions for the achievement of each goal before the NPS centennial in 2016. Under the theme of preserving America's special places, the plan sets the goal for management of resources to increase resilience to climate change stressors. Specific actions include revised management objectives, increases in sustainability, and changes in investments.
Green Parks Plan (NPS 2012b)	The <i>Green Parks Plan</i> (GPP) outlines how the NPS will achieve the commitment set in <i>A Call to Action</i> , to "Go Green." An overarching vision and strategy for sustainable management in the future, the GPP is based on nine strategic goals that focus on the effects of park operations on the environment and human welfare. The goals are to continually improve environmental performance; be climate friendly and climate ready; be energy smart; be water wise; develop a green NPS transportation system, buy green and reduce, reuse, and recycle; preserve outdoor values; adopt best practices; and foster sustainability beyond NPS boundaries.
Revisiting Leopold: Resource Stewardship in the National Parks (NPS 2012c)	In August 2012, the NPS released the <i>Revisiting Leopold</i> , intended as a updated interpretation of the guiding document <i>The Leopold Report</i> (Leopold et al. 1963). Members of the current NPS Science Committee were tasked with revisiting three questions: (1) What should be the goals of resource management in the National Parks? (2) Which policies for resource management are necessary to achieve these goals? (3) Which actions are required to implement these policies? The interpretation presents general principles and guidance for the enlarged scope of all natural and cultural resources of the NPS. The committee stresses that the NPS needs to act quickly on structural changes and long-term investments in management in order to preserve resources through the uncertainties of environmental change.
Climate Change Action Plan 2012—2014 (NPS 2012a)	The 2012 <i>Climate Change Action Plan</i> builds on the 2010 <i>NPS Climate Change Response Strategy</i> to communicate how the NPS can respond to climate change at different geographic scales. The plan outlines parameters for introducing science, adaptation, mitigation, and communication actions to address climate change. The plan also identifies high-priority actions for addressing climate change in NPS operations, and describes how to anticipate and prepare for future changes.

Table 3.1—CMIP5 climate projections for RCP 4.5 and RCP 8.5 scenarios were obtained for these models using the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections” archive at: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections. The first model run was selected for this analysis.

Institution	Climate model	RCP 4.5	RCP 8.5
Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	ACCESS1-0	X	X
Beijing Climate Center, China Meteorological Administration	ACCESS1-3	X	X
Beijing Climate Center, China Meteorological Administration	bcc-csm1-1	X	X
Beijing Climate Center, China Meteorological Administration	bcc-csm1-1-m	X	X
Canadian Centre for Climate Modelling and Analysis	CanESM2	X	X
National Center for Atmospheric Research	CCSM4	X	X
Community Earth System Model Contributors	CESM1-BGC	X	X
	CESM1-CAM5	X	X
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC-CM	X	X
Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5	X	X
Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence	CSIRO-Mk3-6-0	X	X
EC-EARTH consortium	EC-EARTH	X	X
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University	FGOALS-g2	X	X
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University	FGOALS-s2	X	X
The First Institute of Oceanography, State Oceanic Administration, China	FIO-ESM	X	X
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3	X	X
	GFDL-ESM2G	X	X
	GFDL-ESM2M	X	X
NASA Goddard Institute for Space Studies	GISS-E2-H-CC	X	
	GISS-E2-R	X	X
	GISS-E2-R-CC	X	
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HADGEM2-AO	X	X
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HADGEM2-CC	X	X
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	HADGEM2-ES	X	X
Institute for Numerical Mathematics	INM-CM4	X	X
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	X	X
	IPSL-CM5A-MR	X	X
	IPSL-CM5B-LR	X	X
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	X	X
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC-ESM-CHEM	X	X
	MIROC5	X	X
Max Planck Institute for Meteorology (MPI-M)	MPI-ESM-LR	X	X
Max Planck Institute for Meteorology (MPI-M)	MPI-ESM-MR	X	X
Meteorological Research Institute	MRI-CGCM3	X	X
Norwegian Climate Centre	NorESM1-M	X	X
Norwegian Climate Centre	MorESM1-ME	X	X

Table 3.2—The CMIP3 models used by Littell et al. (2011). Two individual models were chosen as bracketing members: pcm1 and miroc_3.2, as well as an ensemble of 10 models from the A1B emission scenario (Nakićenović et al. 2000).

Model or ensemble	Reason for selection
Pcm1	Wetter summers: +10% by 2040s, +4% by 2080s; less temperature increase: +2.9 °F by 2040s, +5.2 °F by 2080s
Miroc_3.2	Drier summers: -12% by 2040s, -28% by 2080s; more temperature increase: +5.6 °F by 2040s, +10.4 °F by 2080s.
Ensemble A1B (comprised of models: bccr, cnrm_cm3, csiro_3_5, echam5, echo_g, hadcm, hadgem1, miroc_3.2, miroc3_2_hi, pcm1)	The suite of models reflects those models that best represented the historical Pacific Northwest climate.

Table 4.1—Adaptation options that address climate change effects on water resources in the Northern Rockies.

Sensitivity to climatic variability and change: Increased flooding will increase damage to roads and infrastructure.			
Adaption Strategy / Approach: Identify and proactively decrease vulnerability of infrastructure to flooding.			
Tactic	Specific Tactic – A Increase resilience of stream resources by identifying and restoring degraded riparian areas to reduce flooding and increase natural storage; add large woody debris, improve floodplain connectivity, increase riparian roughness, restore beavers.	Specific Tactic – B Conduct a basin-wide risk assessment of hydrologic interactions with roads and other infrastructure where vulnerability of infrastructure is highest.	Specific Tactic – C Increase resilience of infrastructure: culvert sizing, hardened fords, road drainage, etc.; remove or relocate infrastructure (e.g., roads, campgrounds).
Where can tactics be applied?	All lands	Federal and private lands	Mostly federal lands
Sensitivity to climatic variability and change: Increased occurrence of disturbances such as drought and flooding will reduce water quality.			
Adaption Strategy / Approach: Build an information base for a timely response to disturbance, thus ensuring that data are available to inform decision making.			
Tactic	Specific Tactic – A Prioritize data collection based on projections of future drought.	Specific Tactic – B Collect pre-disturbance data on stream and riparian conditions, including high-quality values and habitat in need of protection.	Specific Tactic – C Develop a clearinghouse for available funding and programs related to fire and other disturbances.
Where can tactics be applied?	Mostly federal lands	Mostly federal lands	Mostly federal lands

Table 4.1 (cont.)—Adaptation options that address climate change effects on water resources in the Northern Rockies.

Sensitivity to climatic variability and change: Reduced base flows will cause smaller riparian habitats and morphological changes, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaption Strategy / Approach: Increase knowledge about the groundwater resource.			
Tactic	Specific Tactic – A Map aquifers and alluvial deposits	Specific Tactic – B Determine legal availability and better understanding of physical availability of water for aquifer recharge	Specific Tactic – C Improve monitoring of streamflow and groundwater to improve understanding of surface water-groundwater interactions; obtain real-time data
Where can tactics be applied?	All lands	All lands	All lands
Sensitivity to climatic variability and change: Reduced base flows will cause smaller riparian habitats and morphological changes, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaption Strategy / Approach: Increase natural storage and build storage.			
Tactic	Specific Tactic – A Increase natural water storage (mirroring natural processes) with constructed wetlands, beavers, and road obliteration.	Specific Tactic – B Promote distributed small-scale water storage in small dams, retention ponds, and swales in stream channels and uplands.	Specific Tactic – C Improve streamflow and groundwater monitoring to improve understanding of surface water-groundwater interactions and obtain real-time data.
Where can tactics be applied?	Multiple land ownerships	Agricultural lands, headwaters without native fish species	All lands

Table 4.1 (cont.)—Adaptation options that address climate change effects on water resources in the Northern Rockies.

Sensitivity to climatic variability and change: Reduced snowpack will reduce the quantity and quality of municipal water supplies.			
Adaption Strategy / Approach: Reduce erosion potential to protect municipal water supplies; prioritize municipal systems for protection.			
Tactic	Specific Tactic – A Reduce hazardous fuels.	Specific Tactic – B Reduce disturbances (off-road vehicles, grazing, etc.).	Specific Tactic – C Use road management practices that reduce erosion.
Where can tactics be applied?	High-value locations	High value-locations on public and private lands	High value locations on public lands
Sensitivity to climatic variability and change: Higher temperatures and decreased snowpack will reduce water availability.			
Adaption Strategy / Approach: Reduce water use and increase efficiency, demonstrate leadership in water efficiency, and create outreach opportunities.			
Tactic	Specific Tactic – A Communicate water saving tactics and benefits.	Specific Tactic – B Research successful water saving tactics and apply tactics where appropriate.	Specific Tactic – C Install low -low appliances at administrative sites; replace landscaping with drought tolerant plants.
Where can tactics be applied?	All lands, where appropriate	All lands, including administrative locations (campgrounds, visitor centers, etc.)	All lands, including administrative locations (campgrounds, visitor centers, etc.); use Internet, press releases, interpretive signing, etc.

Table 5.1—Projected changes in mean August air temperature, stream temperature, and streamflow for major river basins in the Northern Rockies.

NorWeST unit ^a	2040s (2030–2059)			2080s (2070–2099)		
	Air temperature ^b	Streamflow ^{b,c}	Stream temperature ^d	Air temperature	Streamflow	Stream temperature
	change	change	change	change	change	change
	°F	Percent	°F	°F	Percent	°F
Yellowstone	5.06	- 4.1	1.82	9.14	- 5.4	3.26
Clearwater	5.71	-23.9	2.92	9.81	-34.2	5.00
Spokane-Kootenai	5.49	-20.1	2.29	9.59	-31.5	3.94
Upper Missouri	5.85	-14.9	2.11	9.85	-21.3	3.49
Marias-Missouri	5.24	-10.0	1.35	9.54	-18.7	2.47

^a For boundaries of NorWeST production units, see the NorWeST website (<http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>).

^b Changes in air temperature and streamflow are expressed relative to the 1980s (1970–1999) baseline climate period. Projections are based on the A1B emission scenario represented by an ensemble of 10 global climate models that best projected historical climate conditions during the 20th century in the northwestern United States (Hamlet et al. 2013, Mote and Salathé 2010). Additional details about the scenarios are provided elsewhere (Hamlet et al. 2013, Wenger et al. 2010).

^c For more information on streamflow, see the western United States flow metrics website (http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml) and the Pacific Northwest Hydroclimate Scenarios Project website (<http://warm.atmos.washington.edu/2860>).

^d Changes in stream temperatures account for differential sensitivity to climate forcing within and among river basins as described in Luce et al. (2014) and at the NorWeST website. For more information on stream temperatures, see Isaak et al. (2010), Luce et al. (2014) and the NorWeST website.

Table 5.2—Length of streams in the Northern Rockies, categorized by mean August stream temperature during the baseline climate period and by land administrative status. Values in parentheses are percentages of the total in the last row.

Land status ^{a, b}	<46 °F	46-52 °F	52-57 °F	57-63 °F	63-68 °F	>68 °F	Total
	<i>Miles (percent of total)</i>						
Private	274 (3.2)	5,494 (15.8)	16,524 (47.2)	14,465 (64.4)	8,178 (73)	1,067 (66.1)	46,002 (40.4)
The Nature Conservancy	1 (0)	191 (0.5)	99 (0.3)	9 (0)	1 (0)	0 (0)	301 (0.3)
Tribal	170 (2.0)	769 (2.2)	3,371 (9.6)	4,181 (18.6)	1,593 (14.2)	380 (23.5)	10,464 (9.2)
State/City	137 (1.6)	1,578 (4.5)	2,529 (7.2)	1,156 (5.1)	723 (6.5)	62 (3.8)	6,185 (5.4)
Bureau of Land Management	49 (0.6)	826 (2.4)	838 (2.5)	268 (1.2)	207 (1.8)	55 (3.4)	2,243 (2.0)
National Park Service	537 (6.2)	1,689 (4.9)	654 (1.9)	296 (1.3)	70 (0.6)	1 (0.1)	3,247 (2.9)
Forest Service Wilderness	2,269 (26.2)	3,516 (10.1)	1,174 (3.4)	175 (0.8)	39 (0.3)	1 (0)	7,174 (6.3)
Forest Service Non-Wilderness	4,825 (55.8)	19,299 (55.5)	8,168 (23.3)	1,041 (4.6)	206 (1.8)	16 (1)	33,555 (29.5)
Other	386 (4.5)	1,438 (4.1)	1,596 (4.6)	876 (3.9)	193 (1.7)	33 (2.1)	4,522 (4.0)
Total	8,648	34,800	34,953	22,467	11,210	1,615	113,693

^a Stream reaches with slope less than 15 percent and summer flows greater than 0.20 ft³ s⁻¹, based on the Variability Infiltration Capacity model (see text).

^b Other category includes U.S. Army Corps of Engineers, U.S. Fish and Wildlife Service, U.S. Bureau of Reclamation, and lands with undesignated status.

Table 5.3—Length of streams in the Northern Rockies, categorized by mean August stream temperature during the baseline and two future climate periods and by land administrative status (Forest Service [FS] and non-Forest Service [Non-FS]). Values in parentheses are percentages of the total in the last column.

Land status ^a	<46 °F	46–52 °F	52–57 °F	57–63 °F	63–68 °F	>68 °F	Total
<i>Miles (percent of total) ^b</i>							
<u>FS lands</u>							
1980s	7,094 (17.4)	22,815 (56.0)	9,342 (22.9)	1,216 (3.0)	244 (0.6)	17 (0)	40,728
2040s	2,504 (6.3)	17,858 (44.7)	15,911 (39.8)	3,092 (7.7)	445 (1.1)	121 (0.3)	39,931
2080s	961 (2.4)	12,701 (32.3)	19,051 (48.5)	5,525 (14.1)	836 (2.1)	237 (0.6)	39,311
<u>Non-FS lands</u>							
1980s	1,554 (2.1)	11,986 (16.4)	25,645 (35.1)	21,260 (29.1)	10,963 (15.0)	1,597 (2.2)	73,005
2040s	569 (0.8)	5,960 (8.4)	20,980 (29.5)	24,422 (34.3)	15,434 (21.7)	3,820 (5.4)	71,185
2080s	253 (0.4)	3,448 (4.9)	16,401 (23.3)	25,128 (35.7)	18,410 (26.1)	6,798 (9.7)	70,438

^a Stream reaches with slope less than 15 percent and summer flows greater than 0.20 ft³ s⁻¹, based on the Variability Infiltration Capacity model (see text).

^b Reductions in network extent result from projected decreases in summer flows as described in table 5.1.

Table 5.4—Number and length of cold-water habitats for juvenile cutthroat trout by probability of occurrence for three climate periods and two brook trout invasion scenarios across the Northern Rockies.

		Probability of occurrence (percent)					Total
		<25	25–50	50–75	75–90	>90	
<i>Cold-water habitat number</i>							
0% brook trout prevalence	1980s	71	392	1,140	1,817	1,739	5,159
	2040s	41	328	1,405	1,505	1,148	4,427
	2080s	86	659	949	977	770	3,441
50% brook trout prevalence	1980s	73	501	2,790	1,384	581	5,329
	2040s	41	382	2,571	1,065	367	4,426
	2080s	86	684	1,837	673	161	3,441
<i>Cold-water habitat length</i>				<i>Miles</i>			
0% brook trout prevalence	1980s	268	794	4,068	7,730	32,646	45,506
	2040s	78	558	3,832	6,034	17,964	28,466
	2080s	142	1,031	2,938	4,151	10,459	18,721
50% brook trout prevalence	1980s	387	1,456	6,413	8,203	12,023	28,482
	2040s	126	855	5,079	5,451	6,404	17,915
	2080s	228	1,238	3,931	3,908	2,857	12,162

Table 5.5—Number and length of cold-water habitats for juvenile bull trout by probability of occurrence during three climate periods and two brook trout invasion scenarios in the Northern Rockies.

		Probability of occurrence (percent)					Total
		<25	25–50	50–75	75–90	>90	
<i>Cold-water habitat number</i>							
0% brook trout prevalence	1980s	875	534	248	92	106	1,855
	2040s	664	314	98	41	32	1,149
	2080s	474	274	81	24	13	866
50% brook trout prevalence	1980s	995	484	181	65	28	1,753
	2040s	697	270	63	17	5	1,052
	2080s	535	260	49	5	3	852
<i>Cold-water habitat length</i>				<i>Miles</i>			
0% brook trout prevalence	1980s	2,906	3,168	2,565	1,616	4,657	14,912
	2040s	2,222	1,934	1,129	769	1,340	7,394
	2080s	1,310	1,324	773	386	579	4,372
50% brook trout prevalence	1980s	3,920	3,762	2,712	1,891	2,351	14,636
	2040s	2,728	2,208	1,191	589	408	7,124
	2080s	1,569	1,645	704	153	266	4,337

Table 5.6—Adaptation options that address climate change effects on fisheries in the Northern Rockies.

Sensitivity to climatic variability and change: Reduced snowpack will decrease summer streamflows.			
Adaption Strategy / Approach: Increase streamflows and moderate changes in instream flows.			
Tactic	Specific Tactic – A Pulse flows from regulated streams during critical times (high temperatures)	Specific Tactic – B Reduce water withdrawals and improve efficiency for agriculture (especially irrigation), municipal, and industrial uses	Specific Tactic – C Secure water rights for instream flows
Where can tactics be applied?	All regulated streams	Where water demands overlap with current and future suitable habitat	Where fish and suitable habitat overlap
Sensitivity to climatic variability and change: Reduced snowpack will increase stream temperatures and alter flow regimes.			
Adaption Strategy / Approach: Increase habitat resilience for cold-water aquatic organisms by restoring structure and function of streams.			
Tactic	Specific Tactic – A Restore natural channel and floodplain form and function (e.g., restore areas with human-caused bank and bed instability)	Specific Tactic – B Restore aquatic organism passage structures through design and placement of appropriate structures.	Specific Tactic – C Maintain functional stream channel morphology with adequate width:depth ratios, pool frequency, and healthy riparian vegetation
Where can tactics be applied?	Areas with ongoing restoration activities and where habitat is a primary limiting factor (especially where roads are present)	Drainages with frequent high peakflows, areas with sensitive geology, areas with important rearing streams	Areas with ongoing restoration activities and where habitat is a primary limiting factor (especially where roads are present)

Table 5.6 (cont.)—Adaptation options that address climate change effects on fisheries in the Northern Rockies.

Sensitivity to climatic variability and change: Reduced snowpack will increase stream temperatures and alter flow regimes.			
Adaption Strategy / Approach: Increase habitat resilience for cold-water aquatic organisms by restoring structure and function of streams.			
Tactic	Specific Tactic – A Restore riparian areas to increase hydrologic function and retain cold water	Specific Tactic – B Reintroduce beaver where beaver and management of westslope cutthroat trout are compatible	Specific Tactic – C Remove or relocate roads adjacent to riparian areas, channels, and floodplains where they inhibit complexity; minimize cumulative effect of road network on surface and subsurface flow
Where can tactics be applied?	Where riparian areas limit the availability of cold-water habitat	Where beaver will not affect barriers; in stream reaches >1 mile; in larger population conservation networks; where brook trout are absent	Where roads currently cause problems or may do so in the future, especially where roads occupy lengthy portions of the riparian zone
Sensitivity to climatic variability and change: Reduced snowpack will increase stream temperatures, affecting native species and interactions between natives and nonnatives.			
Adaption Strategy / Approach: Provide opportunities for native fish to move and find suitable stream temperatures.			
Tactic	Specific Tactic – A Increase the patch size of favorable habitat to enhance viable populations and allow migratory life histories	Specific Tactic – B Modify or remove barriers to increase connectivity between areas of cold-water habitat	Specific Tactic – C Identify and map where groundwater inputs provide cold water
Where can tactics be applied?	Where native fish currently exist; where suitable habitat is nearby; where nonnatives are not present or can be effectively managed; where populations are fragmented and need greater connectivity	Where barriers prevent movement to suitable habitat, and where removal will not increase invasion of nonnatives	All locations

Table 5.6 (cont.)—Adaptation options that address climate change effects on fisheries in the Northern Rockies.

Sensitivity to climatic variability and change: Warmer temperatures will increase stream temperature and risk of invasion by nonnative fish species.			
Adaption Strategy / Approach: Manage nonnative fish populations to eliminate or reduce their impact on native fish.			
Tactic	Specific Tactic – A Encourage increased take/harvest of nonnatives, especially near long-term strongholds for natives	Specific Tactic – B Remove nonnatives with manual or chemical techniques	Specific Tactic – C Exclude nonnatives with physical or electrical barriers
Where can tactics be applied?	Areas with heavy recreation and sport fishing; most effective at the front of invasions	Where long-term suitable habitat for natives is available and nonnatives are present	Where long-term suitable habitat for natives is available and nonnatives are present
Sensitivity to climatic variability and change: Continued livestock grazing will compound stress caused by increased stream temperatures.			
Adaption Strategy / Approach: Manage livestock grazing to restore ecological function of riparian vegetation and channels.			
Tactic	Specific Tactic – A Comply with all existing standards and guidelines for maintaining water quality in streams and riparian areas; facilitate compliance through monitoring	Specific Tactic – B Use innovative techniques to fund and maintain and implement improvements (e.g., riparian fencing, rest-rotation systems, off-channel water, exclosures)	Specific Tactic – C Identify and prioritize vacant allotments for retirement
Where can tactics be applied?	All locations, with emphasis on areas that are important in terms of ecological value and large financial investment	All locations, with emphasis on areas that are important in terms of ecological value and prior financial investment; prioritize areas with core conservation fish populations that are under imminent threat	All locations where vacant allotments exist and opportunities allow

Table 5.6 (cont.) —Adaptation options that address climate change effects on fisheries in the Northern Rockies.

Sensitivity to climatic variability and change:			
Higher temperatures will increase wildfire occurrence that can lead to erosion and mass wasting.			
Adaption Strategy / Approach:			
Increase resilience to fire-related disturbance.			
Tactic	Specific Tactic – A Implement fuel treatments (thinning, prescribed burning) to reduce wildfire severity and size	Specific Tactic – B Disconnect roads from stream networks to reduce erosion and sediment delivery to streams	Specific Tactic – C Install erosion control structures following wildfires
Where can tactics be applied?	Areas where canopy and surface fuels are high, adjacent to known native fish populations and habitat	Areas adjacent to known native fish populations and habitat	Where wildfire has occurred and erosion would affect known native fish populations and habitat

Table 6.1—Comparison of attributes characterizing a species' adaptive strategy.¹

Attributes	Adaptive strategy	
	Specialist	Generalist
Factor controlling phenotypic expression of adaptive traits	Genotype	Environment
Mechanisms for accommodating environmental heterogeneity	Genetic variation	Phenotypic plasticity
Range of environments where physiological processes function optimally	Small	Large
Slope of clines for adaptive traits	Steep	Flat
Partitioning of genetic variation in adaptive traits	Largely among populations	Largely within populations

¹ Modified after Rehfeldt (1994).

Table 6.2—Assessment for soils to apply to vegetation concerns in the Northern Rockies (NR).

Broad-scale climate change effect	Ecosystem function	Current condition, existing stressors	Sensitivity to climatic variability and change	Expected effects of climate change	Risk assessment	
					Magnitude of effects	Likelihood of effects
Mainly changes in summer precipitation Higher summer temperatures	Available water (for vegetation)	Relative effective annual precipitation has been mapped for MT. Current condition has not been assessed for ID and ND. Existing stressors: extremes in water year (more frequent droughts), high stand densities.	Variable, depending on species, subregion and slope position.	In western Northern Rockies, decreased precipitation is projected at low elevations; increased summer drought may result. High elevations may have increased precipitation. In eastern Northern Rockies, the higher interannual variation of precipitation would lead to years of increased drought. No trend projected for annual or seasonal precipitation.	High	High
Increased atmospheric CO ₂	Nutrient cycling for vegetation production	Variable. Nitrogen is the most common nutrient deficiency, but other nutrients (phosphorus, potassium, boron) are also limiting. Existing stressors: severe fires, erosion.	Unknown. Potassium is easily lost on some metasediments, during whole-tree yarding.	Nitrogen, phosphorus, potassium and boron will become less available if soils become more acidic. Increased acidity of leachate would contribute to faster parent material decomposition, which would release inherent mineral nutrients in soil.	Unknown	High
Soil temperature, moisture, and CO ₂ levels	Soil biota	Most soils have healthy soil biota. Exceptions occur on abandoned roads and landings. Some stands have reduced biotic health from past management. Existing stressors: Severe fires, erosion	Moderate	Alteration of soil biota (fungi, microbes, nematodes) as well as the communities.	Variable	Very high

Table 6.2(cont.)—Assessment for soils to apply to vegetation concerns in the Northern Rockies (NR).

Broad-scale climate change effect	Ecosystem function	Current condition, existing stressors	Sensitivity to climatic variability and change	Expected effects of climate change	Risk assessment	
					Magnitude of effects	Likelihood of effects
Everything that contributes to increased fire and flood (e.g., more frequent high-intensity storms)	Soil stability	Little surface erosion occurs in the Northern Rockies Existing stressors: Most erosion occurs after severe wildfires or floods. Small amounts may occur in conjunction with roads, timber sales, grazing, and other land management activities.	High—existing stressors will become more prevalent.	Areas with decreased ground cover will be susceptible to increased surface erosion from wind and water.	Moderate	Very high
Changes in spring and autumn precipitation (rain rather than snow, period of saturation longer)	Slope stability	Landslide prone areas have been mapped. Existing stressor: long period of saturation in some years.	Variable	Size and frequency of landslides will increase.	Broad	Very high
Temperature, precipitation and CO ₂ concentrations	Soil carbon storage and dynamics	Soil is currently a major carbon storage pool and will continue to be a carbon sink as long as young stands continue to mature. Current stressors: periodic wildfires and insect outbreaks.	High in areas where disturbances become more prevalent.	If wildfire increases in frequency and extent as much as projected, this will maintain forests in younger age classes with less potential for carbon storage but higher carbon uptake.	Potentially high in drier forests	High in dry forests

Table 6.3—Summary of tree characteristics that indicate possible responses to future climate change. All fields are rated on a scale from one to five, with 1 generally indicating low levels and five generally indicating high levels of the variable (see specific notes below).

Species	Distribution ¹	Tolerances ²			Diversity ³	Genetics		Mycorrhizal dependence ⁶	Insect and disease exposure ⁷	Seed dissemination strategy ⁸
		Shade	Drought	Fire		Geographic Differentiation ⁴	Strategy ⁵			
Limber pine	1	1	5	2	3	3	I	4	4	5,4
Ponderosa pine–var. <i>scopulorum</i>	3	2	4	4	3	2	I	3	2	3,4
Ponderosa pine–var. <i>ponderosa</i>	3	2	4	5	3	2	I,S	3	4	3,4
Douglas-fir	4	4	4	4	2	2	S,G	3	3	3
Western larch	2	2	2	5	3	2	I	2	2	3
Western white pine	1	2	2	5	3	3	G	2	4	3,4
Aspen	2	1	4	1	5	2	G	2	3	3,2
Grand fir	2	4	2	2	2	2	G	2	4	3
Western redcedar	2	5	5	2	1	2	S	1	2	3
Western hemlock	2	5	5	2	2	2	S	2	2	3
Lodgepole pine	4	2	3	3	4	2	S	3	4	6
Whitebark pine	3	3	2	3	4	3	G	3	4	5
Subalpine fir	4	4	4	1	3	2	I	2	3	3
Engelmann spruce	3	4	4	2	3	2	I	2	2	3
Mountain hemlock	1	4	5	1	2	2	S	2	2	3
Alpine larch	1	1	5	1	2	3	S	3	1	3
Green ash	2	1	2	1	2	3	G	4	1	3
Cottonwood	2	1	4	3	3	3	G	3	2	1

¹Distribution of 1 indicates narrow distribution in the Northern Rockies, while distribution of 5 indicates wide distribution.

²Shade, drought, and fire tolerance of 1 indicates high intolerance, while 5 indicates high tolerance.

³Genetic diversity of 1 indicates low diversity and 5 indicates high diversity.

⁴Geographic differentiation of 1 indicates low genetic differentiation (narrow seed zones) and 5 indicates wide differentiation (large seed zones).

⁵Genetic adaptive strategy of G indicates a generalist species (grows under wide range of conditions), I indicates an intermediate species (grows over a moderate range of conditions), and S indicates a specialist species (grows under a narrow range of conditions) (from Scott et al. 2013).

⁶Mycorrhizal dependence of 1 indicates that the species is not dependent on mycorrhizae, while 5 indicates that the species is highly dependent on mycorrhizae.

⁷Insect/disease exposure of 1 indicates that the species is not susceptible to many damaging agents, while 5 indicates that the species is highly susceptible to insects and disease.

⁸Seed dissemination is the primary means of seed dispersal where 1–water, 2–sprouts, 3–wind/gravity, 4–rodent, 5–bird, 6–serotinous.

Table 6.4—Categories used to assess the vulnerability of species, vegetation types, and resource concerns in this chapter.

Evaluation category	Description	Example
Habitat, ecosystem function, or species	Specific biophysical or social entity of interest	Whitebark pine
Broad-scale climate change effect	Overarching change in climate that is expected to affect a resource	Warming temperatures
Current condition, existing stressors	Current status of resource relative to desired conditions, including factors that are reducing the quality or quantity of the resource	Reduced abundance, wildland fire, mountain pine beetle, white-pine blister rust
Sensitivity to climatic variability and change	Specific sensitivity of a habitat, species, or ecosystem function that responds to climate	Low ability to compete with encroaching conifers
Expected effects of climate change	How specific habitat, species, or ecosystem function is expected to respond to climate change (develop inferences from model projections and known responses to climatic variability)	Regeneration may be reduced by combination of warming and low seed availability
Adaptive capacity	Ability to adjust to climate change, to moderate potential damages, or to cope with the consequences; usually more appropriate for species than for systems and processes	Variable: unable to compete with other tree species, but bird-mediated seed dispersal allows quick colonization of burned over areas
Exposure	The extent to which each species' physical environment will change expressed as low, moderate or high	High
Risk assessment, magnitude of effects	Estimate of the magnitude of climate change effects expressed as low, moderate, or high by time period	Moderate
Risk assessment, likelihood of effects	Estimate of the likelihood that climate change effects will occur expressed as low, moderate, or high by time period	High

Table 6.5—Final tree species ratings for the entire Northern Rockies (NR), and the five sub-regions of the NR. The table from lowest to highest vulnerability in the NR. Also included are ratings from the Pacific Northwest in Devine et al. (2012) report and from the northern Rocky Mountains in Hansen and Phillips (2015).

Tree species	NR	West	Central	East	GYA	Grass	Devine et al. (2012)	Hansen and Phillips (2015)
Alpine larch	1	2	1	NA ¹	NA	NA	4	NRT ²
Whitebark pine	2	1	2	1	1	NA	1	1
Western white pine	3	5	3	NA	NA	NA	13	NRT
Western larch	4	6	4	NA	NA	NA	12	8
Douglas-fir	5	8	8	2	2	1	11	9
Western redcedar	6	4	5	NA	NA	NA	15	7
Western hemlock	7	3	6	NA	NA	NA	10	6
Grand fir	8	7	7	NA	NA	NA	5	11
Engelmann spruce	9	9	11	3	4	5	3	5
Subalpine fir	10	10	12	4	5	6	2	4
Lodgepole pine	11	11	10	5	6	7	8	3
Mountain hemlock	12	3	9	NA	NA	NA	7	2
Cottonwood	13	12	13	6	3	2	17	NRT
Aspen	14	13	14	8	7	3	6	NRT
Limber pine	15	NA	15	7	8	4	18	NRT
Ponderosa pine-west	16	14	16	NA	NA	NA	14	10
Ponderosa pine-east	17	NA	NA	8	9	8	NRT	10
Green ash	18	NA	NA	9	10	9	19	NRT

¹NA = Not applicable

²NRT = Not rated

Table 6.6—Adaptation options that address climate change effects on forested vegetation in the Northern Rockies.

Sensitivity to climatic variability and change: The frequency and scale of disturbance will likely increase with climate change.			
Adaption Strategy / Approach: Promote disturbance-resilient species, including western larch and western white pine on moist sites, ponderosa pine on dry sites, Douglas-fir on extremely dry sites, and lodgepole pine on harsh sites that are difficult to regenerate.			
Tactic	Specific Tactic – A Thin to favor disturbance-resilient species.	Specific Tactic – B Plant disturbance-resilient species.	Specific Tactic – C Promote disturbance-resilient species with prescribed fire and/or natural fire use.
Where can tactics be applied?	On sites most likely to be affected by wildfire	On sites most likely to be affected by wildfire	On sites most likely to be affected by wildfire
Sensitivity to climatic variability and change: Increasing temperatures with climate change will lead to increased moisture stress and fire.			
Adaption Strategy / Approach: Reduce forest density and maintain low densities.			
Tactic	Specific Tactic – A Conduct thinning treatments (pre-commercial and commercial).	Specific Tactic – B Use prescribed fire to maintain structure and promote fire-tolerant conifer species.	Specific Tactic – C Use regeneration and planting to influence forest structure.
Where can tactics be applied?	On overstocked sites with low risk of root disease problems	On overstocked sites	Where there are no opportunities for thinning because of species or stand condition.
Sensitivity to climatic variability and change: Areas with limited species and genetic diversity will likely be more susceptible to climate change stressors.			
Adaption Strategy / Approach: Promote species and genetic diversity.			
Tactic	Specific Tactic – A Plant potential microsites with mix of species (hedge your bets).	Specific Tactic – B Maintain species diversity during thinning.	Specific Tactic – C Interplant to supplement natural regeneration and genetic diversity.
Where can tactics be applied?	In sufficiently large openings on sites most at risk for drought stress	In dense or overstocked stands on sites more at risk for drought stress and where sufficient diversity exists for thinning.	In sufficiently large openings on sites most at risk for drought stress.

Table 6.6 (cont.)—Adaptation options that address climate change effects on forested vegetation in the Northern Rockies.

Sensitivity to climatic variability and change: Increasing temperatures with climate change will lead to longer growing seasons, increased drought stress, and increased fire.			
Adaption Strategy / Approach: Promote ecosystem resilience.			
Tactic	Specific Tactic – A Promote legacy trees of western larch, Douglas-fir, western white pine, Engelmann spruce, whitebark pine, and subalpine larch for regeneration and wildlife habitat.	Specific Tactic – B Collect seed for post-wildfire reforestation and other planting needs, especially for subalpine larch, whitebark pine, and high-elevation western larch.	Specific Tactic – C Promote landscape heterogeneity and create connectivity at multiple scales.
Where can tactics be applied?	On dense spruce, fir, and lodgepole pine sites	Where species of interest occur	At the landscape scale
Sensitivity to climatic variability and change: Climate change will likely lead to increased disturbance, increased moisture deficits, and species distribution shifts.			
Adaption Strategy / Approach: Increase knowledge for agency land managers and stakeholders.			
Tactic	Specific Tactic – A Determine what connectivity means for different species and guilds.	Specific Tactic – B Track tree species regeneration and distribution.	Specific Tactic – C Improve integration between wildlife managers and forest ecologists, and between research and management.
Where can tactics be applied?	All lands	All lands	All lands
Tactic	Specific Tactic – D Monitor blister rust resistance within planted white pine stands, and try to understand the relationship between infection rates and climatic drivers (e.g., fog).	Specific Tactic – E Identify other resource management goals (not directly related to stand structure and composition) that may modify management strategies for forest vegetation, such as water yield, snow retention, and wildlife habitat.	Specific Tactic – F Support the adaptive management research framework; develop consistent monitoring framework that can capture long-term change.
Where can tactics be applied?	On sites planted with white pine	Federal lands	Federal lands

Table 6.6 (cont.)—Adaptation options that address climate change effects on forested vegetation in the Northern Rockies.

Sensitivity to climatic variability and change: Climate change will likely lead to increased whitebark pine mortality through increased mountain pine beetle activity, fire and white-pine blister rust. There will also likely be a loss of site conditions that support whitebark pine.			
Adaption Strategy / Approach: Promote resilient whitebark pine communities.			
Tactic	Specific Tactic – A Identify sites that are less likely to be affected by climate change (refugia), and focus on those sites for restoration.	Specific Tactic – B Implement a variety of management strategies and options to promote whitebark pine, including fire management, planting at lower elevations, and removing other dominant species (e.g., lodgepole pine, spruce and fir)	Specific Tactic – C Plant genetically-selected seedlings to promote blister rust resistance
Where can tactics be applied?	Federal lands	Federal lands	Federal lands
Sensitivity to climatic variability and change: Climate change will lead to increased risk of stand-replacing wildfire, mortality from drought, and loss of large ponderosa pine individuals in ponderosa pine forests.			
Adaption Strategy / Approach: Decrease density within stands, and increase structural diversity across the landscape.			
Tactic	Specific Tactic – A Reduce density by thinning, prescribed fire, and wildfire use, with density and structural goals based on past and predicted future conditions.	Specific Tactic – B Promote age class and structural diversity across the landscape, through regeneration harvest, thinning, prescribed fire and wildfire use.	Specific Tactic – C Monitor establishment, survival and development of ponderosa by age class and in different topoedaphic conditions using Forest Inventory and Analysis data and project-level stocking exams.
Where can tactics be applied?	Ponderosa pine, Douglas-fir forests	In locations where activities are allowed	Ponderosa pine, Douglas-fir forests
Sensitivity to climatic variability and change: Climate change stressors cross boundaries, forcing agencies to coordinate and work across boundaries.			
Adaption Strategy / Approach: Work across jurisdictions at a larger scales.			
Tactic	Specific Tactic – A Align budgets and priorities for program of work with neighboring lands	Specific Tactic – B Communicate about projects adjacent to other lands, and coordinate on the ground	Specific Tactic – C Work across boundaries to preserve roads, trails, and access with increasing fire and flood events
Where can tactics be applied?	All lands	All lands	All lands

Table 6.6 (cont.)—Adaptation options that address climate change effects on forested vegetation in the Northern Rockies.

Sensitivity to climatic variability and change: The vigor and extent of aspen may be reduced with increased frequency of disturbance and drought under changing climate.			
Adaption Strategy / Approach: Restore and promote the health and vigor of aspen clones.			
Tactic	Specific Tactic – A Manage ungulates during the regeneration phase (e.g., with slash barriers, increased hunting pressure, grazing management, and salt block placement)	Specific Tactic – B Remove conifers around aspen, at multiple scales and using multiple tools (i.e., hand and commercial treatments)	Specific Tactic – C Monitor the extent and condition of aspen clones to determine the effect of disturbance frequency on aspen survival, effects of sudden aspen decline, and incidence of new clones; this may lead to strategic protection measures for specific clones
Where can tactics be applied?	Wherever aspen regeneration prescriptions are applied	Wherever aspen occurs outside of protected areas	Wherever aspen occurs
Sensitivity to climatic variability and change: The distribution of subalpine forests is likely to shift as a result of increasing temperatures with climate change.			
Adaption Strategy / Approach: Monitor and detect change in seedling survival, species composition, and mortality of mature trees in subalpine forests.			
Tactic	Specific Tactic – A Install and analyze additional plots to gather trend information over time, targeting areas where changes are expected.	Specific Tactic – B Use Forest Inventory and Analysis plot information to determine trends in subalpine forests.	Specific Tactic – C Expand reforestation monitoring and post-treatment monitoring.
Where can tactics be applied?	Federal lands	All lands	In reforestation or treatment locations

Table 6.7—Management recommendations for each of the evaluated species, vegetation types, and resource concerns.

Habitat, ecosystem function, or species	Primary adaptive tactics	Restoration potential	Further management recommendations
Species			
Limber pine	Promote rust-resistance while preserving genetic diversity; monitor mortality rates and distributions; Evaluate which stands need treatment to ensure conservation of species; determine impact of fire exclusion era	Low to moderate – the main drawback is the exotic disease white-pine blister rust. Most management actions should be to increase rust resistance in native populations	Initiate rust-resistant programs; identify plus trees; collect cones and determine rust resistance; map limber pine populations and identify those stands that have become established before and after the fire exclusion era
Ponderosa pine	Restore fire to historically fire-dominated stands; reduce fuel loadings to mitigate uncharacteristic fire severities; use HRV as guide to design and conduct restoration treatments	Moderate to high – reintroducing fire or fire surrogates into fire-excluded stands is the first step; addressing where to plant in the future is the next	Reduce or eliminate Douglas-fir in fire-excluded stands; remove competition through thinnings and prescribed burns; monitor lower treeline in SW Montana and central Idaho to evaluate potential ponderosa pine increases
Douglas-fir	Reduce competition and increase vigor; keep stand density down; replace Douglas-fir with ponderosa pine, western white pine, and western larch in areas where root disease is a concern; emphasize ponderosa pine on lower elevation dry forests	Moderate to high – mitigating effects of the fire exclusion era is the first step; might be more difficult in cool, dry environs	Keep stocking low; change species composition on sites where root disease and soil moisture deficits will be increasing; concentrate planting on the higher elevation, mesic sites and avoid planting in the lower treeline
Western larch	Restore declining larch stands from adverse fire exclusion effects; Prioritize northerly aspects and ash cap soils for treatment; reduce competition; manage larch more intensively on more xeric sites where larch may not be the species to plant on south slopes even though current climate may be suitable Reduce forest density in all successional stages to provide larch with better chance to utilize soil moisture	Moderate to high in west region; moderate in central region	Cut to remove more shade-tolerant species using group selections and thinnings; consider planting options on north slopes where long term persistence will have highest potential; consider genetic stock with best adaptive traits for drought and moisture stress compatibility; Maintain stocking and structure diversity to favor moisture regime for larch in all successional stages and to be more able to cope with fire; Consider most intensive management for larch on sites with least moisture deficits
Western white pine	Promote rust-resistance	Moderate in west region; low to moderate in central region, mainly due to the devastating effects of rust mortality	Increased planting of blister rust resistant material; thinning dense stands to increase young pine vigor
Grand fir	Foster landscape heterogeneity; ensure age class structure is near HRV	High in the west and central regions	Low priority for restoration; no real need to spend valuable restoration dollars restoring this forest unless it is locally declining
Western redcedar	Ensure high landscape heterogeneity; multiple age classes	High in west and central NR regions	Low priority for restoration; no real need to spend valuable restoration dollars restoring this forest unless it is locally declining

Table 6.7(cont.)—Management recommendations for each of the evaluated species, vegetation types, and resource concerns.

Habitat, ecosystem function, or species	Primary adaptive tactics	Restoration potential	Further management recommendations
Species (cont.)			
Western hemlock	Maintain diversity of age classes and high landscape diversity	High in west and central NR regions	Low priority for restoration; no real need to spend valuable restoration dollars restoring this forest unless it is locally declining
Aspen	Restore quasi-historical fire regimes; prioritize areas where aspen already exist albeit at lower than historical levels	Moderate for all NR	Plant aspen where it is now absent but once flourished; manage aspen at the landscape level by ensuring mix of age classes and successional stages
Lodgepole pine	Perhaps the most important subalpine species to manage for mixed age classes and successional stages that approximate HRV	Moderate to high in most of its NR range	Allow WFU fires to burn in moderate years
Subalpine fir	Populations can best be modified by wildfire suppression efforts at local scales	High in most of the NR	Low priority for climate impact mitigation; no real need to spend valuable restoration dollars restoring this forest unless it is locally declining
Engelmann spruce	Populations can best be modified by wildfire suppression efforts at local scales; planting may be warranted in areas with declining populations	High in most of the NR; moderate in those low elevation wetland stands	Low priority for climate change adaptation actions; no real need to spend valuable restoration dollars conserving this forest unless it is declining locally
Mountain hemlock	Increased fire suppression efforts will increase populations if needed	Moderate to High in west and central regions of NR	While this species may have low priority for mitigating adverse climate change effects it is important to monitor the species so it does not go locally extinct
Whitebark pine	Most climate change adaptation strategies are detailed in Keane et al. (2015)[in press]; promote rust resistance; conserve genetic diversity; implement treatments on the higher stands in project areas; plant rust-resistant seedlings in old or recent burns	Low to moderate in most of its range primarily due to the devastating effects of WPBR	Follow Keane et al. (2010) rangewide strategy: protect rust-resistant plus trees; promote rust resistance; implement prescribed burn and mechanical cuttings to reduce competition; plant and direct-seed blister rust resistant seedlings on burn and treated areas; cold hardy and drought tolerant material
Alpine larch	Preserve genetic diversity by collecting and storing seed;	Low to moderate across most of its range	Monitor changes in alpine larch populations; document
Green ash	Reduce grazing; increasing fire suppression and grazing can be used to modify ash populations along with planting in those areas where populations are critically low	High in the eastern NR	Plant in recently burned areas where it last existed
Cottonwood	Foster high variability in river flows to increase seedling establishment potential; eliminate competition	Moderate to high	Prioritize the most mesic sites first; allow fire to burn in areas that are not too dense; conduct cuttings to remove conifer competition

Table 6.7(cont.)—Management recommendations for each of the evaluated species, vegetation types, and resource concerns.

<i>Vegetation types</i>			
Dry ponderosa pine and Douglas-fir forests	Create less dense forests with composition related to moisture deficit tolerance	High all over the Region with in dry settings	Manage density and appropriate composition related to projected moisture limited sites
Western larch mixed conifer forests	Create a greater landscape heterogeneity forest pattern that may limit the extent of large uncharacteristically severe disturbances using mechanical and prescribed fire as tools; Greater moisture deficits, less available moisture for trees will require consideration of appropriate species distribution and forest density in the future; Create within stand structure diversity and more open conditions to allow larch to maintain dominance	High in western portion of the region	Manage pattern of the forest to increase the diversity of successional stages and arrangement; tools in areas suitable for timber production will include timber harvest and prescribed burning, while areas in Roadless areas will be restored with wildfire for resource benefit with some planting where seed source is absent due to large fires; maintain stocking levels to favor larch moisture relationship in all successional stages and to be able to better cope with fire; Mange species composition less susceptible to root disease especially in northern Idaho; manage larch in lynx habitat knowing that larch needs more open conditions to maintain dominance over the long term in a stand
Lodgepole pine and aspen mixed conifer forests		High in most of the NR	Again, manage pattern to increase the diversity of successional stages and arrangement; Roadless areas need wildfire for resource benefit; planting to lodgepole may be needed where seed source is absent due to large fires; Mange species composition in lynx habitat knowing that returning natural fire regimes will reduce subalpine fir populations
Mixed mesic white pine, cedar, hemlock grand fir forests	Attempt to emphasize the restoration of western white pine while also maintaining landscape heterogeneities similar to historical conditions; promote rust resistance and plan treated and burned areas with pine seedlings	Moderate in most of the NR because of the exotic rust	Be careful to monitor local conditions to evaluate losses or gains in the four species so management options can be adjusted
Whitebark pine-spruce-fir forests	Most climate change adaptation strategies are detailed in Keane et al. (2015)[in press]: most important – create landscape heterogeneity in composition and size classes; also promote rust resistance; conserve genetic diversity; implement treatments on the higher stands in project areas; plant rust-resistant seedlings in old or recent burns	Low to moderate in most of its range primarily due to the devastating effects of WPBR	Follow Keane et al. (2010) rangewide strategy: protect rust-resistant plus trees; promote rust resistance; implement prescribed burn and mechanical cuttings to reduce competition; plant and direct-seed blister rust resistant seedlings on burn and treated areas; cold hardy and drought tolerant material

Table 6.7(cont.)—Management recommendations for each of the evaluated species, vegetation types, and resource concerns.

Resource concerns			
Landscape heterogeneity	Design restoration and climate change treatments at multiple scales, especially the landscape scale; allow wildfires to burn	Moderate	Landscape heterogeneity should be evaluated periodically to determine trends and magnitudes
Timber production	Thinning and planting western larch, ponderosa pine and western white pine on appropriate habitats will be important to long term timber production to enable the forest to better cope with disturbance such as fire and root disease, manage density within dry forest settings	High in western portion of region for larch and western white pine. High for ponderosa pine throughout the Region. See appendix for acres of potential larch restoration and other tree species restoration within the suitable for timber production areas and non-suitable for timber production areas; High on all dry forest settings for density reduction	Manage landscapes for species composition, structure and pattern best able to cope with moisture deficits and disturbance, especially root disease, bark beetles and fire. Manage dry forest settings to be more open grown ponderosa pine compared to current dense mixed Douglas-fir forests. Increase percent of ponderosa pine, western larch and western white pine on mixed mesic settings to cope with increase in fire and root disease. Manage for a diversity of lodgepole pine, spruce, subalpine fir, larch and whitebark pine in higher elevations considering increasing soil moisture deficits. Manage for a diversity of successional stages (landscape heterogeneity) in a pattern that will better cope with disturbance agents
Carbon sequestration	Carbon can be best sequestered by embracing ecosystem management and restoring landscapes and ecosystems; Carbon sequestration is a side-effect of an ecosystem treatment, not the objective	N/A	The best management approach for managing carbon sequestration is to foster a timber management program that emphasizes an ecosystem approach

Table 7.1—Approximate area of U.S. Ecological Systems identified as rangelands within the NRAP assessment region. Sagebrush systems were further subdivided into mountain, low, and big or sprouters. These distinct species were grouped into the “big or sprouters” category only for developing map legends because, using the mid-level Ecological Systems mapping approach, without external data, it would be difficult to differentiate each unique cover type dominated by the various *Artemisia* spp. across the landscape.

Rangeland vegetation types	Ecological system	Area	Sagebrush grouping
		Acres	
Northern Great Plains (C3/C4 mix)	Central Tallgrass Prairie	479,899	NA
	Northwestern Great Plains Mixedgrass Prairie	37,818,629	NA
	Western Great Plains Sand Prairie	2,285,234	NA
	Western Great Plains Shortgrass Prairie	39,543	NA
	Western Great Plains Tallgrass Prairie	7,763	NA
	North-Central Interior Sand and Gravel Tallgrass Prairie	209,599	NA
	Northern Tallgrass Prairie	367,864	NA
	Great Plains Prairie Pothole	262,813	NA
Total		41,471,344	NA
Montane shrubs	Northern Rocky Mountain Montane-Foothill Deciduous Shrubland	1,257,671	NA
	Inter-Mountain Basins Curl-leaf Mountain Mahogany Woodland and Shrubland	175,887	NA
	Rocky Mountain Lower Montane-Foothill Shrubland	4,602	NA
		1,438,160	NA
			NA
Montane grasslands (C3)	Columbia Plateau Steppe and Grassland	1,257,642	NA
	Columbia Basin Palouse Prairie	2,692,161	NA
	Columbia Basin Foothill and Canyon Dry Grassland	58,773	NA
	Inter-Mountain Basins Semi-Desert Grassland	42,311	NA
	Northern Rocky Mountain Lower Montane-Foothill-Valley Grassland	14,419	NA
	Northern Rocky Mountain Subalpine-Upper Montane Grassland	5,957	NA
		4,071,263	NA
Total			
Sagebrush systems	<i>Artemisia tridentata</i> ssp. <i>vaseyana</i> Shrubland Alliance	2,931,640	Mountain
	Inter-Mountain Basins Big Sagebrush Steppe	9,656,339	Big or sprouter
	Inter-Mountain Basins Big Sagebrush Shrubland	2,451,624	Big or sprouter
	Inter-Mountain Basins Montane Sagebrush Steppe	1,993,178	Big or sprouter
	Columbia Plateau Low Sagebrush Steppe	156,012	Low
	Wyoming Basins Dwarf Sagebrush Shrubland and Steppe	49,723	Low
	Inter-Mountain Basins Semi-Desert Shrub-Steppe	41,572	Big or sprouter
	Great Basin Xeric Mixed Sagebrush Shrubland	17,970	Low
	Columbia Plateau Scabland Shrubland	14,529	Big or sprouter
		17,312,587	
Total			
All rangelands total		64,293,354	

Table 7.2—Area of rangeland vegetation classes evaluated in each NRAP subregion.

Subregion	Rangeland vegetation classes	Area	Proportion
		<i>Acres</i>	<i>Percent</i>
Western Rockies	Montane grasslands	596,837	34.4
	Montane shrubs	298,153	35.7
	Sagebrush systems	358,086	29.9
Total		1,253,076	
Central Rockies	Montane grasslands	845,539	43.6
	Montane shrubs	173,980	18.6
	Sagebrush systems	507,391	37.8
Total		1,526,909	
Eastern Rockies	Montane grasslands	735,758	13.5
	Montane shrubs	328,306	12.5
	Northern Great Plains (C3/C4 mix)	221,193	5.9
	Sagebrush systems	2,572,138	68.2
Total		3,857,395	
Grassland	Montane grasslands	1,343,858	1.8
	Montane shrubs	266,233	0.7
	Northern Great Plains (C3/C4 mix)	41,204,297	80.6
	Sagebrush systems	8,586,897	16.8
Total		51,401,285	
Greater Yellowstone Area	Montane grasslands	549,271	6.1
	Montane shrubs	371,488	8.5
	Northern Great Plains (C3/C4 mix)	45,848	0.7
	Sagebrush systems	5,288,075	84.7
Total		6,254,682	
All subregions total		128,586,695	

Table 7.3—Adaptation options that address climate change effects on rangelands in the Northern Rockies.

Sensitivity to climatic variability and change: Increased susceptibility of vegetation communities (e.g., grasslands) to invasive species.			
Adaption Strategy / Approach: Increase proactive management actions in order to prevent invasive species			
Tactic	Specific Tactic – A Conduct ecologically based invasive plant management; implement prescriptive grazing, fire, herbicide and re-seeding.	Specific Tactic – B Develop weed management areas and coordinate with multiple agencies, non-governmental organizations, and the public.	Specific Tactic – C Apply early detection rapid response (EDRR) and inventory and mapping.
Where can tactics be applied?	Prioritize small/new invasions by most critical species; work back to road corridors and developed areas	Recreation high use areas (roads); administrative areas	All lands
Tactic	Specific Tactic – D Use best invasive management practices to address vectors; emphasize invasive species education (e.g., teach people how to clean their equipment, boots).	Specific Tactic – E Remove conifers with mechanical treatments, prescribed fire, and harvest.	Specific Tactic – F Conduct integrated weed management (i.e., spraying, chemical, biological, mechanical, manual control, targeted grazing).
Where can tactics be applied?	Forest/grassland/region level	Encroached communities	Recreation high use areas (roads), administrative areas

Table 7.3(cont.)—Adaptation options that address climate change effects on rangelands in the Northern Rockies.

Sensitivity to climatic variability and change: Increased temperature and drought will cause more and larger wildfires, leading to mortality of sagebrush and grasslands and increased dominance of fire-adapted herbaceous and non-native species.			
Adaption Strategy / Approach: Maintain intact ecosystems, and increase resilience and resistance of native sagebrush-grass ecosystems.			
Tactic	Specific Tactic – A Inventory intact areas with high native cover (i.e., weed free areas).	Specific Tactic – B Employ preventative measures to reduce the spread and introduction of invasive species into intact/weed free plant communities.	Specific Tactic – C Manage priority invasive species on priority acres.
Where can tactics be applied?	On all land	Areas that are currently weed free	In priority areas
Tactic	Specific Tactic – D Restore to minimize or reverse adverse effects.	Specific Tactic – E Manage fire for resource benefits.	Specific Tactic – F Promote the occurrence and growth of native species.
Where can tactics be applied?	Degraded non-forest vegetation communities	Priority areas based on current condition and potential response to fire	Sagebrush-dominated areas where native species have significant populations and non-natives are not dominant
Tactic	Specific Tactic – G Determine and implement proper grazing; conduct adaptive management that recognizes climate changes will lead to different availability of range; use rest and rotation practices; reduce grazing in July and August to encourage perennial growth.	Specific Tactic – H Manage livestock grazing through planning efforts that serve as livestock movement guides (within-season triggers) and allow for the maintenance and/or enhancement of plant health (end-point indicators).	Specific Tactic – I Use targeted grazing to address contemporary vegetation management challenges (e.g., control invasive exotic and noxious weeds and undesirable species, and reduce fire risk).
Where can tactics be applied?	On all grazed lands	On all grazed lands	Priority areas based on current condition and potential response to treatment

Table 7.3(cont.)—Adaptation options that address climate change effects on rangelands in the Northern Rockies.

Sensitivity to climatic variability and change: Phenological mismatch between pollinators and host plants.			
Adaption Strategy / Approach: Maintain and restore natural grassland habitat to ensure pollination.			
Tactic	Specific Tactic – A Encourage native pollinators; provide other habitats for pollinators (nesting cover, feeding cover, brooding cover).	Specific Tactic – B Restore and enhance habitat (using tools such as grazing, fire, herbicide application, reseeding).	Specific Tactic – C Implement long term monitoring of pollinators (e.g., research, tech transfer, education, citizen science projects, and monitor existing populations).
Where can tactics be applied?	Throughout current range of grasslands	Use ecological site descriptions to identify priority areas for restoration or enhancement	Look at native and non-native ecosystems, overlap in these ecosystems and the types of pollinators present
Sensitivity to climatic variability and change: Loss of topsoil and invasion of weeds in montane shrublands.			
Adaption Strategy / Approach: Maintain and increase montane shrublands.			
Tactic	Specific Tactic – A Educate fuels specialists, forest ecologists, wildlife biologists and silviculturists on ecology and disturbances affecting shrublands; effects of repeated burns; shifting mosaics (creating a balance of types across landscapes); and weeds (identification, awareness, reporting).	Specific Tactic – B Maintain adequate shrub cover, vigor, and species richness, and avoid bare ground; create different age classes and compositions of shrubfields (shifting mosaic); no action is a viable alternative dependent on system; tools include removal of timber products, targeted grazing, prescribed burning, and mastication/slashing.	Specific Tactic – C Apply early detection rapid response (EDRR), and use ecologically based invasive plant management (EBIPM); tools include biocontrol, herbicides, timing burning prescriptions (to avoid annual brome expansion), and targeted grazing.
Where can tactics be applied?	Throughout and across jurisdictional boundaries	Throughout and across jurisdictional boundaries	Throughout and across jurisdictional boundaries

Table 8.1—Characteristics used to describe disturbance regimes.^a

Disturbance characteristic	Description	Example
Agent	Factor causing the disturbance	Mountain pine beetle is the agent that kills trees
Source, cause	Origin of the agent	Lightning is a source for wildland fire
Frequency	How often the disturbance occurs or its return time	Years since last fire or beetle outbreak (scale dependent)
Intensity	A description of the magnitude of the disturbance agent	Mountain pine beetle population levels; wildland fire heat output
Severity	The level of impact of the disturbance on the environment	Percent mountain pine beetle tree mortality; fuel consumption in wildland fires
Size	Spatial extent of the disturbance	Mountain pine beetles can kill trees in small patches or across entire landscapes
Pattern	Patch size distribution of disturbance effects; spatial heterogeneity of disturbance effects	Fire can burn large regions but weather and fuels can influence fire intensity and therefore the patchwork of tree mortality
Seasonality	Time of year at which a disturbance occurs	Species phenology can influence wildland fires effects; spring burns can be more damaging to growing plants than fall burns on dormant plants
Duration	Length of time of that disturbances occur	Mountain pine beetle outbreaks usually last for 3-8 years; fires can burn for a day or for an entire summer
Interactions	Disturbance interact with each other, climate, vegetation and other landscape characteristics	Mountain pine beetles can create fuel complexes that facilitate or exclude wildland fire
Variability	The spatial and temporal variability of the above factors	Highly variable weather and mountain pine beetle mortality can cause highly variable burn conditions resulting in patchy burns of small to large sizes

^aFrom Keane (2013).

Table 8.2— Risk assessment for fire regime changes.^a

Fire regime component	Predicted direction of change	Main driver(s) of change	Projected duration of change	Likelihood of change
Ignitions	Unknown	Changes in lightning frequency and anthropogenic ignitions	Unknown	Unknown
Area burned	Increase	Increased fire season length, decreased fuel moistures, increased extreme fire conditions	Until a sufficient proportion of the landscape has been exposed to fire, thus decreasing fuel loads and increasing structural and species heterogeneity	High
Fire frequency	Increase	Increased ignitions, increased fuel loads, decreased fuel moistures, increased fire season length	In forested systems until a sufficient proportion of the landscape has been exposed to fire, reducing fuel loads and continuity; in grass- and shrubland systems, until global climate stabilizes	Moderate
Average fire size	Increase	Increased fire season length, decreased fuel moistures, increased extreme fire conditions	Until a sufficient proportion of the landscape has been exposed to fire, thus increasing the likelihood that previous fires will restrict growth of current year fires	High
Fire season length	Increase	Increased temperatures, decreased precipitation, decreased winter snowpack, decreased runoff	Until the global climate system stabilizes; predicted to increase as climate changes become more severe	High
Fire severity	Increase	Decreased fuel moistures, increased extreme fire conditions	In dry forest types, until fires decrease surface fuel loads; in mesic forests, if increased fire frequency decreases fuel loads	Moderate

^a Developed using expert opinion and information from literature as summarized in this chapter.

Table 8.3—Bark beetle species that cause economic impacts in the Northern Rockies.

Bark beetle species		
Common name	Scientific name	Host tree species
Western pine beetle	<i>Dendroctonus brevicomis</i>	Ponderosa pine
Mountain pine beetle	<i>D. ponderosae</i>	Limber pine, lodgepole pine, ponderosa pine, western white pine, whitebark pine
Douglas-fir beetle	<i>D. pseudotsugae</i>	Douglas-fir
Spruce beetle	<i>D. rufipennis</i>	Engelmann spruce
Pine engraver beetle	<i>Ips</i> spp.	Lodgepole pine, ponderosa pine, western white pine
Fir engraver	<i>Scolytus ventralis</i>	Grand fir

Table 8.4—Risk assessment for mountain pine beetle outbreaks.^a

Elevation	Direction of change	Main driver(s) of change	Projected duration of change	Likelihood of change
<3,300 ft	Increase if host trees available	Temperature–caused shift to bivoltinism ⁱ	Increasing risk through 2100	High
3,300-6600 ft	Decrease	Temperature-caused disruption of seasonality	Decreasing risk through 2100	High
6,600-10,000 ft	Increase initially, then decrease	Initially temperature-caused shift from semivoltine ⁱⁱ to univoltine ⁱⁱⁱ , then disruption of seasonality	Decreasing risk through 2100	High
>10,000 ft	Increase	Temperature-caused shift from semivoltine to univoltine	Increasing risk through 2100	High

^a Developed using model simulations and expert opinion and information from literature as summarized in this chapter.

ⁱ Two generations in one year.

ⁱⁱ One generation in two years.

ⁱⁱⁱ One generation in one year.

Table 8.5—Pine and mountain pine beetle (MPB) metrics by elevation category. Pine forests <6600 ft have relatively low current hazard for MPB and low univoltine growth potential, although bivoltine potential is moderate. Pine forests >6600 ft have relatively high current stand hazard conditions for MPB and relatively high univoltine growth potential, although bivoltine potential is zero.

	<3,300 ft	3,300-6,600 ft	6,600-10,000 ft	>10,000 ft
Current stand density pine (trees per acre [standard deviation]) ^a	46.4 (58.7)	142 (206)	471 (434)	223 (223)
Proportion of area (percent) ^b rated as:				
Low hazard	97	69	30	18
Moderate hazard	2	13	14	13
High hazard	1	18	56	68
MPB potential for population success (2015-2025), based on simulation with CanEMS2 GCM, emission scenario RCP-45				
Univoltine population growth rate (R)	0.00	0.44	1.62	0.65
Bivoltine (percent of points within elevation category projected to have a thermal regime supporting bivoltinism for >50 percent of years between 2015 and 2025)	24	5	0	0
MPB potential for population success (2015-2025), based on simulation with CanEMS2 GCM, emission scenario RCP-85				
Univoltine population growth rate (R)	0.04	0.86	2.0	1.05
Bivoltine (as above)	35	7	0	0

^a From Blackard et al. (2009).

^b Current MPB hazard based on host stand conditions (from Krist et al. 2014).

Table 8.6—Risk assessment for white pine blister rust.^a

	Direction of change	Main driver(s) of change	Predicted duration of change	Likelihood of change
Infection frequency and severity	Little to moderate Increase	Possibility of increased wave years in high elevation ecosystems	Until a sufficient proportion of the landscape has populations of rust-resistant pine trees, there will always be high infections regardless of climate	Low

^a Developed using expert opinion and information from literature as summarized in this chapter.

Table 8.7—Risk assessment for forest diseases.^a

Pathogen component	Direction of change	Main driver(s) of change	Projected duration of change	Likelihood of change
Needle disease	Significant increase if appropriate precipitation timing occurs	Increased precipitation in spring and early summer	May occur sporadically in association with weather events	High
Root disease	Little change	Host stress	While hosts are maladapted	Moderate
Dwarf mistletoe	Could decrease mistletoe populations	Temperature could influence flowering and seed production/dispersal	Unknown	Low
Abiotic disease	Significant increase	Temperature and decreased precipitation	Unknown	High

^a Developed using expert opinion and information from literature as summarized in this chapter.

Table 8.8—Prominent nonnative species in the Northern Rockies and their primary habitats.

Species	Habitat
Cheatgrass (<i>Bromus tectorum</i>)	Xeric shrublands and grasslands
Spotted knapweed (<i>Centaurea maculosa</i>)	Xeric shrublands and grasslands, dry forest openings
Rush skeletonweed (<i>Chondrilla juncea</i>)	Xeric shrublands and grasslands
Canada thistle (<i>Cirsium arvense</i>)	Wetland/riparian areas, disturbed sites in moist grasslands
Houndstongue (<i>Cynoglossum officinale</i>)	Highly disturbed mesic and xeric grasslands, roadsides
Leafy spurge (<i>Euphorbia esula</i>)	Riparian areas, mesic and xeric grasslands
Orange hawkweed (<i>Hieracium aurantiacum</i>)	Forest openings, moist meadows, roadsides
Yellow hawkweed complex (<i>Hieracium</i> spp.)	Forest openings, roadsides
St. Johnswort (<i>Hypericum perforatum</i>)	Xeric grasslands and shrublands
Dalmatian toadflax (<i>Linaria dalmatica</i>)	Xeric grasslands and shrublands
Yellow toadflax (<i>Linaria vulgaris</i>)	Mesic to xeric grasslands and shrublands, burned areas
Sulfur cinquefoil (<i>Potentilla recta</i>)	Xeric grasslands and shrublands
Common tansy (<i>Tanacetum vulgare</i>)	Riparian areas

Table 8.9—Risk assessment for nonnative plant species.^a

Invasive species component	Direction of change	Main driver(s) of change	Likelihood of change
Area infested	Variable by species, from low to high	Altered temperature and precipitation patterns; increased atmospheric CO ₂ ; altered fire regimes	High
Species response to habitat disturbance	High	Increased fire frequency and severity, which can increase the amount of habitat vulnerable to nonnative invasion	High
Altered fire regimes	High	Increased fire frequency in areas with fire-tolerant and flammable invasive species (e.g., cheatgrass-fire cycle)	High

^a Developed using expert opinion and information from literature as summarized in this chapter.

Table 9.1—Species included in the Northern Rockies Adaptation Partnership vulnerability assessment, including species discussed at subregional workshops.

Habitat / Species	Western Rockies	Central Rockies	Eastern Rockies	Greater Yellowstone Area	Grassland
Dry forest					
Flammulated owl		X		X	
Pygmy nuthatch		X	X	X	
Riparian/wetland					
American beaver		X	X	X	
Moose				X	
Northern bog lemming				X	
Townsend's big-eared bat		X	X	X	
Harlequin duck		X		X	
Columbia spotted frog		X		X	
Western toad		X		X	
Quaking aspen					
Avian cavity nesters		X	X	X	
Ruffed grouse				X	
Sagebrush grasslands					
Pronghorn				X	
Pygmy rabbit			X		
Brewer's sparrow				X	
Greater sage-grouse				X	X
Mountain grasslands					
Mountain quail	X				
Mesic old-growth forest					
Fisher		X		X	
Snow-dependent species					
American pika				X	
Canada lynx		X		X	
Wolverine		X		X	

Table 9.2—Adaptation options that address climate change effects on riparian habitat and associated wildlife species in the Northern Rockies.

Sensitivity to climatic variability and change: Decreased streamflow reduces riparian vegetation, affecting food supply and habitat structure for multiple species.			
Adaption Strategy / Approach: Improve riparian habitat by maintaining healthy beaver populations on the landscape.			
Tactic	Specific Tactic – A Inventory current and potential habitat (include multiple factors)	Specific Tactic – B Restore riparian habitat e.g. plant willows, manage grazers, raise water level	Specific Tactic – C Translocation, manage trapping
Where can tactics be applied? (geographic)	Range-wide	Suitable habitat range-wide	Suitable habitats range-wide

Table 9.3—Adaptation options that address climate change effects on aspen habitat and associated wildlife species in the Northern Rockies.

Sensitivity to climatic variability and change: A warmer climate will lower water tables, leading to loss of quaking aspen.			
Adaption Strategy / Approach: Promote aspen resilience.			
Tactic	Specific Tactic – A Promote disturbance (fire, cutting) in older aspen stands	Specific Tactic – B Protect from grazing (fencing, manage grazing)	Specific Tactic – C Reduce conifer competition (fire, cutting) in any age aspen stand
Where can tactics be applied? (geographic)	Range-wide	Range-wide	Range-wide

Table 9.4—Adaptation options that address climate change effects on dry forest (ponderosa pine) habitat and associated wildlife species in the Northern Rockies.

Sensitivity to climatic variability and change: A warmer climate will potentially convert drier ponderosa pine to grassland; in addition, many ponderosa stands have converted to Douglas-fir because of fire exclusion and are susceptible to projected increases in fire frequency.				
Adaption Strategy / Approach: Promote ponderosa pine resilience				
Tactic	Specific Tactic – A Reduce competition from Douglas-fir and grand fir (thin, burn) in current mature ponderosa pine stands	Specific Tactic – B Frequent understory burning	Specific Tactic – C Retain current mature and older ponderosa pine stands	Specific Tactic – D Plant ponderosa pine where it has been lost
Where can tactics be applied? (geographic)	Range-wide	Range-wide	Range-wide	Range-wide

Table 9.5—Adaptation options that address climate change effects on old-growth, mesic forest habitat and associated wildlife species in the Northern Rockies.

Sensitivity to climatic variability and change: A warmer climate will create drier conditions and cause more wildfire, potentially eliminating old forest structure and mesic habitat.				
Adaption Strategy / Approach: Maintain current habitat, restore historical habitat, and promote potential future inland maritime forest habitat.				
Tactic	Specific Tactic – A Conserve current old-growth cedar and larch, but reduce density to increase resilience to drought	Specific Tactic – B Restore white pine with a cedar understory to create future habitat	Specific Tactic – C Maintain or create necessary structure in modeled future fisher habitat	Specific Tactic – D Conserve current old-growth cedar and larch, but reduce density to increase resilience to drought
Where can tactics be applied? (geographic)	Northern Idaho, Kootenai, Bitterroot divide Where risk of loss is greatest (edge of range) Need redundancy across landscape to buffer against future fire or drought mortality	Northern Idaho, Kootenai, Bitterroot divide. Need redundancy across landscape to buffer against future fire or drought mortality	Mission side of Swan Range. Need redundancy across landscape to buffer against future fire or drought mortality	Northern Idaho, Kootenai, Bitterroot divide Where risk of loss is greatest (edge of range) Need redundancy across landscape to buffer against future fire or drought mortality

Table 9.6—Adaptation options that address climate change effects on mountain sagebrush-grassland habitat and associated wildlife species in the Northern Rockies.

Sensitivity to climatic variability and change: A warmer climate will dry soils, reducing the forb component of mountain sagebrush-grassland habitat.			
Adaption Strategy / Approach: Maintain current and restore historical habitat.			
Tactic	Specific Tactic – A Manage fire to maintain desired habitat	Specific Tactic – B Control invasive vegetation	Specific Tactic – C Restore formerly cultivated land
Where can tactics be applied? (geographic)	Range-wide	Range-wide	Range-wide

Table 9.7—Adaptation options that address climate change effects on sagebrush habitat and associated wildlife species in the Northern Rockies.

Sensitivity to climatic variability and change: A warmer climate and increased wildfire will reduce the distribution and abundance of sagebrush habitat.				
Adaption Strategy / Approach: Maintain adequate sagebrush habitat.				
Tactic	Specific Tactic – A Manage fire to maintain desired habitat	Specific Tactic – B Control invasive vegetation	Specific Tactic – C Restore formerly cultivated land	Specific Tactic – D Prevent fragmentation of sagebrush habitat (roads, energy development lines)
Where can tactics be applied? (geographic)	Range-wide	Range-wide	Range-wide	Range-wide

Table 9.8—Adaptation options that address knowledge gaps in climate change effects on wildlife populations in the Northern Rockies.

Sensitivity to climatic variability and change: Species requirements and/or climate sensitivities are largely unknown for many species.				
Adaption Strategy / Approach: Increase knowledge of species needs and climate sensitivities				
Tactic	Specific Tactic – A Analyze female lynx home ranges to determine necessary mix of habitat patches: distribution and size	Specific Tactic – B Update and expand knowledge of existing pygmy distribution	Specific Tactic – C Understand climate influences on pygmy rabbits	Specific Tactic – D Understand succession after fire in sagebrush
Where can tactics be applied? (geographic)	Range-wide	Range-wide	Range-wide	Range-wide
Sensitivity to climatic variability and change: Loss of connectivity can be caused by changes in water supply and snowpack dynamics, habitat loss, habitat shifts, vegetation phenology shifts, and human population expansion and redistribution.				
Adaption Strategy / Approach: Maintain multiple levels of connectivity (daily, seasonal, dispersal range shift).				
Tactic	Specific Tactic – A Monitor connectivity using genetics, tracking, remote sensing tools (e.g., multi-carnivore genetic monitoring across the Northern Continental Divide Ecosystem with multiple partners	Specific Tactic – B Compile table of connectivity vulnerability by species (daily through range shift)	Specific Tactic – C Identify dispersal habitat requirements for selected species (e.g., wolverine)	Specific Tactic – D Identify and remove or mitigate barriers
Sensitivity to climatic variability and change: Disease transmission may increase with warmer temperatures.				
Adaption Strategy / Approach: Increase knowledge of disease-climate relationships.				
Tactic	Specific Tactic – A Monitor environmental conditions at bat hibernacula to understand environmental conditions that promote white-nose syndrome	Specific Tactic – B Monitor moose and bighorn sheep disease trends to determine if there are climatic drivers	Specific Tactic – C Work with the state wildlife departments to monitor West Nile virus	
Where can tactics be applied? (geographic)	Region-wide	Region-wide	Region-wide	

Table 9.9—Adaptation options that address climate change effects on connectivity for wildlife populations in the Northern Rockies.

Sensitivity to climatic variability and change: Connectivity depends multiple factors, including water supply, habitat shifts, vegetation phenology, snow pack dynamics, and human population expansion and redistribution.

Adaption Strategy / Approach: Maintain connectivity

Tactic	Specific Tactic – A Monitor connectivity through genetics, tracking, and remote sensing	Specific Tactic – B Compile table of known connectivity vulnerabilities by species	Specific Tactic – C Identify and remove barriers
Where can tactics be applied? (geographic)	Region-wide	Region-wide	Region-wide

Table 10.1—Participation in different recreational activities in national forests in the Northern Region and Greater Yellowstone Area.

Activity	Relationship to climate and environmental conditions	National Forest visitors who participated in this activity as their main activity ^a	
		Percent of total NF visits	Number
<i>Warm-weather activities</i>	Participation typically occurs during warm weather; dependent on the availability of snow- and ice-free sites, dry weather with moderate daytime temperatures, and the availability of sites where air quality is not impaired by smoke from wildfires.	35.9	4,770,616
Hiking/walking		16.9	2,248,171
Viewing natural features		8.6	1,136,245
Developed camping		2.8	375,174
Bicycling		2.2	286,707
Other non-motorized		2.0	265,476
Horseback riding		1.3	168,175
Picnicking		1.2	164,638
Primitive camping		0.6	74,876
Backpacking		0.4	51,154
<i>Winter activities</i>	Participation depends on the timing and amount of precipitation as snow and cold temperatures to support consistent snow coverage. Inherently sensitive to climate variability and inter-annual weather patterns.	25.0	3,318,426
Downhill skiing		12.8	1,695,621
Snowmobiling		6.4	843,778
Cross-country skiing		5.9	779,027
<i>Wildlife activities</i>	Wildlife is a significant input for these activities. Temperature and precipitation are related to habitat suitability through effects on vegetation, productivity of food sources, species interactions, and water quantity and temperature (for aquatic species). Disturbances (wildland fire, invasive species, insect and disease outbreaks) may affect amount, distribution, and spatial heterogeneity of suitable habitat.	18.5	2,452,053
Hunting		11.3	1,503,520
Fishing		5.3	708,589
Viewing wildlife		1.8	240,944
<i>Gathering forest products</i>	Depends on availability and abundance of target species (e.g., berries, mushrooms), which are related to patterns of temperature, precipitation, and snowpack. Disturbances may alter availability and productivity of target species in current locations and affect opportunities for species dispersal.	2.4	313,475
<i>Water-based activities, not including fishing</i>	Participation requires sufficient water flows (in streams and rivers) or levels (in lakes and reservoirs). Typically considered a warm-weather activity, and depends on moderate temperatures and snow- and ice-free sites. Some participants may seek water-based activities as a heat refuge during periods of extreme heat.	0.7	96,643

^a Source: USDA FS (n.d.). Total estimated National Forest visits is 13,273,685. Percentage calculations are based on the percent of total visits accounted for by each activity and category

Table 10.2—Total annual expenditures by non-local and local visitors to Northern Rockies and Greater Yellowstone Area national forests, by spending category.

Spending category	<u>Non-local spending^{a,b}</u>		<u>Local spending</u>	
	Total annual expenditures	Spending for each category	Total annual expenditures	Spending for each category
	<i>Thousands of \$ (2014)</i>	<i>%</i>	<i>Thousands of \$ (2014)</i>	<i>%</i>
Lodging	185,355	31	14,743	6
Restaurant	109,743	18	29,618	13
Groceries	74,003	12	44,886	19
Gasoline, oil	104,319	17	78,880	34
Other transportation	3,013	1	1,059	0
Activities	36,376	6	14,195	6
Admissions, fees	39,482	7	19,103	8
Souvenirs	48,839	8	28,075	12
Total	601,128		230,562	

^a Non-local refers to trips that required traveling more than 50 miles.

^b Source: USDA FS (n.d.).

Table 10.3—Summary of climate change assessment ratings for recreation by activity category.

Activity category	Magnitude of climate effect	Likelihood of climate effect	Direct effects	Indirect effects
Warm-weather activities	Moderate (+)	High	Warmer temperature (+) Higher likelihood of extreme temperatures (-)	Increased incidence, area, and severity of wildfire (+/-) Increased smoke from wildfire (-)
Snow-based winter activities	High (-)	High	Warmer temperature (-) Reduced precipitation as snow (-)	
Wildlife activities	Terrestrial wildlife: low (+) Fishing: moderate (-)	Moderate	Warmer temperature (+) Higher incidence of low streamflow (fishing -) Reduced snowpack (hunting -)	Increased incidence, area, and severity of wildfire (terrestrial wildlife +/-) Reduced cold-water habitat, incursion of warm-water tolerant species (fishing -)
Gathering forest products	Low (+/-)	Moderate	Warmer temperature (+)	More frequent wildfires (+/-) Higher severity wildfires (-)
Water-based activities, not including fishing	Moderate (+)	Moderate	Warming temperatures (+) Higher likelihood of extreme temperatures (-)	Lower streamflows and reservoir levels (-)

Note: Positive (+) and negative (-) signs indicate expected direction of effect on overall benefits derived from recreation activity

Table 10.4—Adaptation options that address climate change effects on recreation in the Northern Rockies.

Sensitivity to climatic variability and change: Ice- and snow-based recreation is highly sensitive to variations in temperature and the amount and timing of precipitation as snow.			
Adaption Strategy / Approach: Transition to address shorter average winter recreation seasons and changing use patterns.			
Tactic	Specific Tactic – A Maintain current infrastructure and expand facilities in areas where concentrated use increases.	Specific Tactic – B Develop options for diversifying snow-based recreation, such as cat-skiing, helicopter skiing, additional ski lifts, additional higher elevation runs, toboggan runs, snow making, and back country yurts	Specific Tactic – C Conduct safety education to make the public aware of increased risk of avalanche and thin ice
Where can tactics be applied?	Snow recreation areas and major lakes	In and around existing permitted areas; within driving distance of population centers	Snow recreation areas and major lakes
Sensitivity to climatic variability and change: The warm weather recreation season will increase in length with increasing temperatures and earlier snowmelt.			
Adaption Strategy / Approach: Provide sustainable recreation opportunities in response to changing demand.			
Tactic	Specific Tactic – A Assess to understand changes in use patterns and identify demand shifts	Specific Tactic – B Adjust capacity of recreation sites (e.g., enlarge campgrounds, collect additional fees, and install infrastructure such as fences, signs and gates)	Specific Tactic – C Adjust timing of actions such as road and trail closures, food storage orders, and special use permits
Where can tactics be applied?	At multiple levels (national, regional, forest-level, and local)	Where demand increases on federal lands, as appropriate	Federal lands

Table 10.4(cont.)—Adaptation options that address climate change effects on recreation in the Northern Rockies.

Sensitivity to climatic variability and change:			
The seasonality of whitewater rafting will shift with increasing temperatures and shifts in the timing of peak streamflows.			
Adaption Strategy / Approach:			
Increase management flexibility and facilitate transitions to meet user demand and expectation.			
Tactic	Specific Tactic – A Vary permit season to adapt to changes in peakflow and duration	Specific Tactic – B Educate the public about changing river conditions	Specific Tactic – C n/a
Where can tactics be applied?	Permitted rivers	Permitted rivers	n/a
Sensitivity to climatic variability and change:			
Increases in flooding, fire, and other natural disturbances will cause damage to infrastructure.			
Adaption Strategy / Approach:			
Manage recreation sites to mitigate risks to public safety and infrastructure and to continue to provide recreation opportunities.			
Tactic	Specific Tactic – A Assess to determine what recreation sites and infrastructure are at risk from increased flooding and other natural hazards	Specific Tactic – B Prioritize post-disturbance treatments, including relocation, arming, and other mitigation measures	Specific Tactic – C Invest strategically in developed recreation facilities, prioritizing those that will be viable in the future and accommodate changing use patterns
Where can tactics be applied?	Federal lands	Federal lands	Federal lands

Table 10.B1—National Forest visits by NRAP subregion and activity category.

Activity category	<u>Subregion^a</u>				
	Western Rockies	Central Rockies	Eastern Rockies	Grassland	Greater Yellowstone Area
<i>Percent of annual visitors reporting main activity</i>					
Warm-weather activities ^{b,c}	36.7	36.9	33.3	60.8	36.2
Snow-based winter activities	7.4	26.0	27.2	1.6	31.3
Wildlife activities	23.3	19.6	18.8	30.5	15.1
Forest product gathering	6.5	1.9	2.1	0.0	1.1
Water-based activities, not including fishing	0.5	0.8	1.6	0.2	0.1

^a To estimate activity participation, subregions are defined by groups of national forests: Western Rockies (Idaho Panhandle, Kootenai, Nez Perce-Clearwater), Central Rockies (Bitterroot, Flathead, Lolo), Eastern Rockies (Beaverhead-Deerlodge, Custer, Gallatin, Helena, Lewis and Clark), Grassland (Dakota Prairie Grasslands), Greater Yellowstone Area (Bridger-Teton, Caribou-Targhee, Shoshone). Geospatial definitions of the subregions include parts of several forests divided between two subregions—for example, parts of Custer, Beaverhead-Deerlodge, and Gallatin National Forests are divided between the Eastern Rockies and Greater Yellowstone Area subregions, but tabulated as part of the Eastern Rockies subregion; these forests are also summarized in table 10.B2 separately from the other Greater Yellowstone Area forests.

^b Source: USDA FS (n.d.).

^c Percentages do not sum to 100 because not all visitors report activities, and not all activities are included in climate-sensitive categories (e.g., nature center activities, visiting historic sites).

Table 10.B2—Recreation visits to Greater Yellowstone Area units and Glacier National Park.

Unit	Total annual visits	Most frequent activity	Year
Yellowstone National Park ^{a,b}	3,390,000	Viewing wildlife (93% of visitors)	2010-2014 annual average
Grand Teton National Park ^{a,b}	2,650,000	Viewing scenery (88% of visitors)	2010-2014 annual average
Red Rock Lakes National Wildlife Reserve ^c	12,000	Viewing wildlife (45% of visitors)	2014
National Elk Refuge ^{a,d}	900,000	Viewing wildlife (53% of visitors)	2008, 2004
Gallatin National Forest ^e	2,010,000	Hiking/walking (29% of visitors)	2009
Beaverhead-Deerlodge National Forest ^e	583,000	Hunting (32% of visitors)	2010
Caribou-Targhee National Forest ^e	1,850,000	Hiking/walking (18% of visitors)	2010
Shoshone National Forest ^e	646,000	Viewing natural features (25% of visitors)	2009
Bridger-Teton National Forest ^e	2,180,000	Downhill skiing (31% of visitors)	2008
Custer National Forest ^e	314,000	Downhill skiing (26% of visitors)	2008
Glacier National Park ^{b,f}	2,149,000	Sightseeing (97% of visitors)	2010-2014 annual average 1990 (visitor activities)

^a Source: NPS (2006).

^b Source: NPS (2014).

^c Source: USDI (2014).

^d Source: Sexton et al. (2012).

^e Source: USDA FS (n.d.); most frequent activity is the reported main activity (visitors may engage in other secondary or tertiary activities).

^f Source: Littlejohn (1991).

Note: Visitor data are not available for John D. Rockefeller Parkway.

Table 11.1—Mean Social Vulnerability Index scores across industries. Counties were ranked by industry shares for each industry and separated into quartiles. Scores are first (on the left) compared scores for the lower and upper quartiles, then (on the right) the lower and upper half of counties, sorted by shares of employment in that industry. Significance levels are shown by the test statistics for comparison of the means and the associated p-values.

	Lower quartile	Upper quartile	Test statistic	p-value	Lower half	Upper half	Test statistic	p- value
Timber	2.93	0.94	4.32	0.00	2.90	0.76	5.44	0.00
Grazing	-0.20	3.69	-8.03	0.00	0.61	3.04	-6.37	0.00
Recreation	2.56	0.63	3.56	0.00	2.39	1.28	2.67	0.01
Oil & gas	2.45	1.68	1.38	0.17	1.94	1.74	0.47	0.64
			No	Yes	Test Statistic	p-value		
Counties in National Forest Impact Zones			1.75	2.13	0.923	0.34		

Table 11.10—Unsuitable land area in the Christie Creek and Sherwin Creek allotments in the Nez Perce-Clearwater National Forest, including forage production reduced from conversion of desirable vegetation to “weedy” species.^a

Allotment	Pasture	Unsuitable land area	Forage reduced
		<i>Acres</i>	<i>Animal unit months</i>
Christie Creek	Rhett	83	11
	Christie Creek	106	11
	Deer Creek	151	20
Sherwin Creek	Lower Center Ridge	238	32
Total		578	74

^a Source: Nez Perce–Clearwater National Forest assessment (June 2014 review draft).

Table 11.11—Changes in non-federal rangeland area, 1982-2007.^a

	Net change				Historic rangeland <i>Thousands of acres</i>	Change from historic rangeland	Rangeland threatened by residential development <i>Thousands of acres</i>
	Rangeland	Pasture	CRP land	Crop land		<i>Percent</i>	
	<i>Acres</i>						
Montana	-897.8	671.6	-3,084	-28.8	67,604	-24	28
South Dakota	-784.8	-556.2	-245	1.6	45,924	-52	46
North Dakota	-507.4	-5.8	-3,034	85.1	43,214	-71	29
Idaho	-177.6	103.4	-1,154	94.6	29,763	-20	77
Wyoming	221.0	-178.0	-458	10.0	49,306	-8	13

^a Source: Reeves and Mitchell (2012).

Table 11.2—Number of counties significantly below and above regional means.

	Unemployment rate (5.4%)		Percent employed in service industry (17.8%)		Median household income (\$45,235)		Median age (43.4)		Percent foreign born (2.7%)		Percent population minority (15.9%)		Percent population in rural areas (75.3%)	
	Below	Above	Below	Above	Below	Above	Below	Above	Below	Above	Below	Above	Below	Above
Grazing	54	18	44	21	49	24	16	57	57	12	62	15	13	66
Timber	27	40	19	43	43	34	34	39	25	32	57	23	45	29
Recreation	37	36	18	44	41	32	37	36	31	26	59	21	47	31
Oil and gas	54	21	31	34	33	43	32	39	38	25	65	12	37	41

Table 11.3—Total water use in Montana^a.

Planning basin	Hydropower (non- consumptive)	Irrigation	Reservoir evaporation	Municipal, industrial, livestock	In-stream flow (non- consumptive)
<i>Percent</i>					
Statewide	86.0	12.4	1.2	0.5	0
Clark Fork / Kootenai River	94.4	4.7	0.5	0.4	0
Upper Missouri	88.0	11.2	0.5	0.3	0
Lower Missouri	39.4	19.5	6.0	0.3	35.0
Yellowstone River	24.5	23.0	0.4	1.4	50.7

^a Data from Montana DNRC (2014).

Table 11.4—Consumptive water use in Montana.^a

Planning basin	Irrigation	Reservoir evaporation	Domestic & municipal	Livestock	Industrial	Thermo-electric
<i>Percent</i>						
Statewide	67.3	28.0	2.4	1.2	0.3	0.8
Clark Fork / Kootenai River	67.0	27.0	3.9	0.5	1.2	0
Upper Missouri	82.2	13.7	3.0	0.9	<0.1	0
Lower Missouri	42.0	56.3	0.4	1.4	<0.1	0
Yellowstone River	83.3	7.2	2.8	2.1	0.3	4.2

^a Data from Montana DNRC (2014).

Table 11.5—Threatened and impaired waterways in Montana.^a

	Rivers and streams	Lakes, reservoirs, and ponds
Use	<i>Percent</i>	
Agriculture	14.3	22.1
Aquatic life	83.6	76.7
Drinking water	29.3	65.5
Primary contact recreation	38.7	13.5
Causes of impairment		
<i>Rivers and streams</i>	<i>Miles</i>	
Alteration in streamside or littoral vegetation	8,352	
Sedimentation, siltation	7,456	
Phosphorus	5,091	
Low flow alterations	4,936	
Nitrogen total	4,846	
<i>Lakes, reservoirs, and ponds</i>	<i>Acres</i>	
Mercury	311,192	
Lead	246,950	
Phosphorous, total	73,324	
Sedimentation, siltation	69,411	
Nitrogen, total	68,354	
Sources of impairment		
<i>Rivers and streams</i>	<i>Miles</i>	
Agriculture	6,000	
Grazing in riparian or shoreline zones	5,862	
Irrigated crop production	4,570	
Natural sources	4,518	
Source unknown	4,223	
<i>Lakes, reservoirs, and ponds</i>	<i>Acres</i>	
Impacts from abandoned mine lands	279,490	
Atmospheric deposition – toxics	250,570	
Historic bottom sediments (not sediment)	237,654	
Municipal point source discharges	97,542	
Source unknown	86,868	

^a Data from U.S. Environmental Protection Agency Watershed Assessment, Tracking and Environmental Results System database (<http://water.epa.gov/scitech/datait/tools/waters/index.cfm>).

Table 11.6—Threatened and impaired waterways in Idaho.^a

	Rivers and streams	Lakes, reservoirs, and ponds
Use	<i>Percent</i>	
Cold water aquatic life	52.5	91.3
Primary contact recreation	18.3	2.6
Salmonid spawning	45.9	86.0
Warm water aquatic life	68.0	99.4
Domestic water supply	3.2	0
Seasonal cold water aquatic life	0	100
Secondary contact recreation	15.3	97.0
Causes of impairment		
<i>Rivers and streams</i>	<i>Miles</i>	
Temperature, water	18,494	
Sedimentation, siltation	14,988	
Phosphorus	6,017	
<i>Escherichia coli</i>	4,480	
Combined benthic, fish bioassessments	4,306	
Other flow regime alterations	3,877	
<i>Lakes, reservoirs, and ponds</i>	<i>Acres</i>	
Phosphorus	146,576	
Mercury	121,329	
Other flow regime alterations	84,682	
Sediment, siltation	80,169	
Dissolved oxygen	77,473	
Sources of impairment		
<i>Streams and rivers</i>	<i>Miles</i>	
Grazing in riparian or shoreline zones	2,230	
Rangeland grazing	1,782	
Livestock (grazing, feeding)	1,152	
Flow alterations from water diversions	643	
Loss of riparian habitat	608	
Managed pasture grazing	561	
<i>Lakes, reservoirs, and ponds</i>	<i>Acres</i>	
Highways, roads, bridges, infrastructure	340	
Post-development erosion and sedimentation	340	
Natural sources	340	
Agriculture	340	
Loss of riparian habitat	340	

^a Data from U.S. Environmental Protection Agency Watershed Assessment, Tracking and Environmental Results System database (<http://water.epa.gov/scitech/datait/tools/waters/index.cfm>).

Table 11.7—Threatened and impaired waterways in North Dakota.^a

	Rivers and streams	Lakes, reservoirs, and ponds
Use		<i>Percent</i>
Agriculture	0	0
Fish and other aquatic biota	16.6	0.1
Fish consumption	80.8	81.3
Industrial	0	0
Municipal and domestic	0	0
Recreation	27.2	0.9
Causes of impairment		
<i>Rivers and streams</i>		<i>Miles</i>
Fecal coliform bacteria		3,820
Physical substrate habitat alterations		2,423
<i>Escherichia coli</i>		1,882
Sedimentation, siltation		1,783
Combined benthic, fish bioassessments		604
<i>Lakes, reservoirs, and ponds</i>		<i>Acres</i>
Fecal coliform bacteria		3,820
Physical substrate habitat alterations		2,423
<i>Escherichia coli</i>		1,882
Sedimentation, siltation		1,783
Combined benthic, fish bioassessments		604
Sources of impairment		
<i>Rivers and streams</i>		<i>Miles</i>
Grazing in Riparian or shoreline zones		5,797
Animal feeding operations		3,909
Crop production (crop land or dry land)		2,549
Loss of riparian habitat		2,415
Source unknown		1,148
<i>Lakes, reservoirs, and ponds</i>		<i>Acres</i>
Grazing in Riparian or shoreline zones		5,797
Animal feeding operations		3,909
Crop production (crop land or dry land)		2,549
Loss of riparian habitat		2,415
Source unknown		1,148

^a Data from U.S. Environmental Protection Agency Watershed Assessment, Tracking and Environmental Results System database (<http://water.epa.gov/scitech/datait/tools/waters/index.cfm>)

Table 11.8—Sold timber volumes from national forests in the U.S. Forest Service Northern Region and Greater Yellowstone Area subregion over the last two decades.^a

National Forest	1980			2013			Difference		
	Number of sales	Sold volume	Inflation adjusted sold value	Sales	Sold volume	Inflation adjusted sold value	Sales	Sold volume	Inflation adjusted sold value
		<i>ft³</i>	<i>Dollars</i>		<i>ft³</i>	<i>Dollars</i>		<i>Percent</i>	
Beaverhead-Deerlodge	630	47,137	1,971,012	845	8,176	59,067	34	-83	-97
Bitterroot	268	42,751	3,883,685	266	8,123	459,684	-1	-81	-88
Bridger-Teton	425	20,141	885,087	627	9,641	150,834	48	-52	-83
Caribou-Targhee	7,347	98,301	7,726,627	743	7,234	93,922	-90	-93	-99
Custer	127	1,653	81,794	292	1,573	18,088	130	-5	-78
Flathead	289	194,340	22,504,836	334	14,797	963,163	16	-92	-96
Gallatin	310	23,575	628,518	551	4,480	44,820	78	-81	-93
Helena	113	21,916	1,451,979	393	3,431	34,000	248	-84	-98
Idaho Panhandle	669	317,157	64,207,103	866	40,180	3,562,340	29	-87	-94
Kootenai	616	175,803	36,705,744	820	35,589	1,820,020	33	-80	-95
Lewis and Clark	277	12,423	134,615	387	2,152	21,160	40	-83	-84
Lolo	367	40,744	2,281,829	597	6,402	298,537	63	-84	-87
Nez Perce-Clearwater	414	255,741	18,881,743	699	44,402	6,567,655	69	-83	-65
Shoshone	307	11,883	198,089	415	7,667	225,075	35	-35	14

^a Source: U.S. Forest Service, accessed via Headwaters Economics (<http://headwaterseconomics.org/interactive/national-forests-timber-cut-sold>)

Table 11.9—Employment in the timber industry, by county and region, 2012.^a

County	Total private employment	Timber employment	Employment in timber (%)	Change in timber employment, 1998-2012 (%)
<i>All subregions</i>	365,255	9,531	2.6	-44
<i>Western Rockies subregion</i>	112,143	6,511	5.8	
Asotin County, WA	4,605	9	0.2	-95
Benewah County, ID	2,130	677	31.8	-25
Bonner County, ID	10,972	401	3.7	-70
Boundary County, ID	2,239	410	18.3	-3
Clearwater County, ID	1,896	358	18.9	-59
Idaho County, ID	3,165	386	12.2	18
Kootenai County, ID	44,080	913	2.1	-52
Latah County, ID	8,398	349	4.2	-11
Lewis County, ID	717	132	18.4	-47
Lincoln County, MT	3,771	191	5.1	-79
Nez Perce County, ID	16,061	1,693	10.5	-13
Pend Oreille County, WA	1,403	83	5.9	-67
Sanders County, MT	1,910	122	6.4	-55
Shoshone County, ID	4,183	94	2.2	-28
Stevens County, WA	6,613	693	10.5	-30
<i>Central Rockies subregion</i>	110,451	2,374	2.1	
Flathead County, MT	31,316	977	3.1	-45
Glacier County, MT	2,205	1	0.0	0
Lake County, MT	5,121	119	2.3	-51
Mineral County, MT	895	231	25.8	175
Missoula County, MT	47,885	574	1.2	-69
Powell County, MT	1,024	243	23.7	37
Ravalli County, MT	8,522	220	2.6	-69
Silver Bow County, MT	13,483	9	0.1	125
<i>Eastern Rockies subregion</i>	114,783	595	0.5	
Beaverhead County, MT	2,234	9	0.4	-40
Broadwater County, MT	790	178	22.5	78
Carbon County, MT	2,169	3	0.1	50
Cascade County, MT	29,168	25	0.1	19
Chouteau County, MT	723	4	0.6	0
Fergus County, MT	3,291	9	0.3	-89
Gallatin County, MT	37,409	103	0.3	-59
Granite County, MT	481	47	9.8	-69
Jefferson County, MT	1,679	34	2.0	89
Lewis and Clark County, MT	23,623	48	0.2	129
Madison County, MT	1,943	10	0.5	67
Meagher County, MT	268	4	1.5	-73
Park County, MT	4,394	86	2.0	-28
Powder River County, MT	329	0	0.0	-100
Rosebud County, MT	2,562	0	0.0	-100

Stillwater County, MT	2,683	35	1.3	-58
Sweet Grass County, MT	1,037	0	0.0	-100
<i>Greater Yellowstone Area subregion</i>	26,609	50	0.2	
Fremont County, ID	1,429	19	1.3	-75
Park County, WY	9,876	25	0.3	-36
Teton County, WY	15,304	6	0.0	100
<i>Grassland subregion</i>	1,269	1	0.1	
Carter County, MT	184	0	0.0	-100
Harding County, SD	402	1	0.2	0
McHenry County, ND	683	0	0.0	0

^a Source: U.S. Department of Commerce (2014).

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Table 12.1—Summary of climate change stressors and potential effects on cultural resources in the Northern Rockies (see also Rockman 2014, UNESCO 2007). Human activities can exacerbate some of the expected effects of climate change (see text).

Climate change stressor	Biophysical effects	Effects on cultural sites and landscapes
Temperature increase	• Wildfire • Drought, erosion • Vegetation changes • Spread of invasive species • Ice patch melt • Altered freeze-thaw cycles	• Combustion, damage, destruction • Exposed artifacts and cultural features • Altered physical appearance, integrity • Altered physical appearance, integrity • Artifact decay and theft • Saturation, desiccation, warping, biochemical changes
Altered precipitation	• Earlier seasonal runoff, flooding • Debris flows, slumping • Down-cutting, mass wasting • Increased moisture and humidity • Extreme precipitation events	• Removal, damage, degradation • Burial, removal, degradation • Removal, damage, degradation • Decay, oxidation, exfoliation, corrosion, biochemical changes • Removal, damage, degradation, collapse, exposure

Table 13.1—Risk assessment for resources in the vulnerability assessment for the Northern Rockies. The qualitative and quantitative approach for estimating magnitude and likelihood of climate change effects varies by resource and availability of information (see individual chapters for more detail).

Resource	Habitat, ecosystem function or species	Magnitude of effects	Likelihood of effects
Water resources	Snowpack and glaciers	High to low, depending on elevation and winter temperatures	High
	Streamflow	High to low across the region, depending on local climate	High to low across the region, depending on local climate
Fisheries	Bull trout	Moderate for 2040s, high by 2080s	High for 2040s, moderate for 2080s
	Westslope cutthroat trout and Yellowstone cutthroat trout	Low for 2040s, moderate for 2080s	High for 2040s, moderate for 2080s
Vegetation – general types	Dry ponderosa pine and Douglas-fir	High	High
	Lodgepole pine and aspen mixed conifer	Moderate	High
	Mixed mesic white pine, western redcedar, western hemlock grand fir	Moderate	Low
	Western larch mixed conifer	High	Very high
	Whitebark pine/spruce-fir	High	High
	Big sagebrush	Highly variable	Moderate
	Mountain big sagebrush and basin big sagebrush	Mountain big sagebrush – moderate; basin big sagebrush – high	High
	Threetip sagebrush and silver sagebrush	Moderate	High
	Western grasslands	High	High
	Alpine larch	High	High
Vegetation – tree species	Cottonwood	Moderate	Moderate
	Douglas-fir	High	High
	Engelmann spruce	Moderate	Moderate
	Grand fir	Moderate	Moderate
	Green ash	Moderate	High
	Limber pine	Low	Low
	Lodgepole pine	Moderate	High
	Mountain hemlock	High	High
	Ponderosa pine - var. <i>ponderosa</i>	Moderate	Moderate
	Ponderosa pine – var. <i>scopulorum</i>	Moderate	Moderate
	Quaking aspen	Moderate	High
	Subalpine fir	High	High
	Western hemlock	Moderate	Moderate
	Western larch	High	Very high
	Western redcedar	Moderate	Moderate
	Western white pine	Moderate	Moderate
	Whitebark pine	Moderate	Moderate
Vegetation – resource concerns	Carbon sequestration	High	Moderate
	Landscape heterogeneity	Moderate	High
	Timber production	Moderate to high in northern Idaho	High in north Idaho
	Bark beetle disturbances	Moderate	Varies
	Invasive plant species	High	High
	Wildfire regimes	Low-moderate	Moderate-high

Table 13.1(cont.)—Risk assessment for resources in the vulnerability assessment for the Northern Rockies.

Wildlife	American beaver	Moderate by 2100	Moderate by 2100
	American pika	Low in 2030, 2050; moderate by 2100	Varies
	Canada lynx	Moderate by 2030, high by 2050, extreme by 2100	High
	Fisher	Low by 2030, moderate by 2050, probably high by 2100	High
	Moose	Moderate by 2100	Moderate by 2100
	Northern bog lemming	Moderate by 2050; high by 2100	High by 2050
	Pronghorn	Moderate by 2100	Moderate by 2100
	Pygmy rabbit	Moderate by 2050; could be high by 2100	High by 2050
	Townsend's big-eared bat	Moderate by 2100	Moderate by 2100
	Ungulates (elk, mule deer, white-tailed deer)	Uncertain, but probably low to moderate by 2100	Low to moderate in all time periods
	Wolverine	Low by 2030, moderate by 2050, high to very high by 2100	High in all time periods
	Brewer's sparrow	Low to moderate by 2050; moderate to high by 2100	Moderate, depending on sagebrush habitat
	Flammulated owl	Largely unknown across all time periods	Largely unknown across all time periods
	Greater sage-grouse	Largely unknown across all time periods	Largely unknown across all time periods
	Harlequin duck	Moderate across all time periods	Moderate across all time periods
	Mountain quail	Low to moderate across all time periods	Low to moderate across all time periods
	Pygmy nuthatch	Largely unknown across all time periods	Largely unknown across all time periods
	Ruffed grouse	Low to moderate across all time periods	Low to moderate across all time periods
	Columbia spotted frog	Moderate across all time periods, depending on fungal infections	Moderate across all time periods
	Western toad	Moderate across all time periods	Moderate across all time periods
Recreation	Warm-weather activities	Moderate	High
	Snow-based recreation activities	High	High
	Wildlife-based activities	Hunting, wildlife viewing—low; fishing—moderate to high	Hunting, wildlife viewing—moderate; fishing—high
	Gathering forest products	Low	Moderate
	Water-based activities	Low to moderate	Moderate
Ecosystem services	Building materials/wood products	Large from non-climate forces	Likely from non-climate forces
	Cultural and heritage values	Highly variable	Highly variable
	Erosion regulation	Landslides and flooding have the potential for large sudden damages; costs of soil erosion are high.	High
	Fuel (firewood/biofuels)	Firewood — low; biofuels — uncertain	High
	Mining, minerals	Large from non-climate forces	High
	Viewsheds/clean air	High	High
	Water quality	High	High
	Water quantity	Moderate	High

Table 13.2—Example of how information on climate change vulnerability and adaptation can be used in land management applications for dry forests.

Vulnerability and adaptation information	Land management application
<i>Sensitivity to climatic variability and change</i> • Potential conversion to grassland • Many ponderosa pine forests have converted to Douglas-fir types due to fire exclusion and are therefore more susceptible to future fires	• Forest/grassland planning: assessment phase • Project National Environmental Policy Act (NEPA) analysis: existing condition and best science on effects of climate change on resource
<i>Adaption strategy</i> • Restore fire-adapted ponderosa pine stand conditions in order to facilitate transition	• Forest/grassland planning: desired conditions • Project NEPA analysis: purpose and needs
<i>Tactics</i> • Reduce competition from Douglas-fir and grand fir (thin, burn) in current mature pine stands • Conduce frequent understory burning • Retain current mature and older ponderosa pine stands • Plant ponderosa pine where it has been lost	• Forest/grassland planning: objectives • Project NEPA analysis: project design features and other mitigation

Figures

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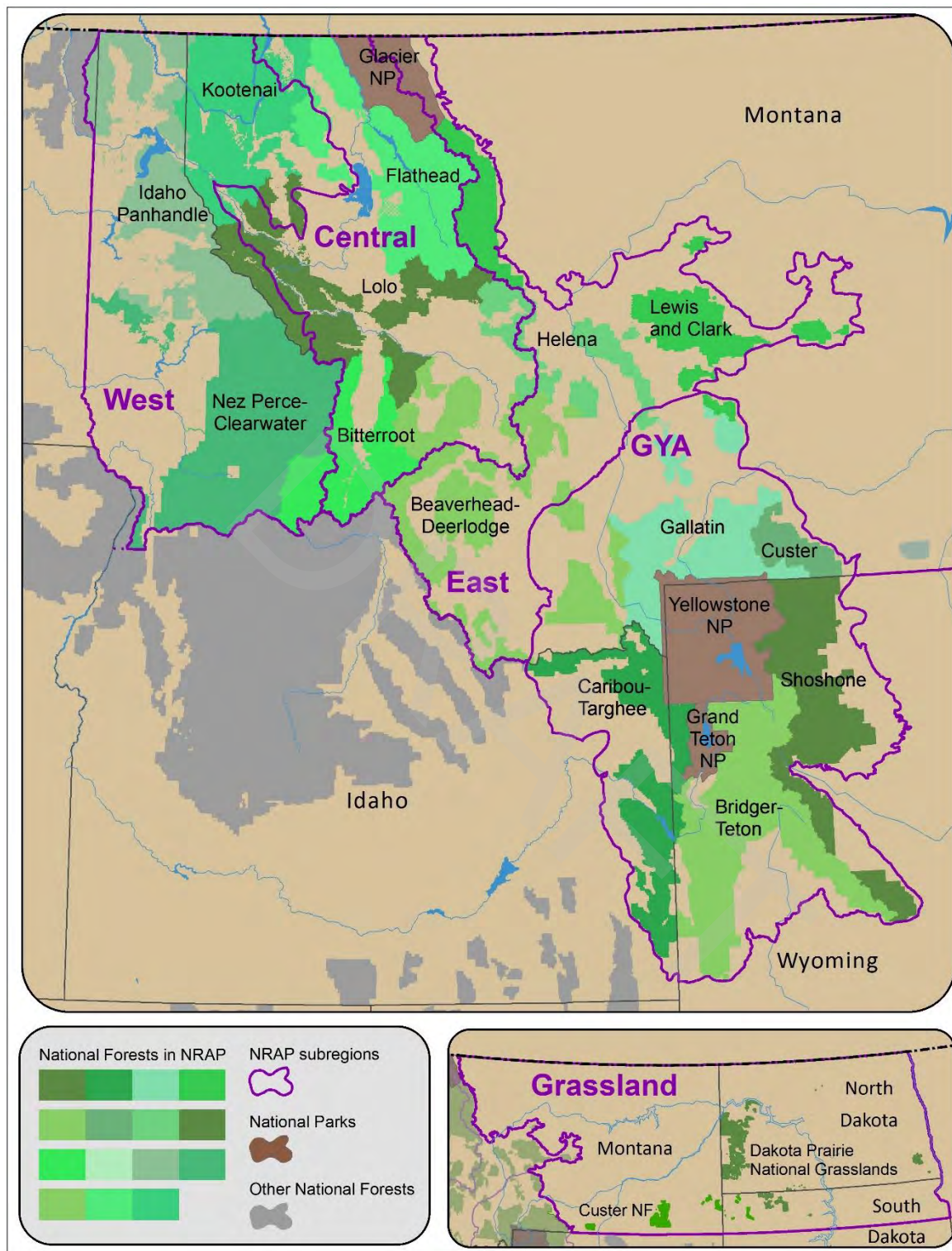


Figure 1.1—Project area for the Northern Rockies Adaptation Partnership (NRAP). Map by Robert Norheim.



Figure 2.1—Highly dissected watersheds with mixed conifer forest adjacent to streams are common in the Western Rockies subregion. (Photo by U.S. Forest Service).



Figure 2.2—Glacially carved landscapes, dense coniferous forest, and deep lakes are common in the Central Rockies subregion. (Photo by National Park Service)



Figure 2.3—The expedition of Lewis and Clark has created a historical legacy in the Eastern Rockies subregion. This painting by Alfred Russell depicts Sacajawea guiding the expedition from Mandan through the Rocky Mountains. (Photo by Bettmann/CORBIS)



Figure 2.4—Populations of the grizzly bear, an iconic species in the Greater Yellowstone Area subregion, have increased over the past several decades as a result of successful conservation efforts. (Photo by U.S. Fish and Wildlife Service)



Figure 2.5—A rich diversity of grasses and forbs, often mixed with ponds and lakes provide excellent habitat for waterfowl in the Grassland subregion. (Photo by Jim Ringelman, Ducks Unlimited).

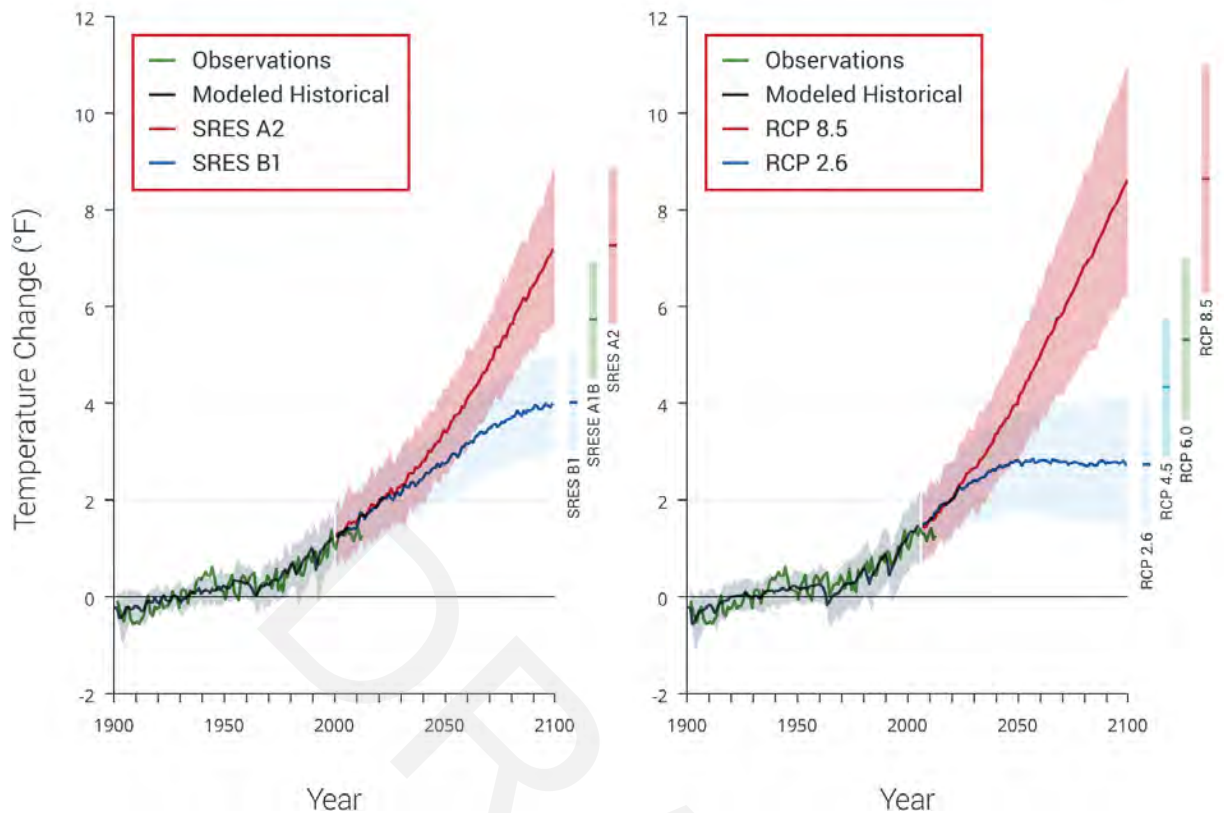


Figure 3.1—Comparison of global temperatures projected with emission levels from CMIP3 (left panel) and with emission levels from CMIP5 (right panel) (figure 2.4 from Walsh et al. 2014). Different amounts of heat-trapping gases released into the atmosphere by human activities produce different projected increases in Earth’s temperature. In the figure, the red and blue lines represent a central estimate of global average temperature rise (relative to the 1901-1960 average) for a specific emissions pathway. The shaded areas for a given color indicate the range (5th to 95th percentile) of results from a suite of climate models. The bars to the right of each panel indicate projections in 2099 for additional emissions pathways are indicated. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. (Left) The panel shows the two main scenarios (SRES – Special Report on Emissions Scenarios): A2 assumes continued increases in emissions throughout this century, and B1 assumes much slower increases in emissions beginning now and significant emissions reductions beginning around 2050, though not due explicitly to climate change policies. (Right) The panel shows results from the most recent generation of climate models (CMIP5) using the most recent emissions pathways (RCPs – Representative Concentration Pathways). The newest set includes both lower and higher pathways than did the previous set. The lowest emissions pathway shown here, RCP 2.6, assumes immediate and rapid reductions in emissions and would result in about 2.5 °F of warming in this century. The highest pathway, RCP 8.5, roughly similar to a continuation of the current path of global emissions increases, is projected to lead to more than 8 °F warming by 2100, with a high-end possibility of more than 11 °F. (Data from CMIP3, CMIP5, and NOAA NCDC). These results draw on raw GCM data summarized for the entire Earth rather than bias corrected to spatially downscaled GCM models for our regions depicted in all other graphics.

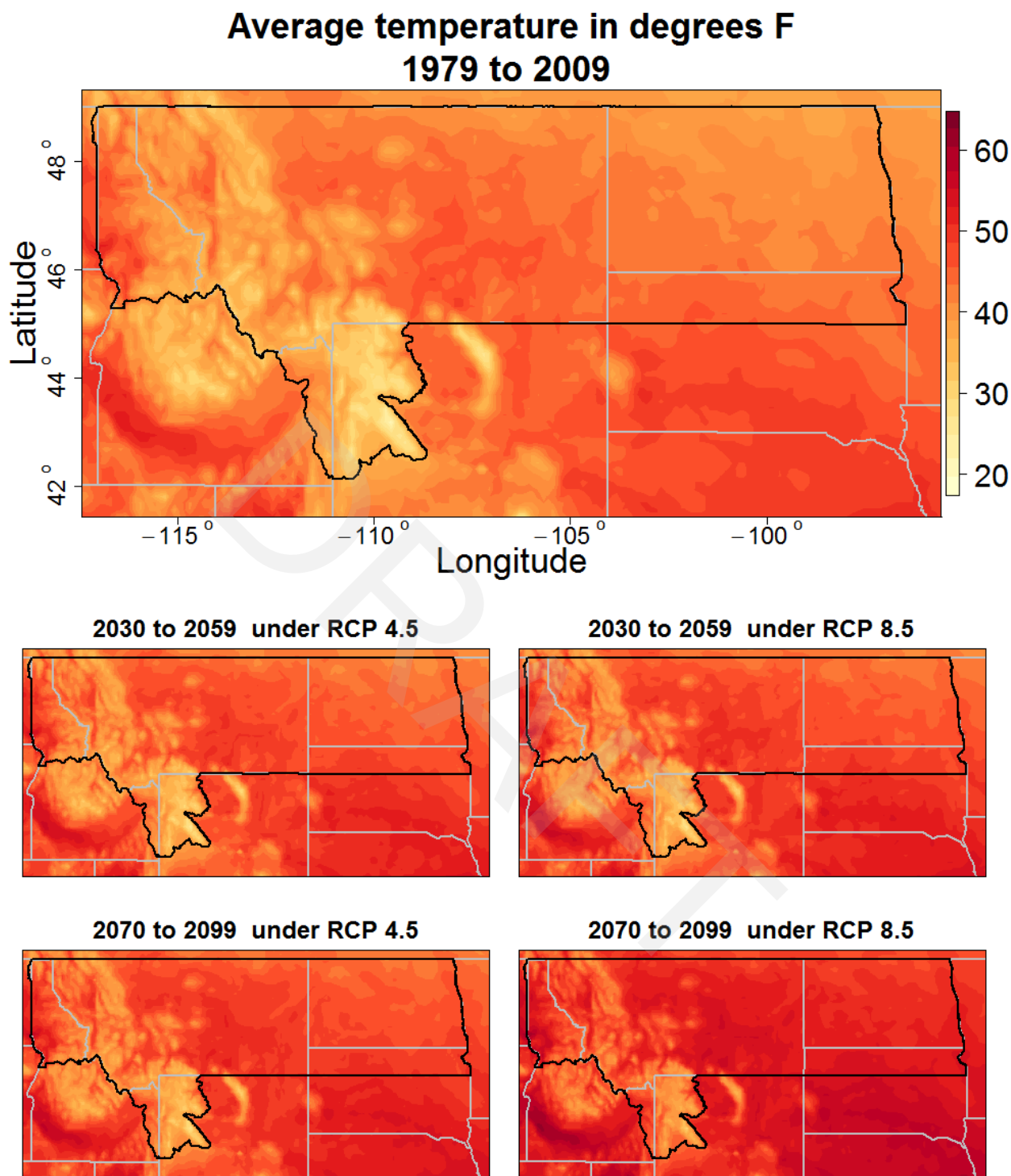


Figure 3.2—Historical (1970-2009) and projected (2030-2059 and 2070-2099) mean annual monthly temperature (°F) for Northern Rockies Adaptation Partnership Region (NRAP) under RCP 4.5 and RCP 8.5 scenarios. Projected climate results are the mean of 36 models for RCP 4.5 and 34 models for RCP 8.5 (see table 3.1). Spatial resolution of the data is 1/8-degree latitude-longitude.

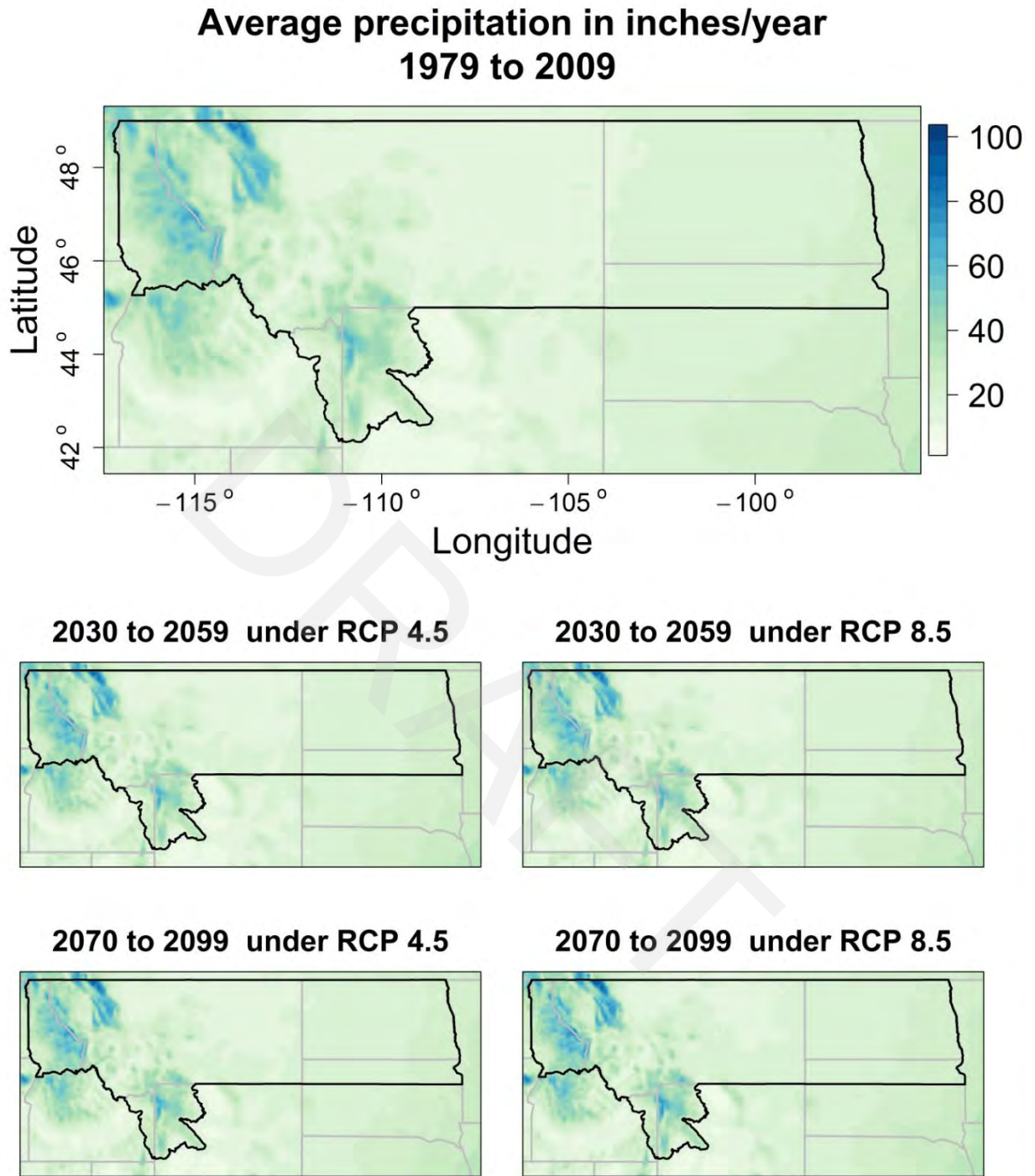


Figure 3.3—Historical (1970-2009) and projected (2030-2059 and 2070-2099) total annual precipitation (inches) under RCP 4.5 and RCP 8.5. Projected climate results are the mean of 36 models for RCP 4.5 and 34 models for RCP 8.5 (see Table 3.1). Spatial resolution of the data is 1/8 degree latitude-longitude.

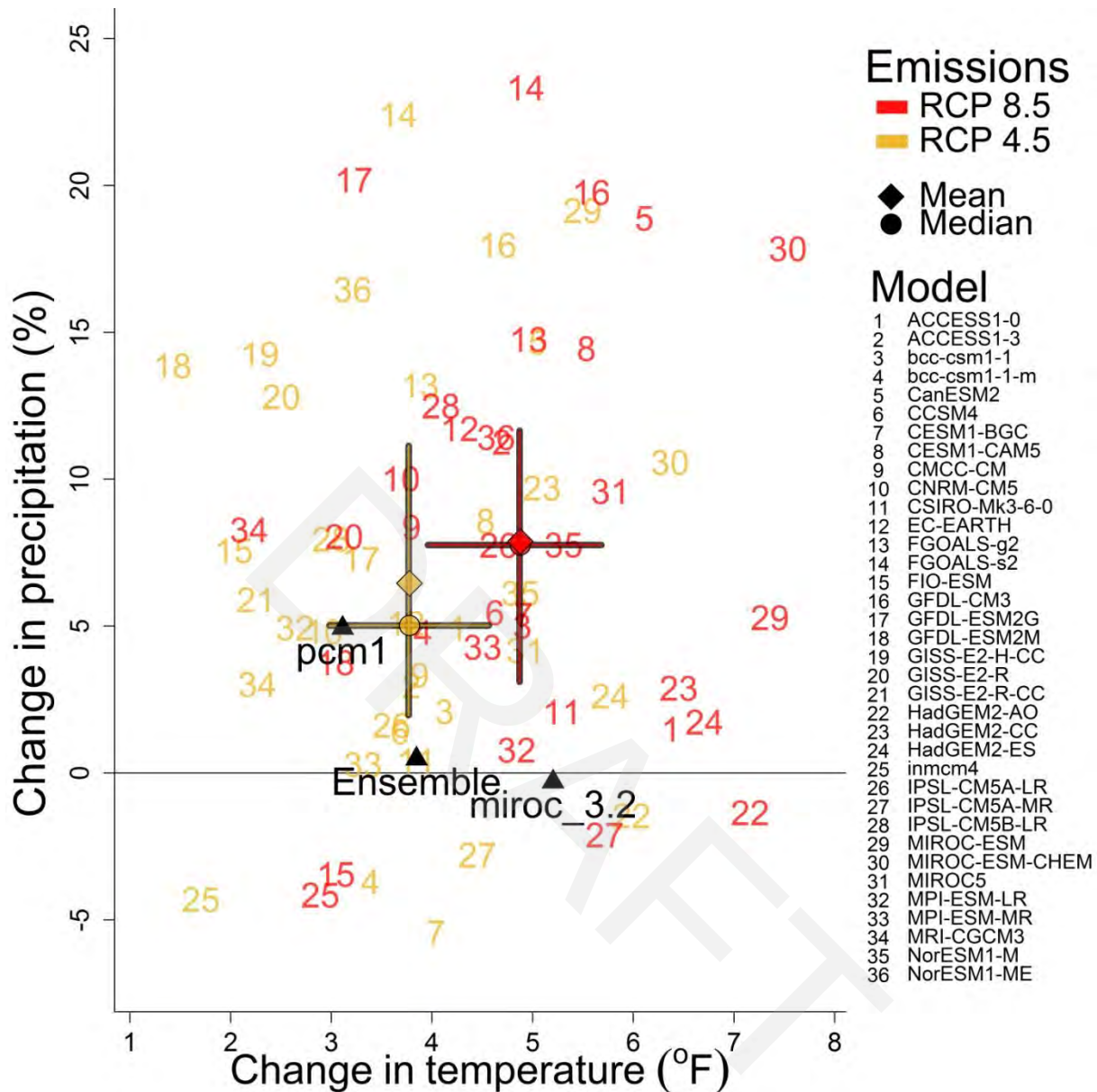


Figure 3.4—For the entire NRAP region, percent change in total annual precipitation (%) and change in mean annual temperature ($^{\circ}\text{F}$) from the simulated historical climate (1979-2009) and the projected climate (2040-2060) using the CMIP5 RCP 4.5 and RCP 8.5 scenarios and the CMIP3 A1B scenario. Each CMIP5 model result is labeled by a number with a key in the legend (e.g., 29 is MIROC-ESM) in colors to indicate RCP 4.5 (yellow) and RCP 8.5 (red) (see table 3.1). The crosses in the middle represent the median and 25-75% of the RCP 4.5 and the RCP 8.5 projections used in this study. The mean values for the CMIP5 changes are shown on the figure as colored diamonds. The CMIP3 results are labeled in black triangles (see table 3.2 and Littell et al. 2011).

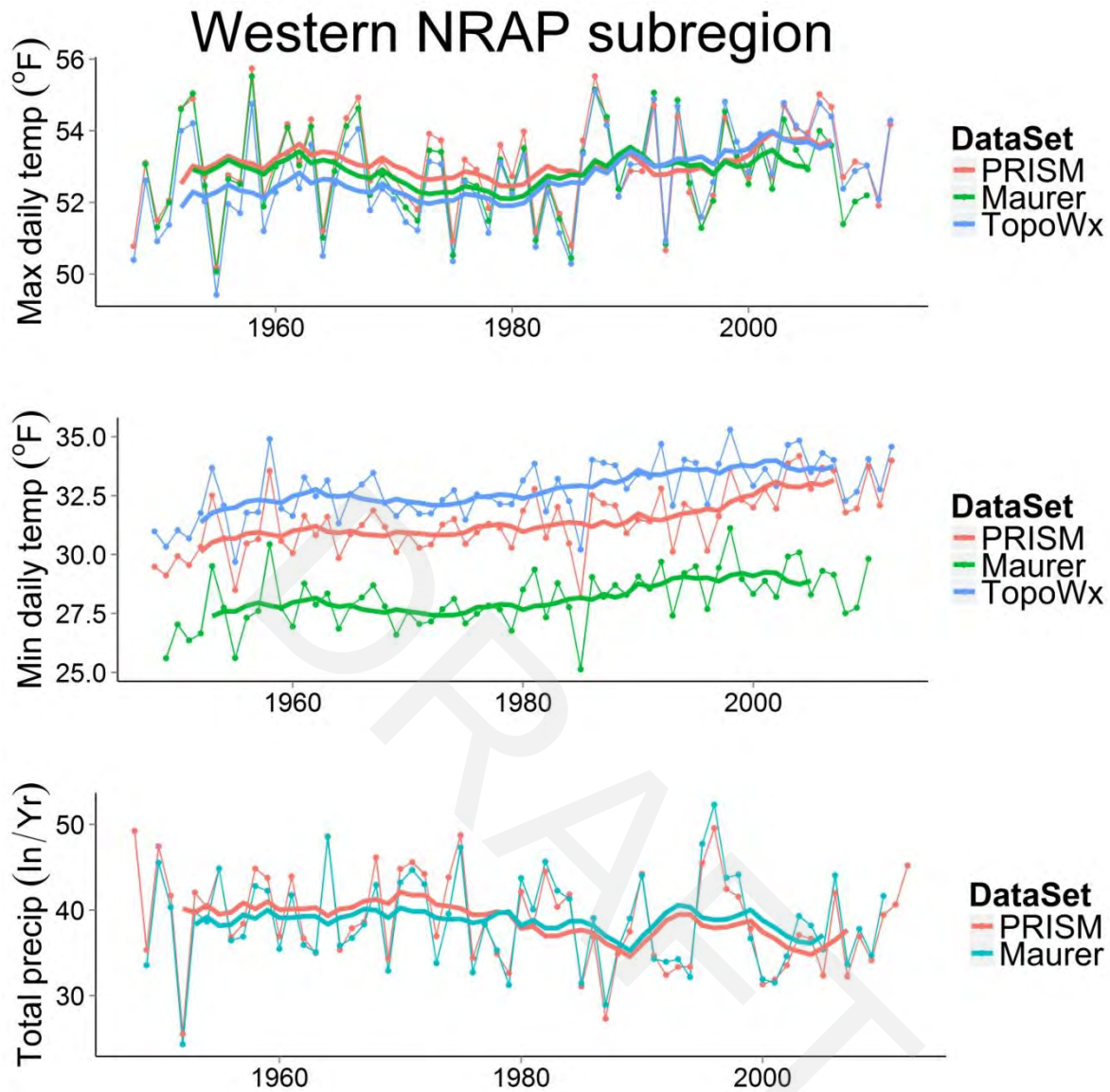


Figure 3.5—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Western subregion. The heavy lines are the 10-year rolling average to show short-term trends.

Western NRAP subregion model projections

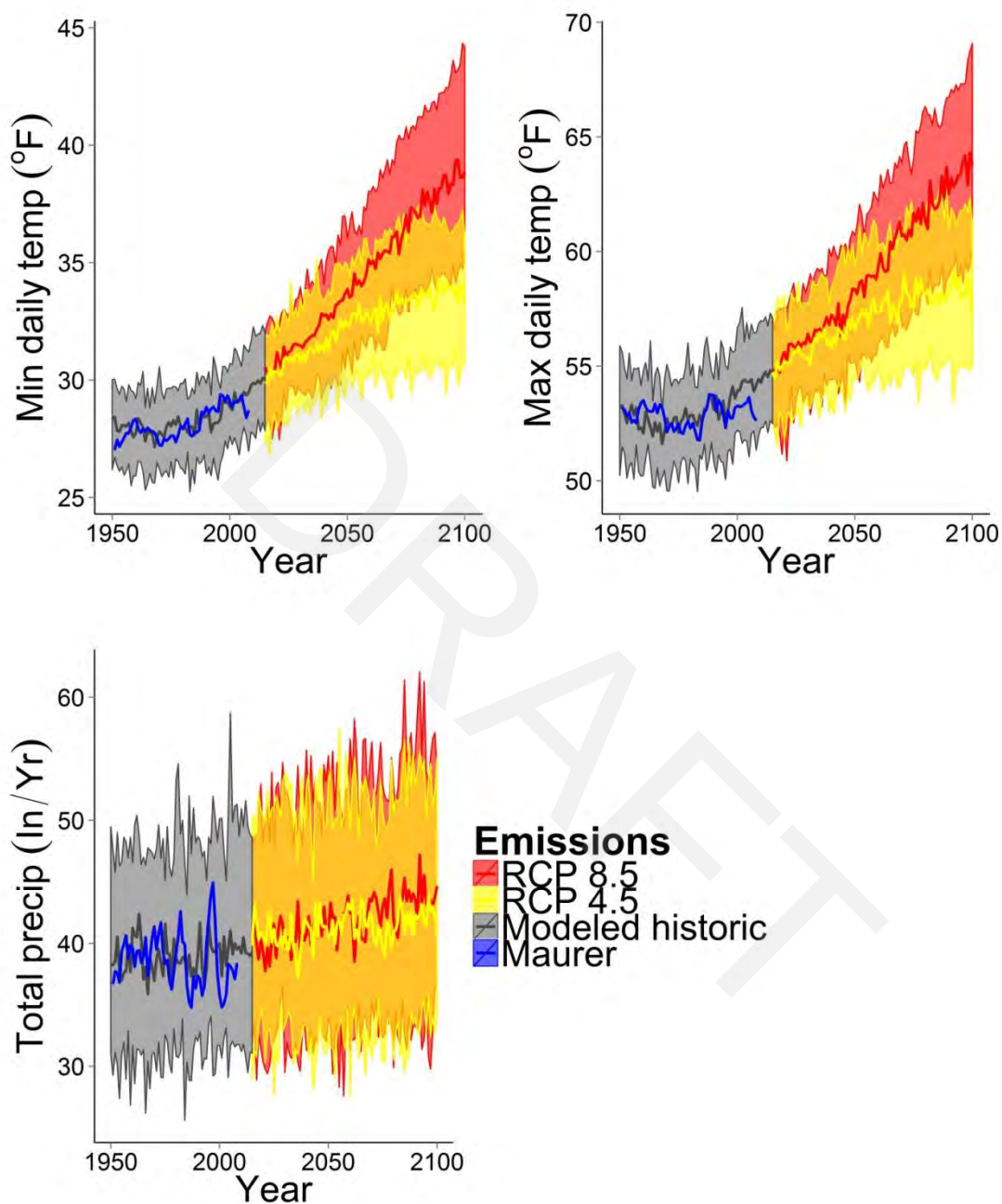


Figure 3.6—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Western subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

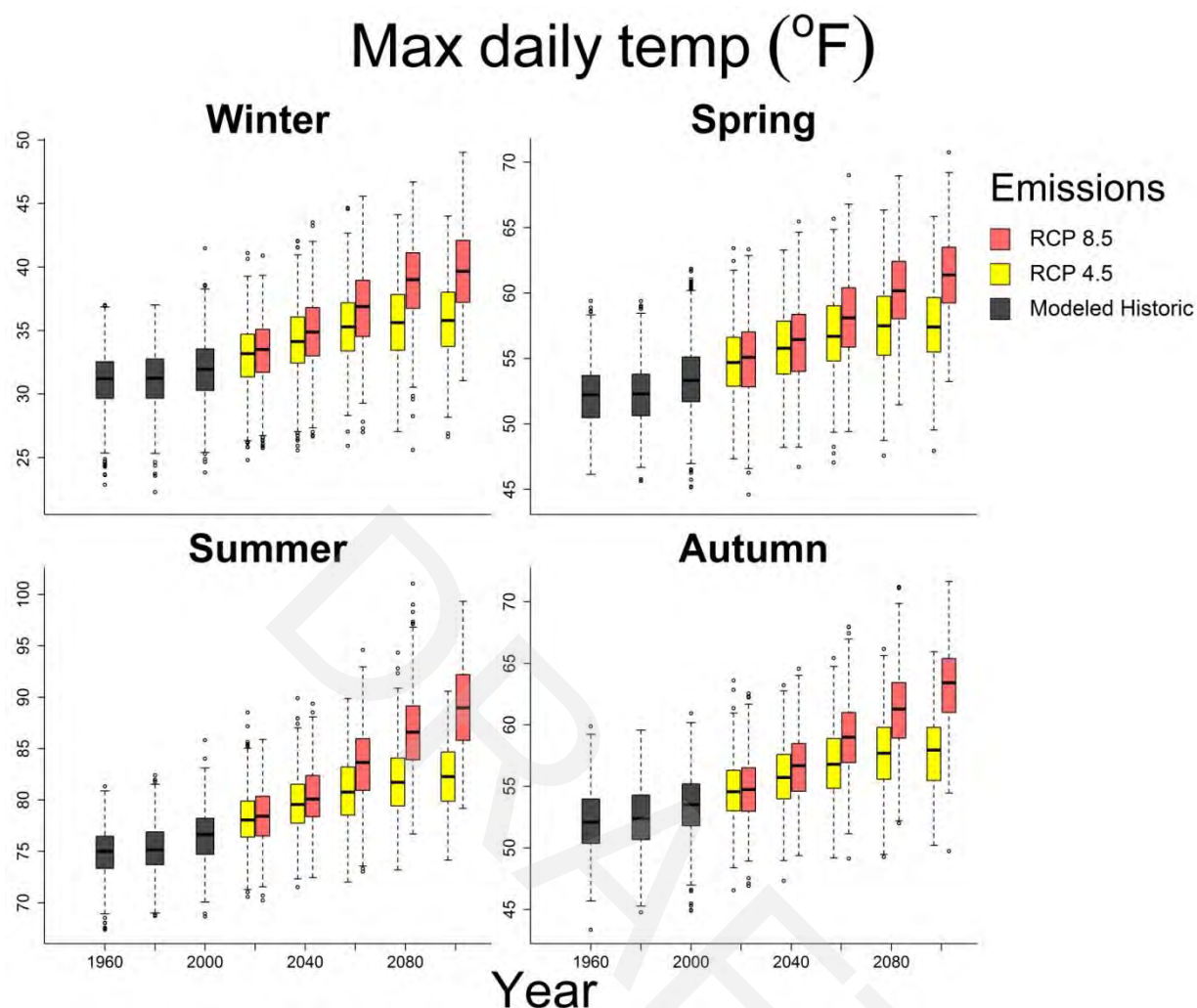


Figure 3.7—Seasonal mean monthly maximum temperature for 1950-2100 for the NRAP Western subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data centered on the year listed (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

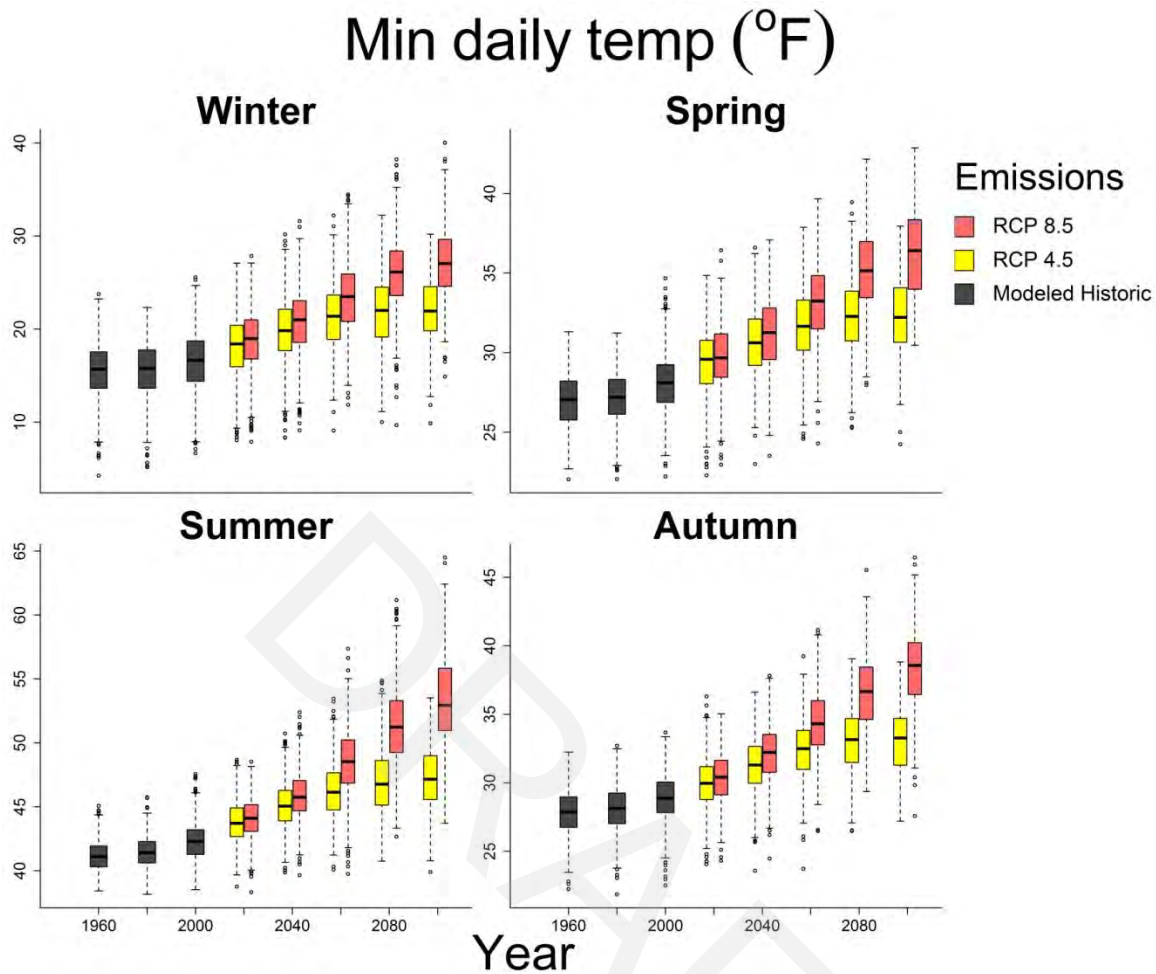


Figure 3.8—Seasonal mean monthly minimum temperature for 1950-2100 for the NRAP Western region. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

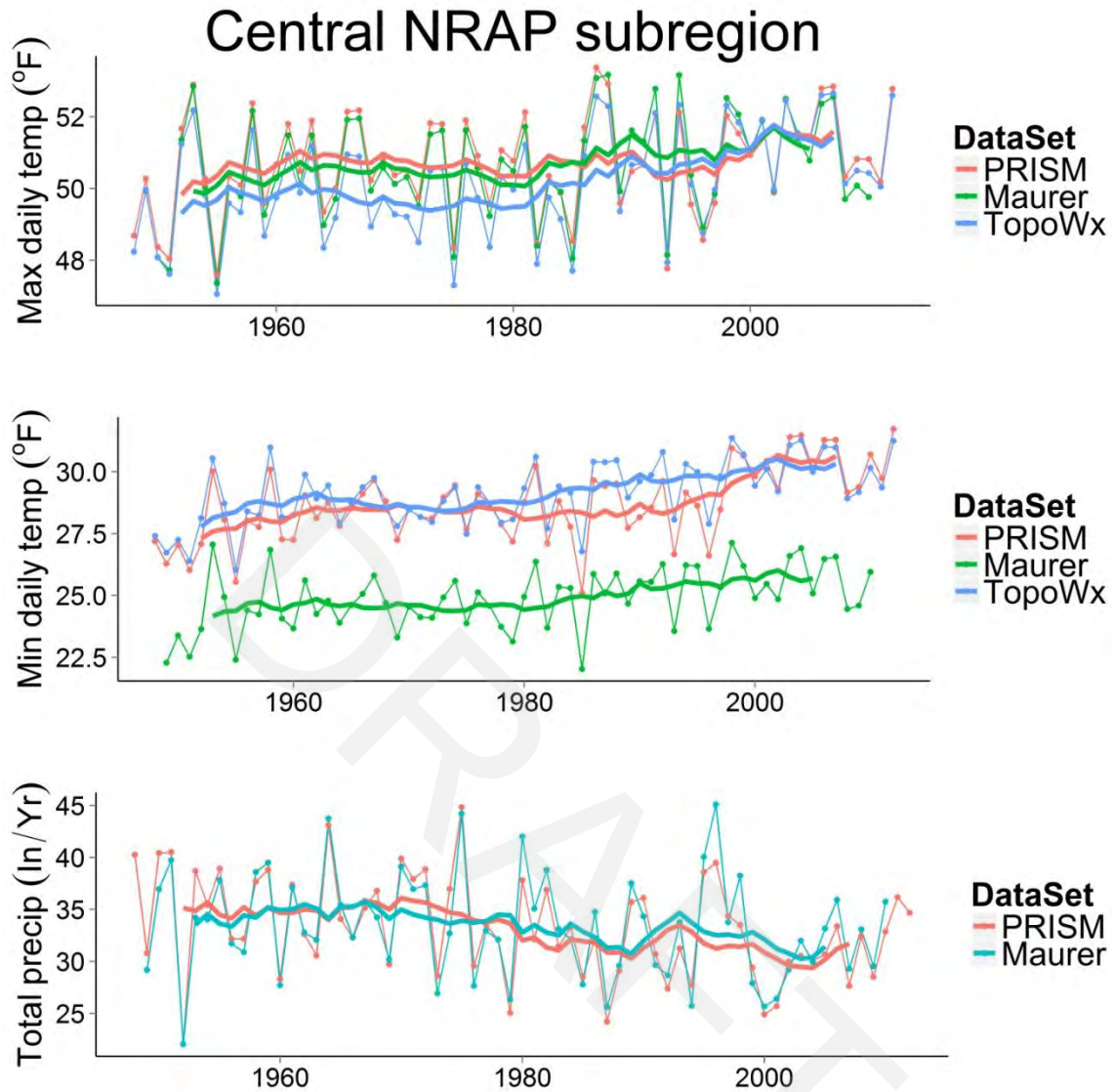


Figure 3.9—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Central subregion. The heavy lines are the 10-year rolling average which show short-term trends.

Central NRAP subregion model projections

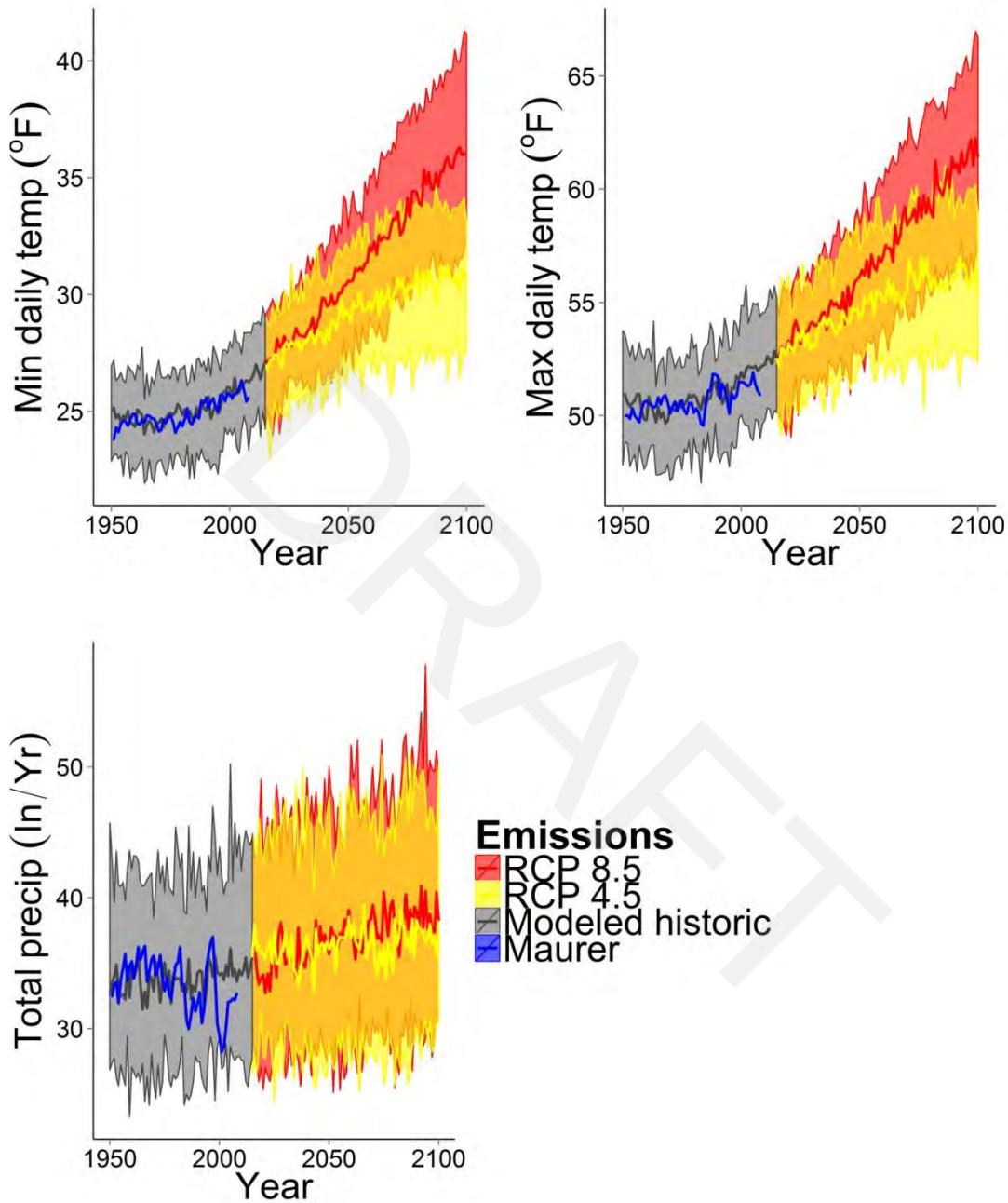


Figure 3.10—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Central subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

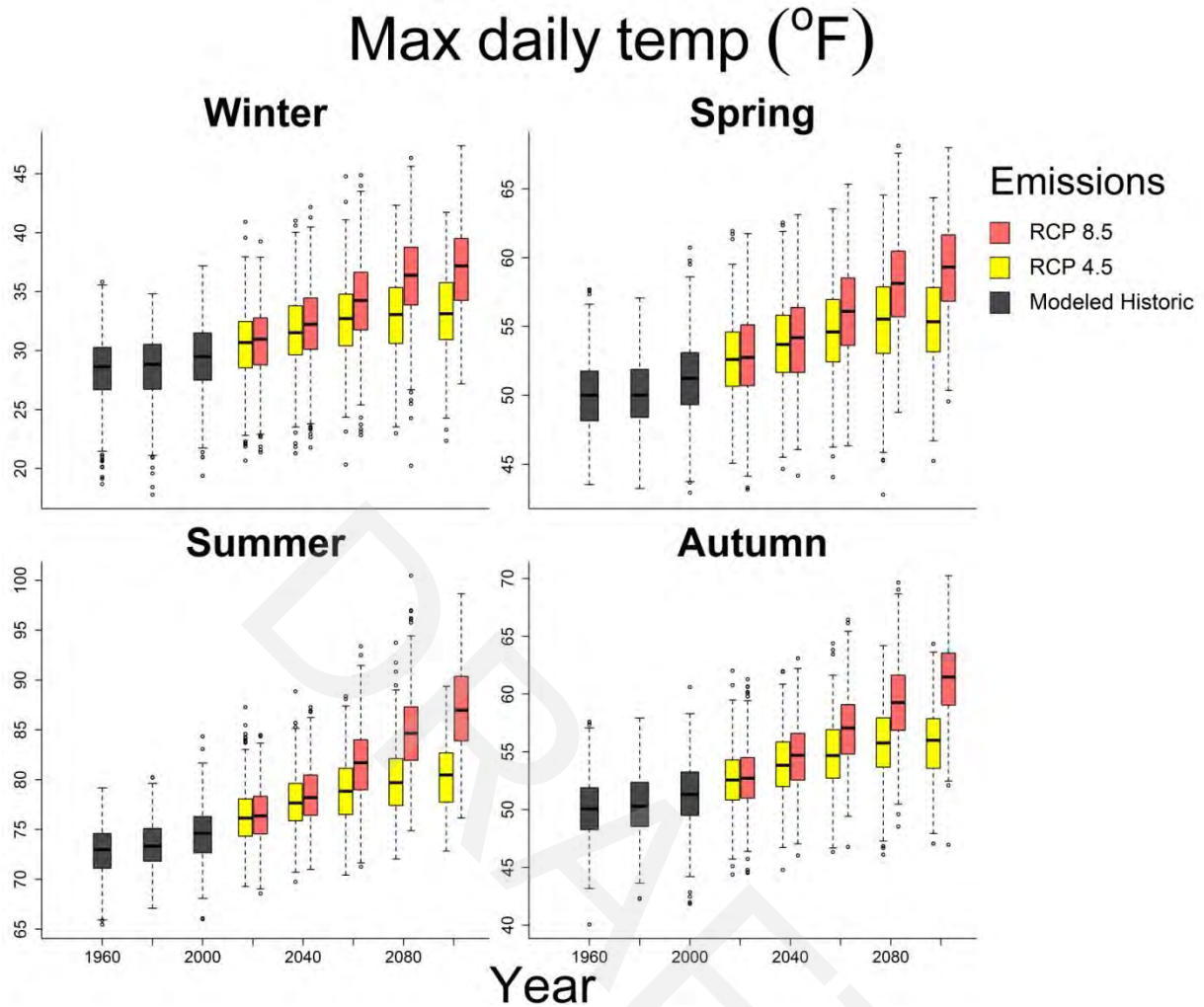


Figure 3.11—Seasonal mean monthly maximum temperature for 1950-2100 for the NRAP Central subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

Min daily temp (°F)

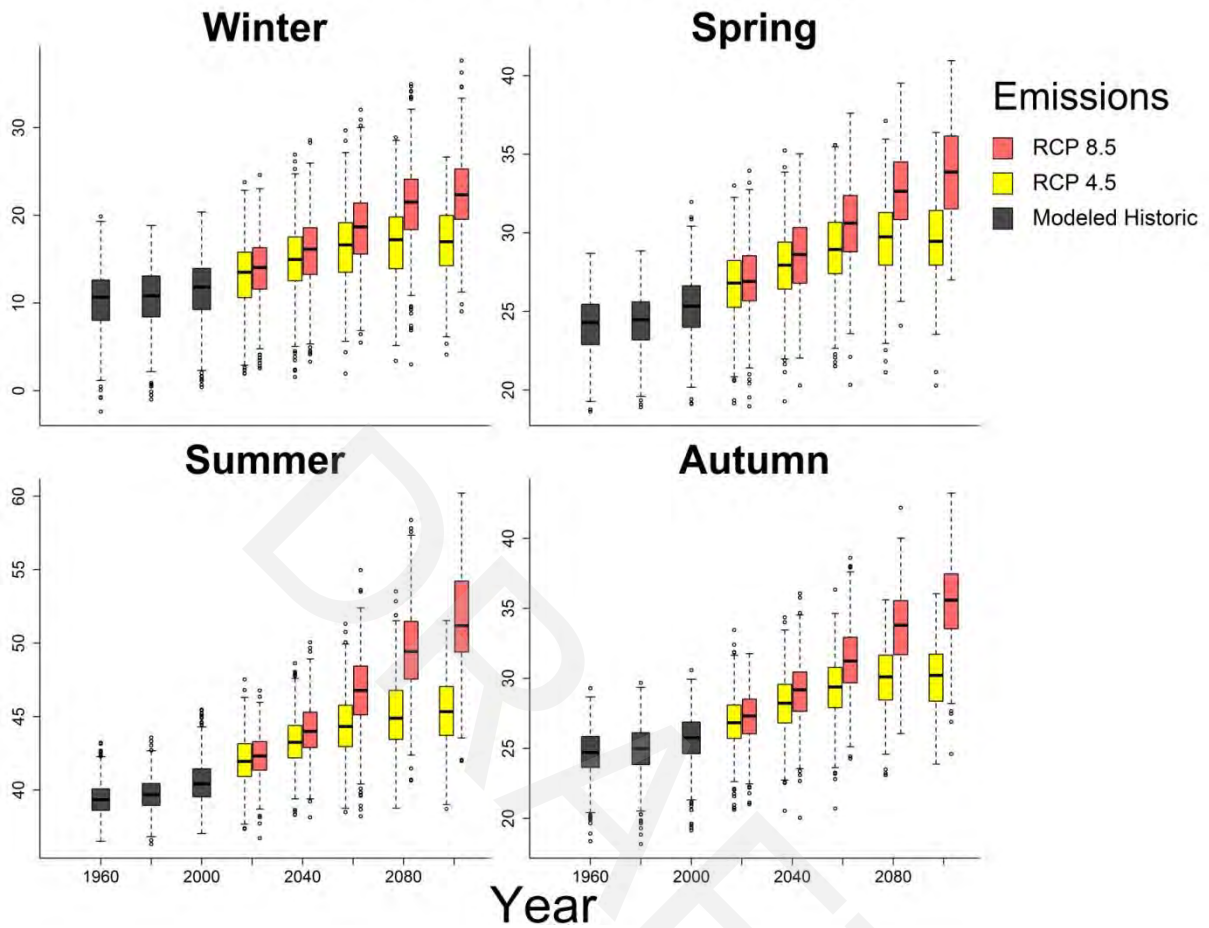


Figure 3.12—Seasonal mean monthly minimum temperature for 1950-2100. Each box is an aggregation of 20 years of modeled historical or projected seasonal data for the NRAP Central subregion (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

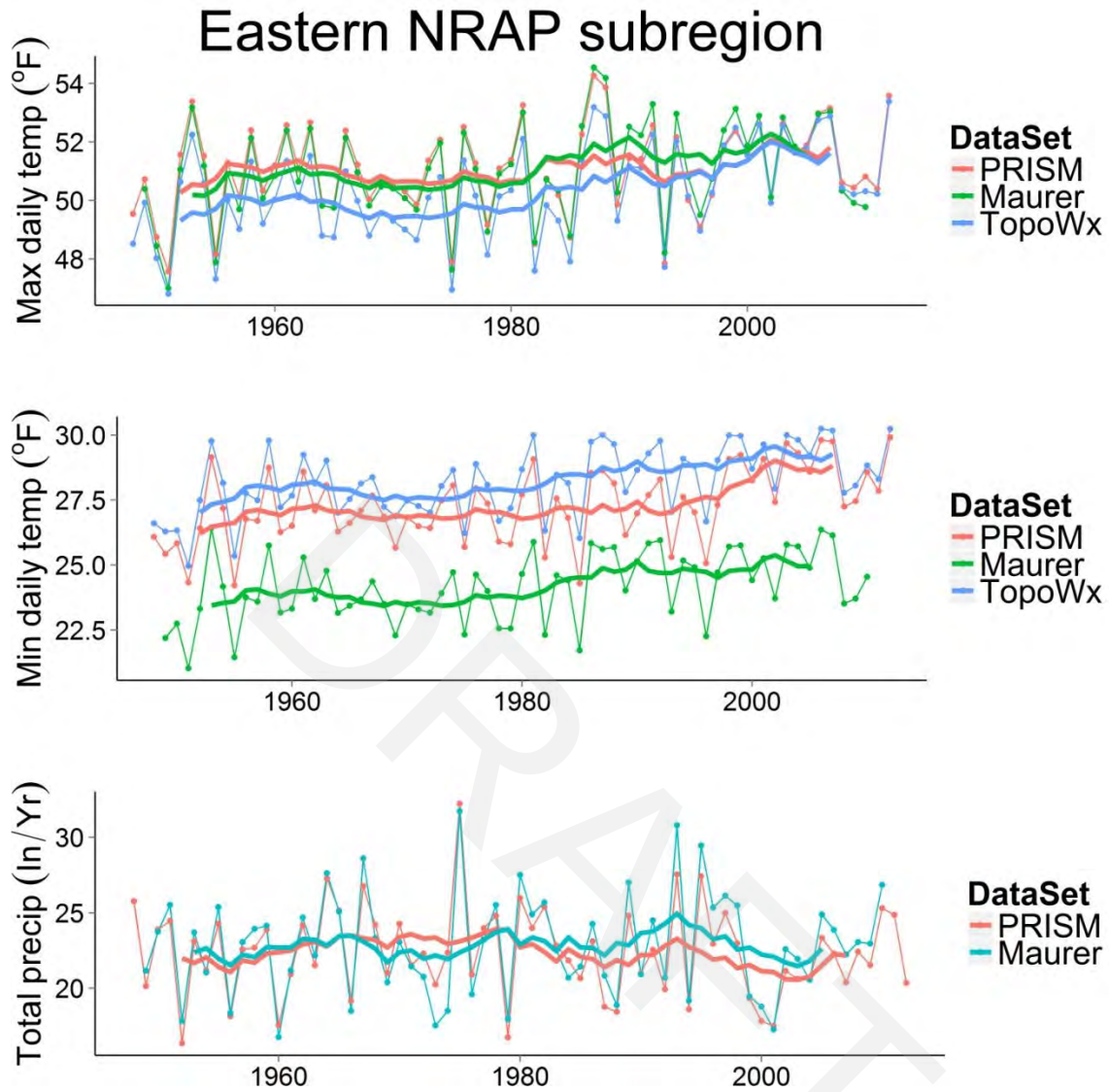


Figure 3.13—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Eastern subregion. The heavy lines are the 10-year rolling average which show short-term trends

Eastern NRAP subregion model projections

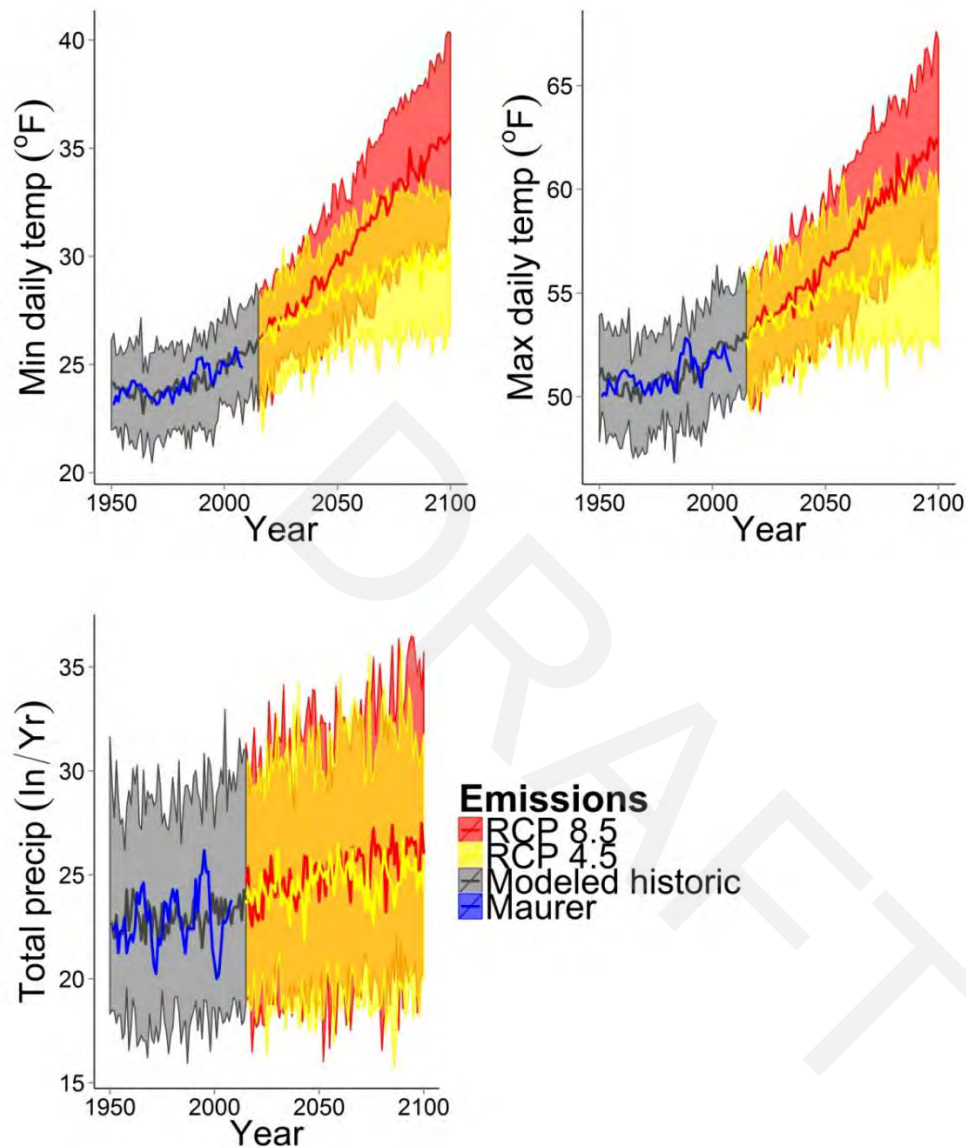


Figure 3.14—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Eastern subregion. Historic modeled results are indicated in gray, projections in colors. The 5th and 95th percent quantiles for all models are shown by the shaded area. The ensemble median is illustrated by the grey, red, or yellow heavy line; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

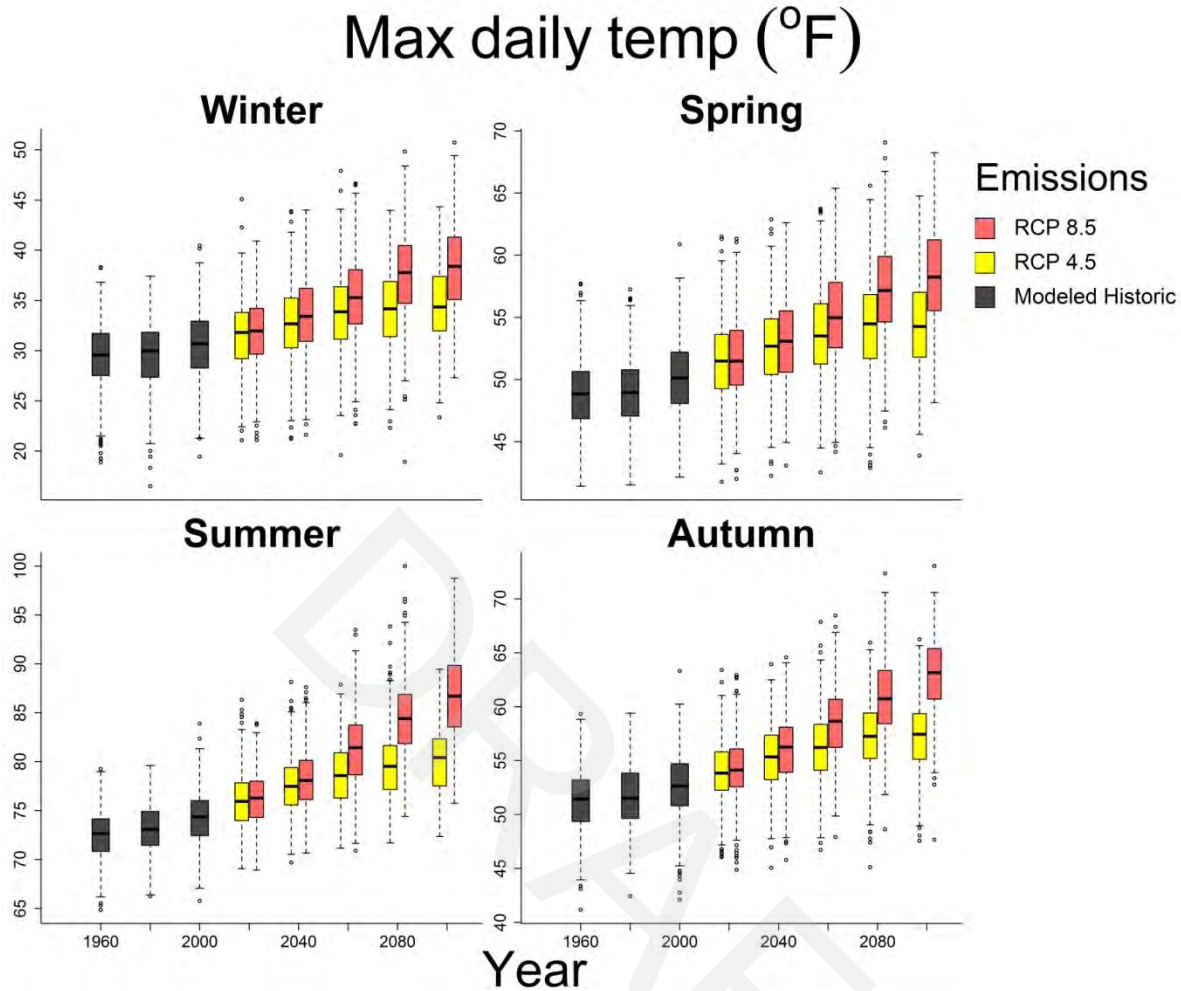


Figure 3.15—Seasonal mean monthly maximum temperature for 1950-2100 for the NRAP Eastern subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

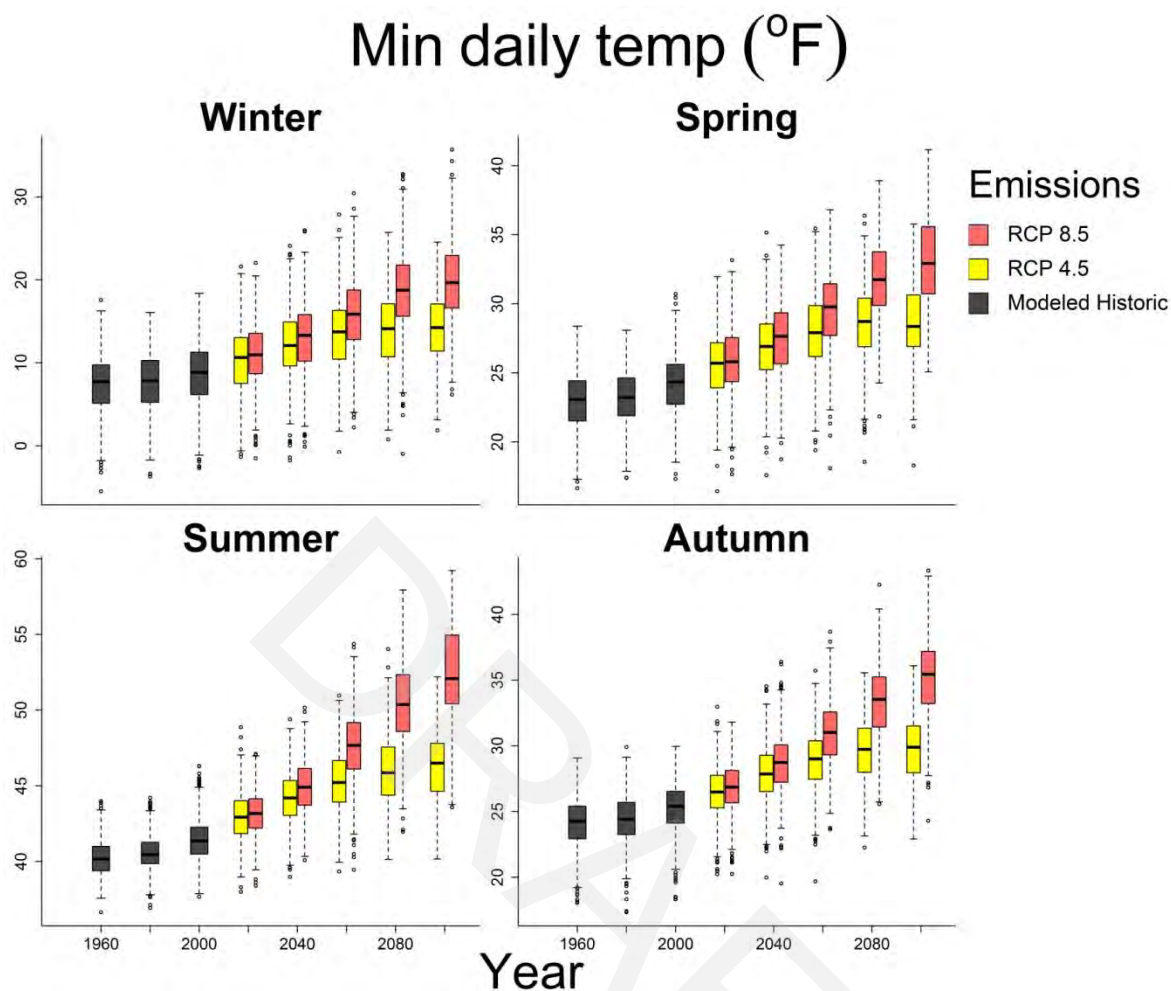


Figure 3.16—Seasonal mean monthly minimum temperature for 1950-2100 for the NRAP Eastern subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

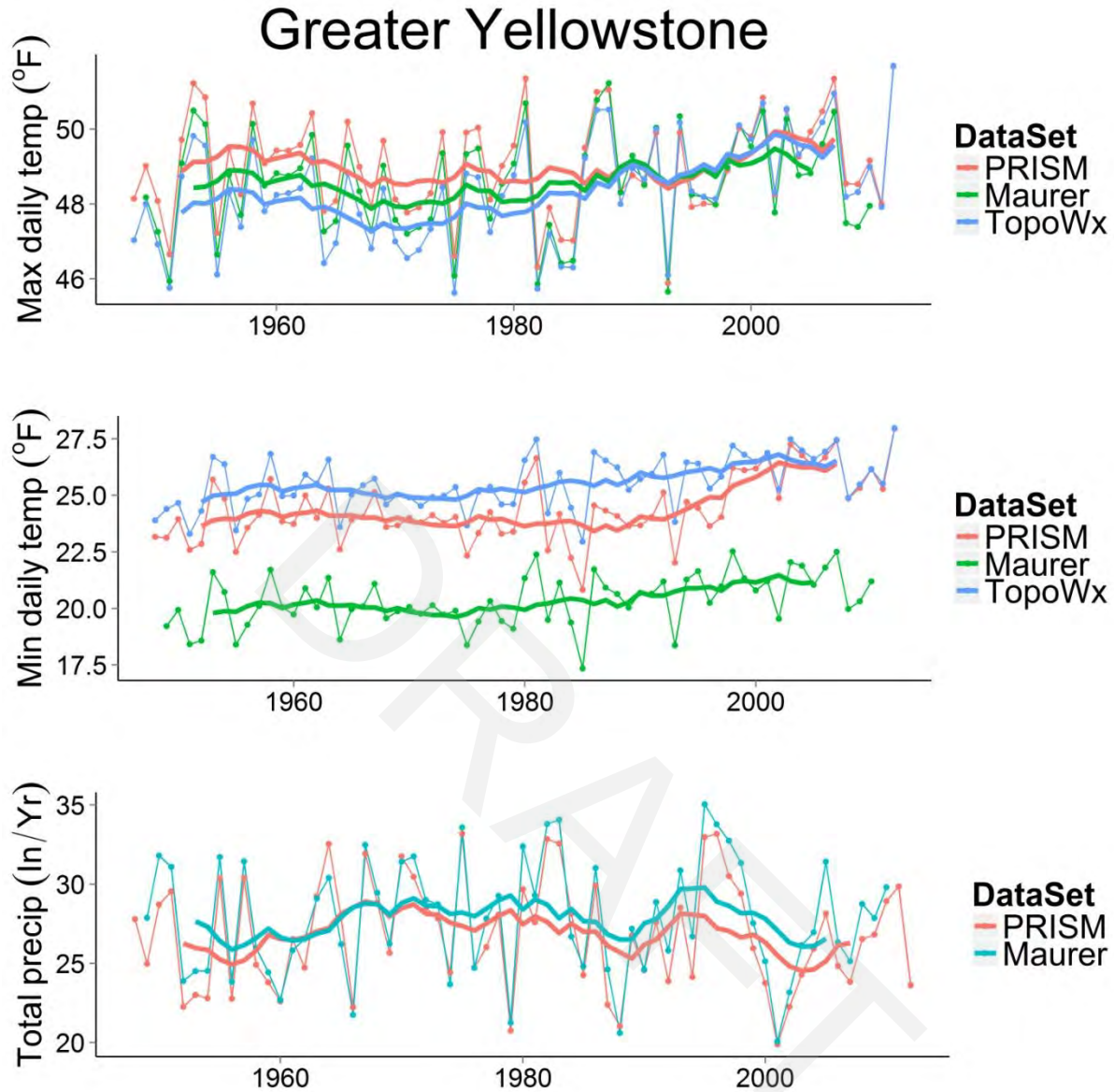


Figure 3.17—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Greater Yellowstone subregion. The heavy lines are the 10-year rolling average which show short-term trends.

Greater Yellowstone model projections

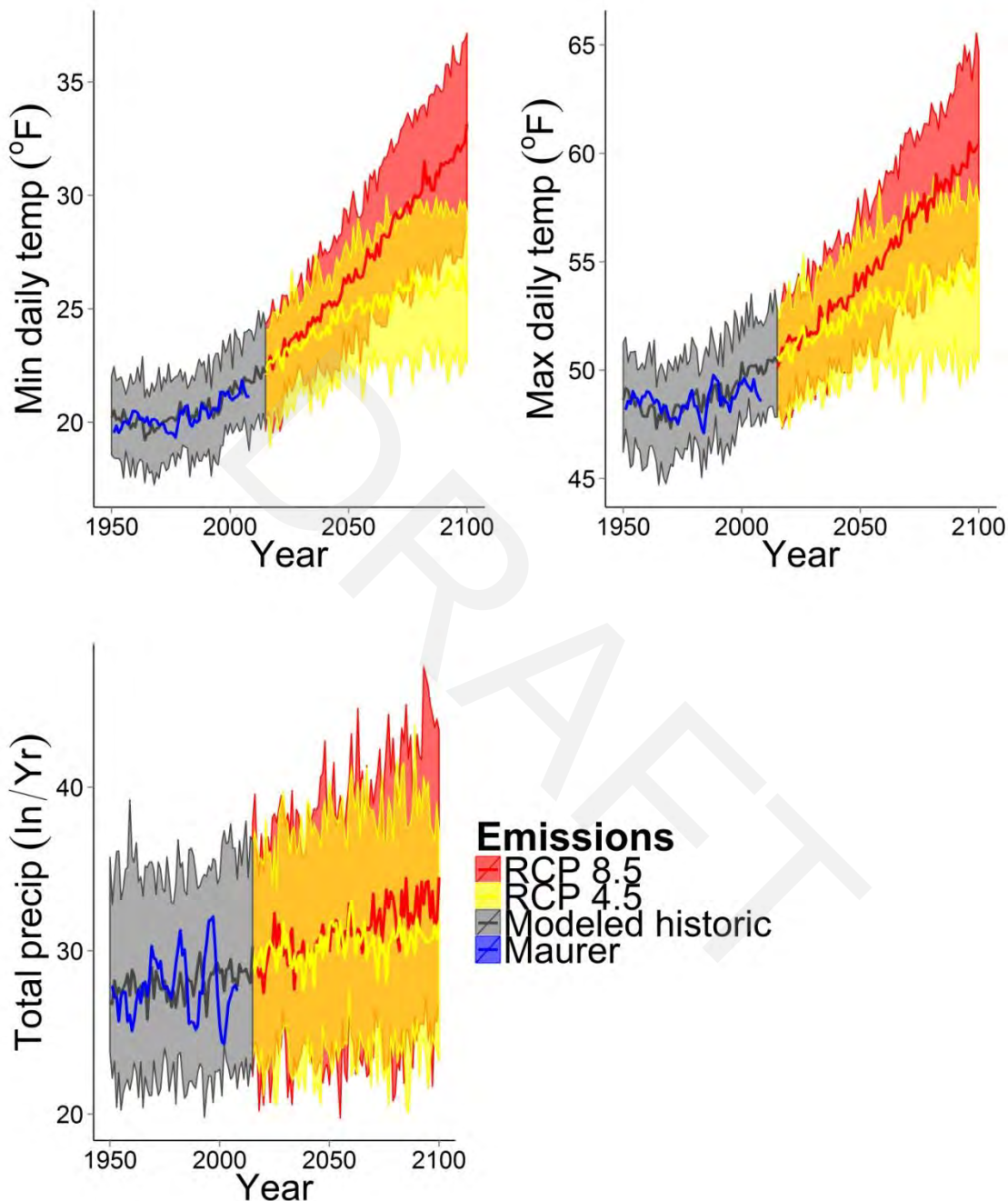


Figure 3.18—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Greater Yellowstone subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

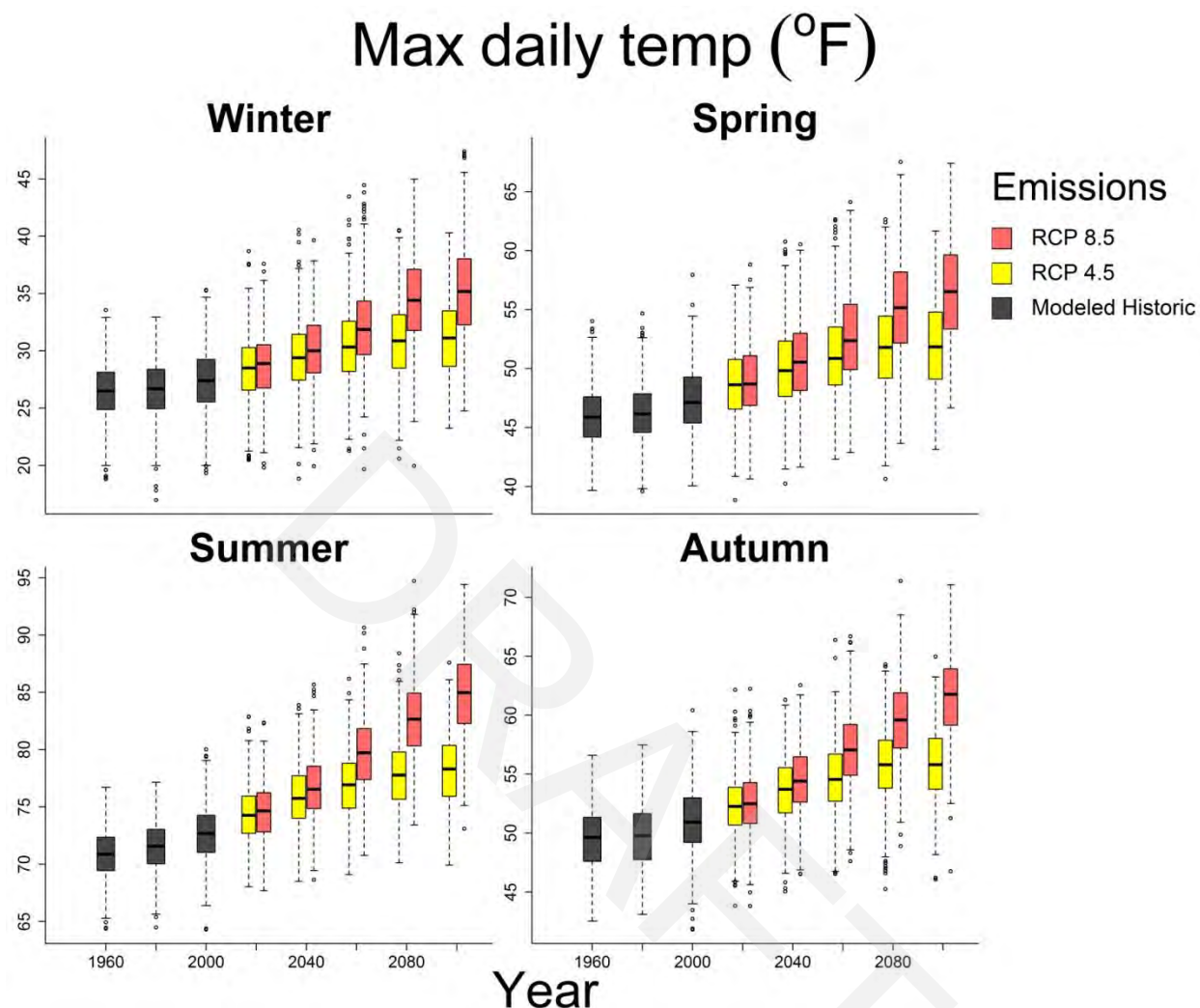


Figure 3.19—Seasonal mean monthly maximum temperature for 1950-2100 for the NRAP Greater Yellowstone subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

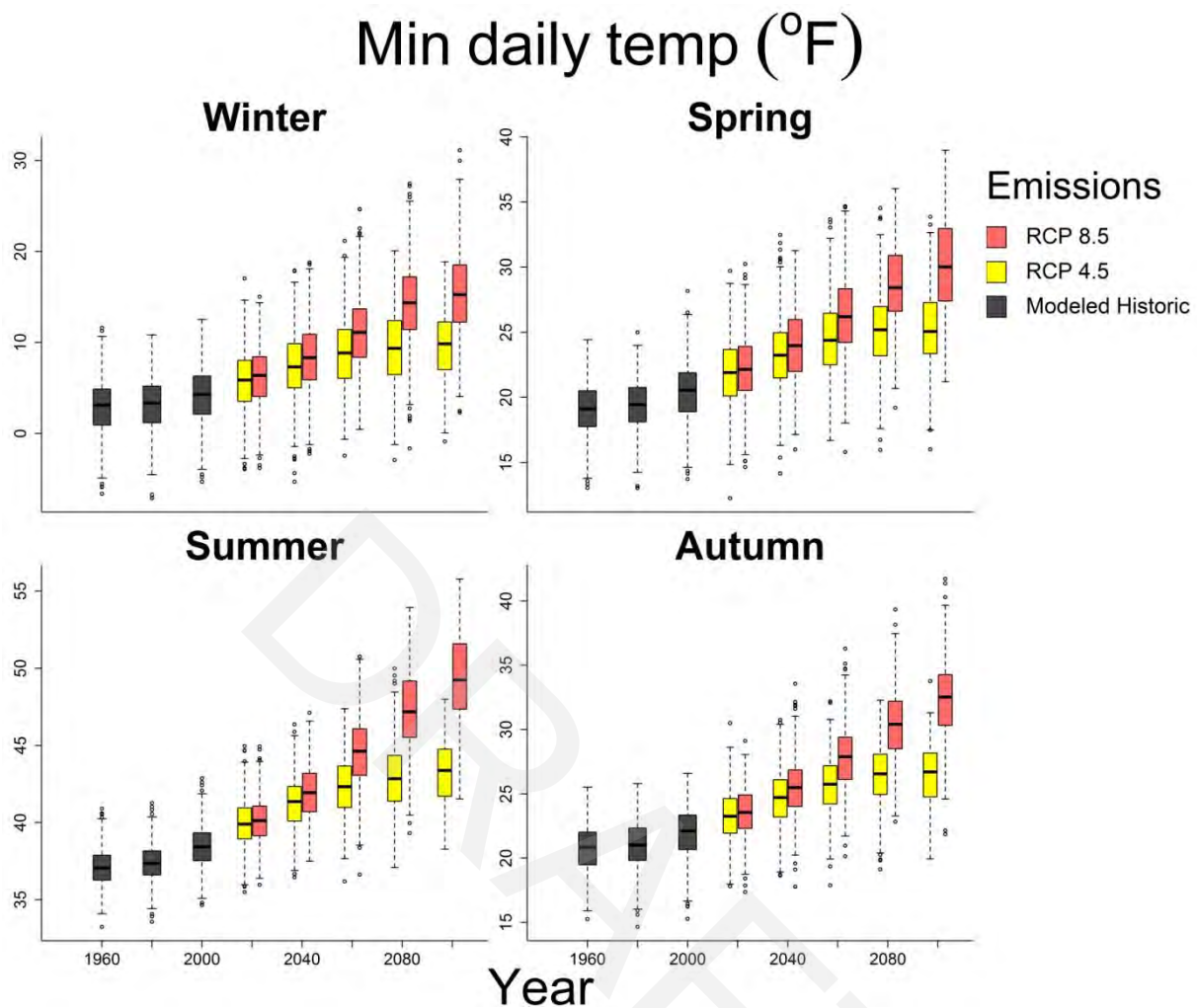


Figure 3.20—Seasonal mean monthly minimum temperature for 1950-2100 for the NRAP Greater Yellowstone subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

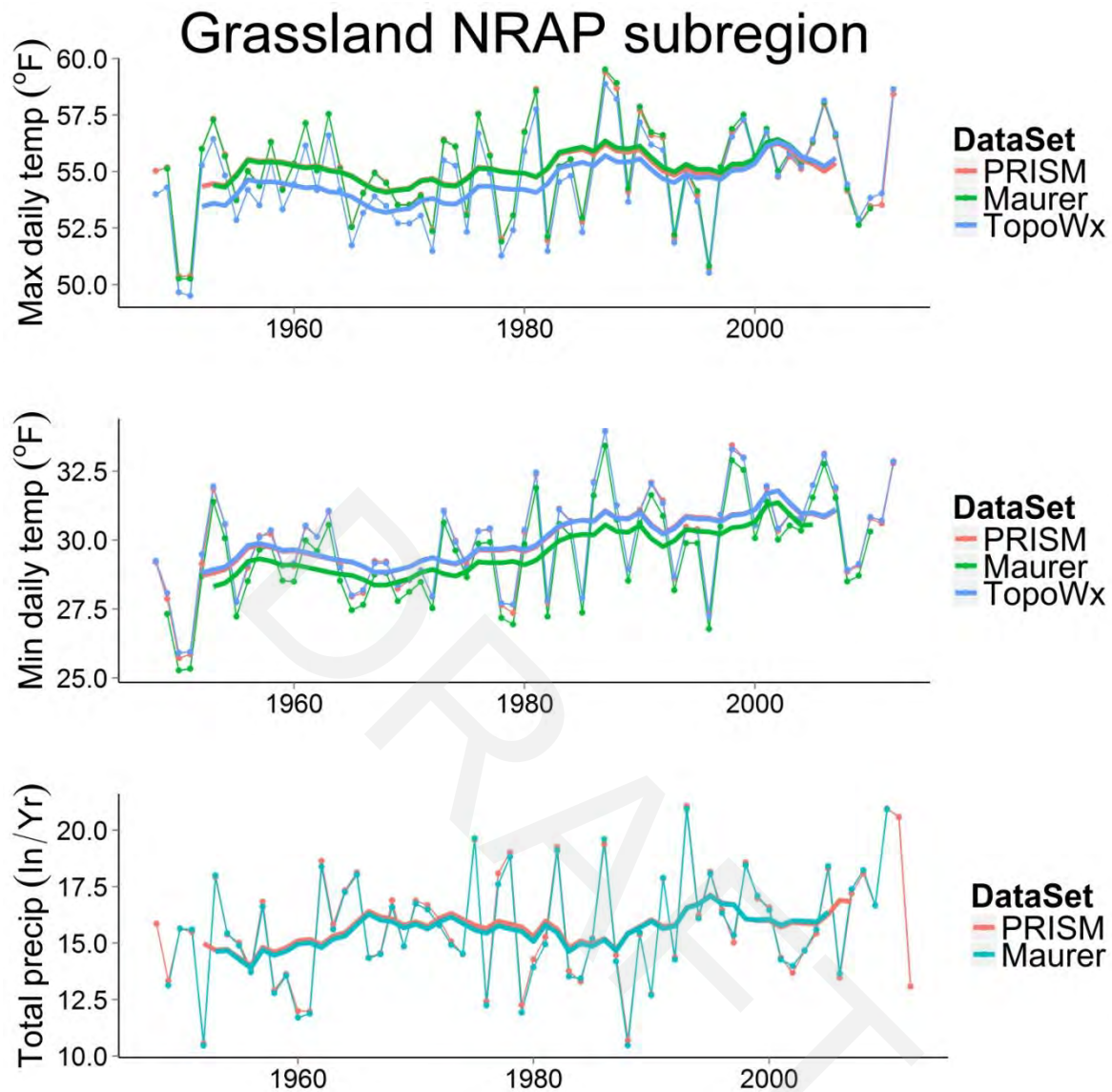


Figure 3.21—Annual historical mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation from monthly gridded PRISM, Maurer and TopoWx for 1949 to 2010 for the NRAP Grassland subregion. The heavy lines are the 10-year rolling average which show short-term trends.

Grassland NRAP subregion model projections

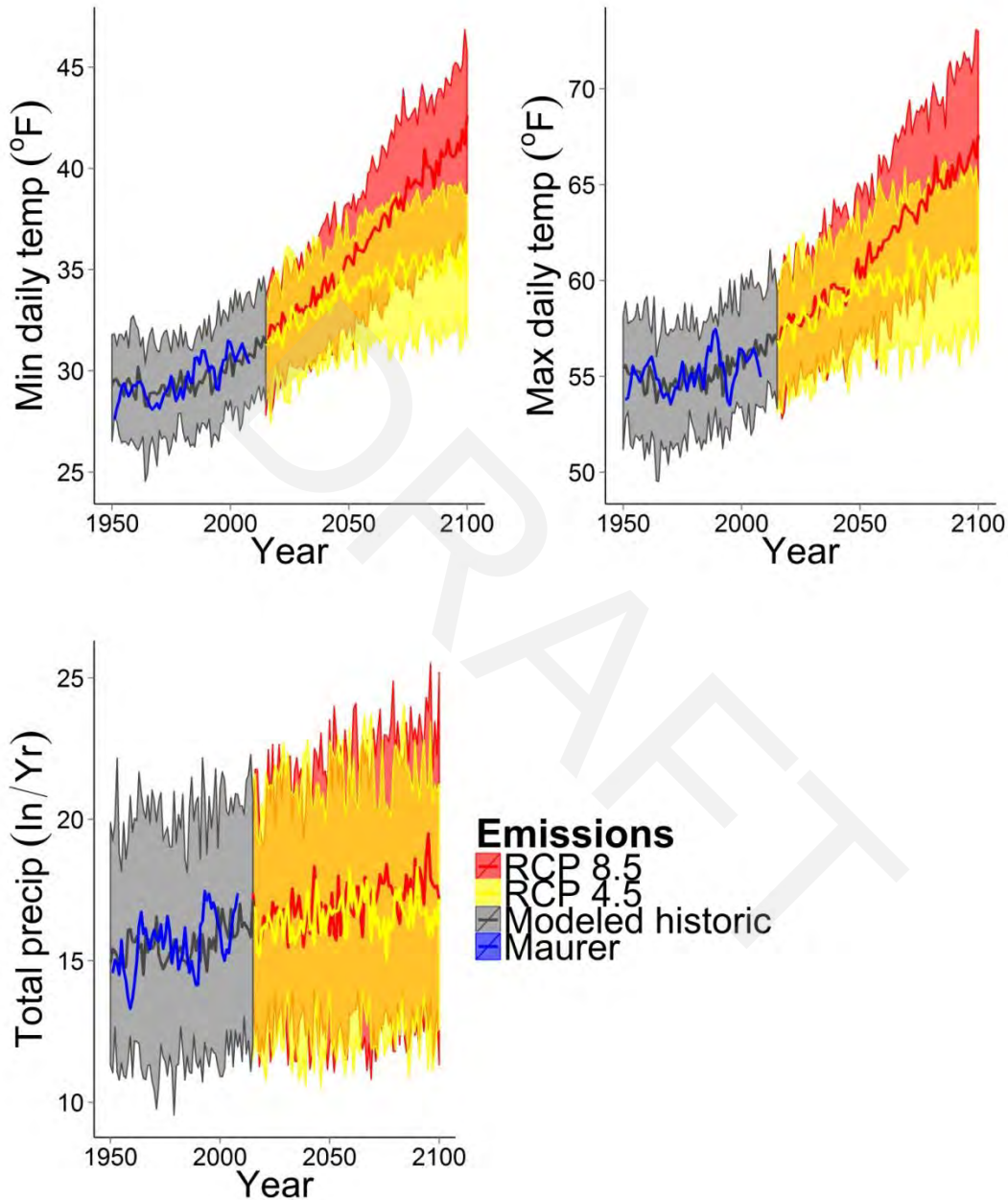


Figure 3.22—Historical modeled and projected annual mean monthly maximum temperature, annual mean monthly minimum temperature, and total annual precipitation for the RCP 4.5 and RCP 8.5 emission scenarios based on CMIP5 data for the NRAP Grassland subregion. Historic modeled results are indicated in gray, projections in colors. The shaded area shows the 5th and 95th percent quantiles for all models. The grey, red, or yellow heavy line illustrate ensemble median; the heavy blue line is the gridded historical observed data from Maurer et al. (2002).

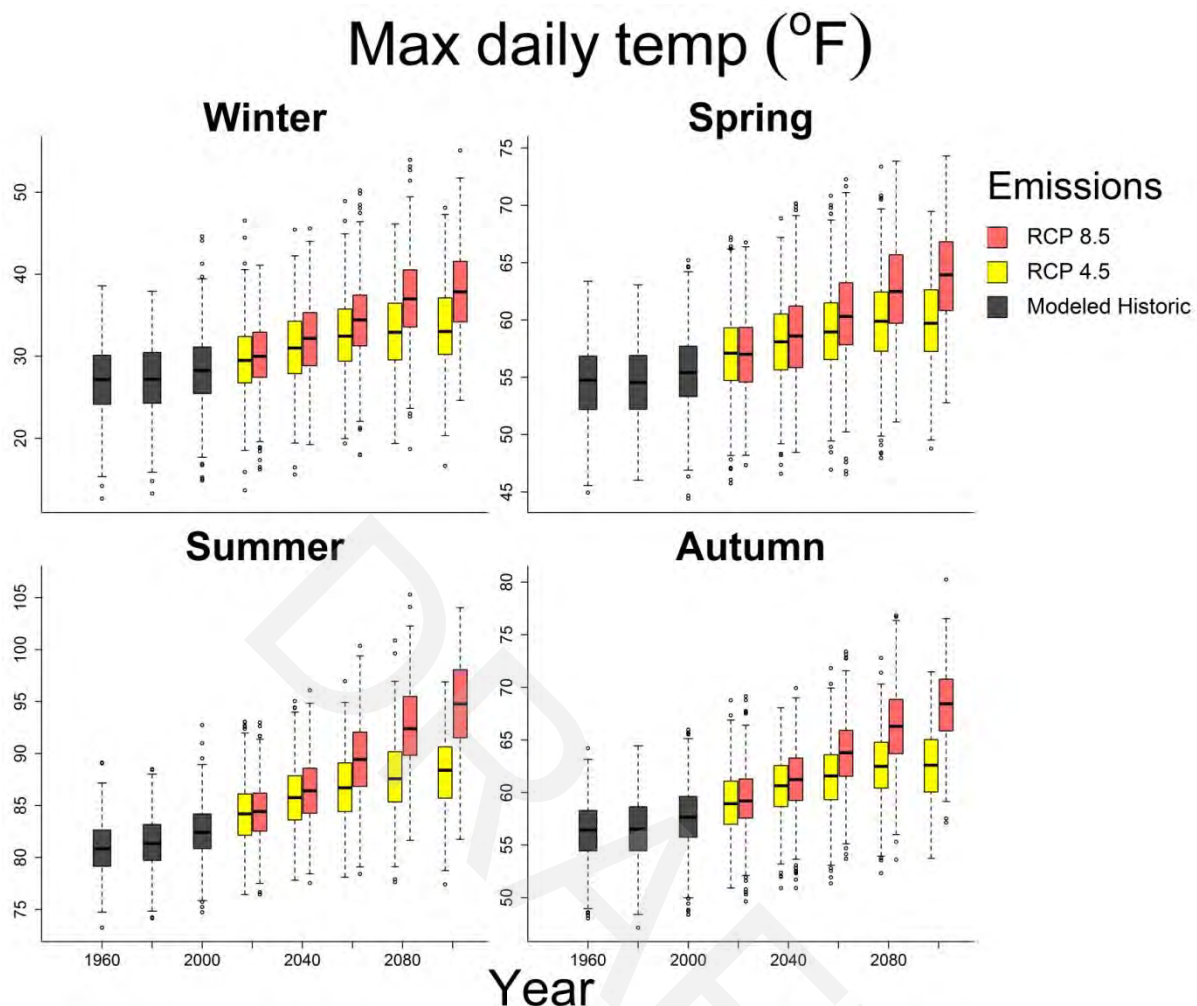


Figure 3.23—Seasonal mean monthly maximum temperature for 1950-2100 for the NRAP Grassland subregion. Each box is an aggregation of 20 years of modeled historical or projected seasonal data (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

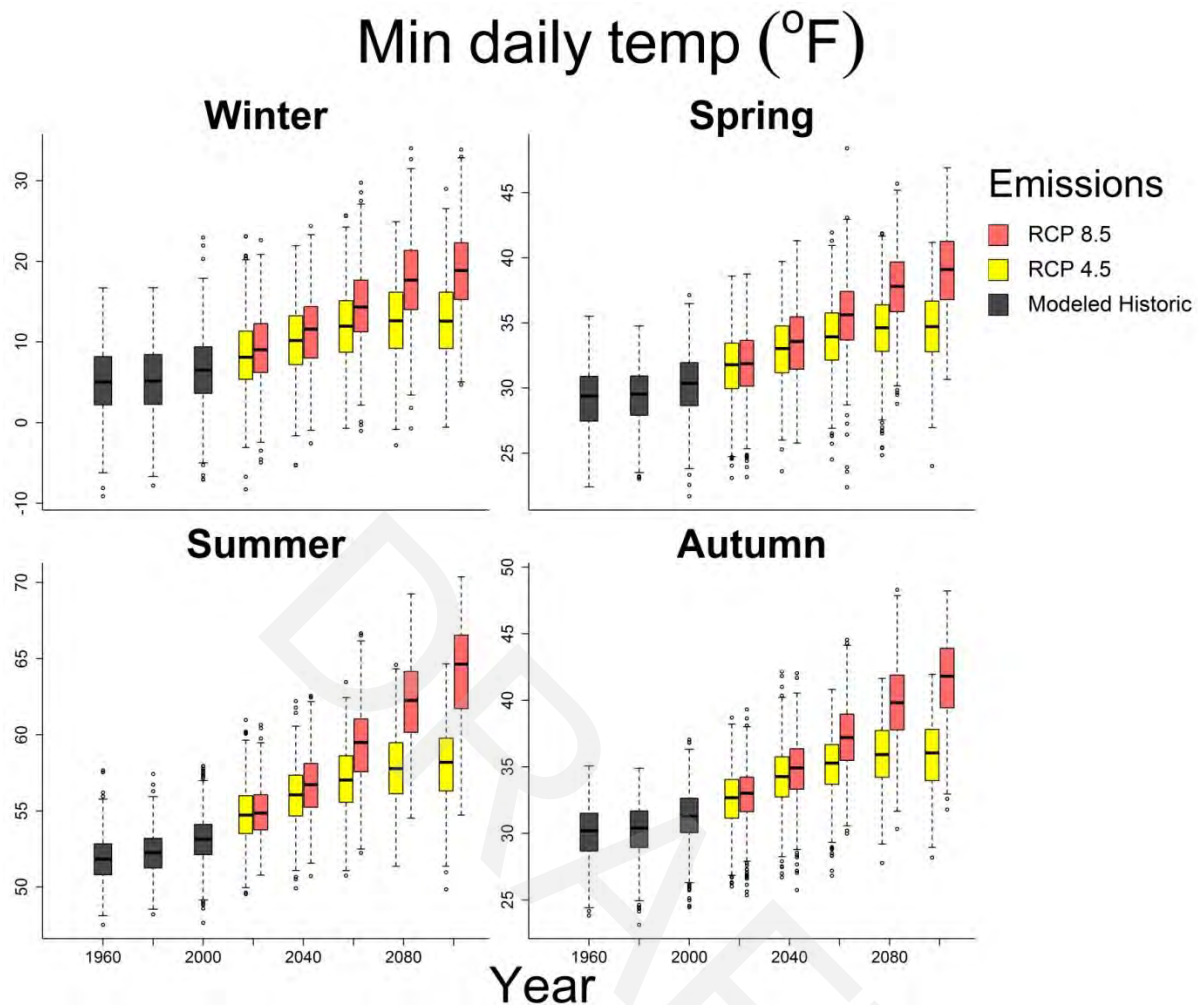


Figure 3.24—Seasonal mean monthly minimum temperature for 1950-2100 for the NRAP Grassland subregion (historical, grey boxes; RCP 4.5, yellow boxes; RCP 8.5, red boxes). Each box is an aggregation of 20 years of modeled historical or projected seasonal data. For example, 1960 represents the seasonal average of 1950 to 1969. The central line in each box is the median. Hinges or edges of the boxes are the first and third quartiles; whiskers extend past the first and third quartile by 1.5 times the interquartile range (middle 50); points outside of the whiskers are extreme values.

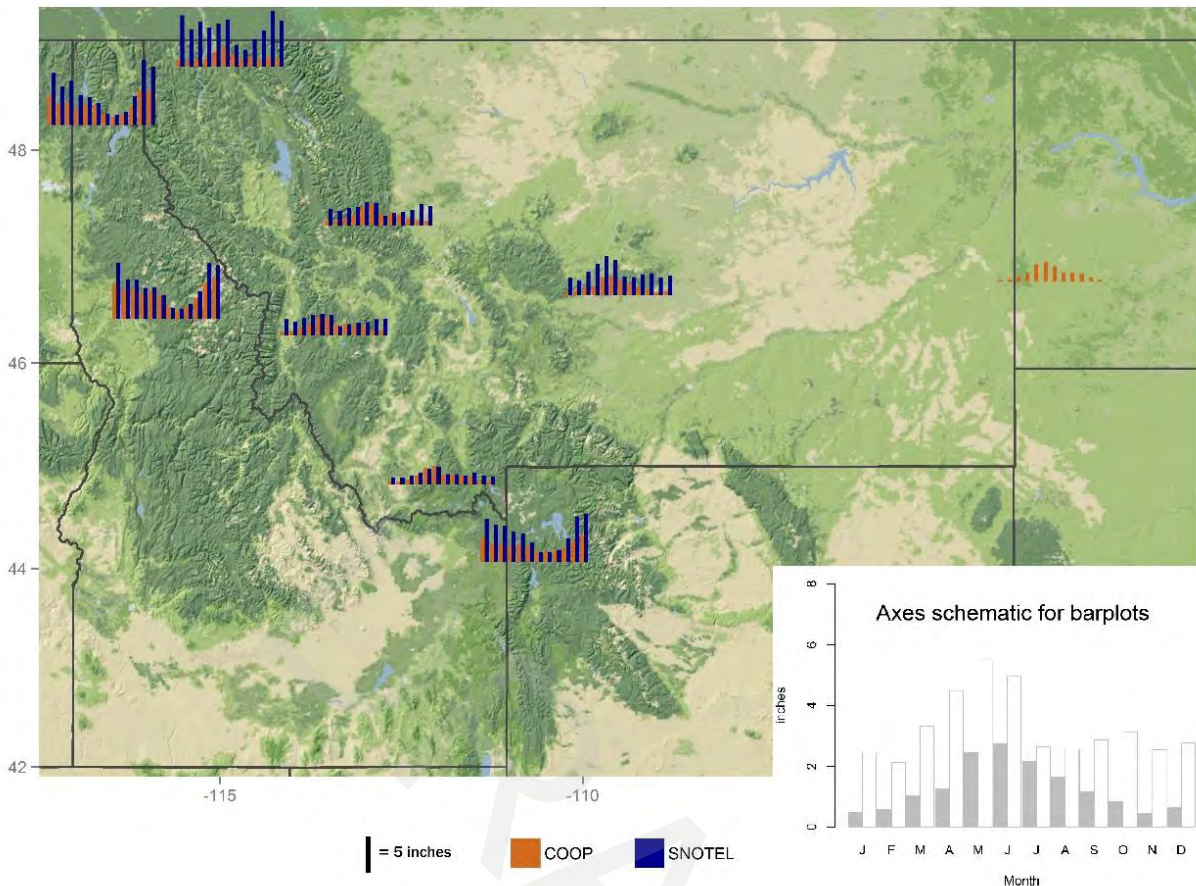


Figure 4.1—Bar graphs of annual precipitation amounts and distribution from several representative locations. More western and higher elevation sites tend to have stronger winter precipitation, with a pronounced lull in July and August. May and June precipitation is generally more pronounced than July and August precipitation and so is likely an important water source for vegetation during the summer drought.

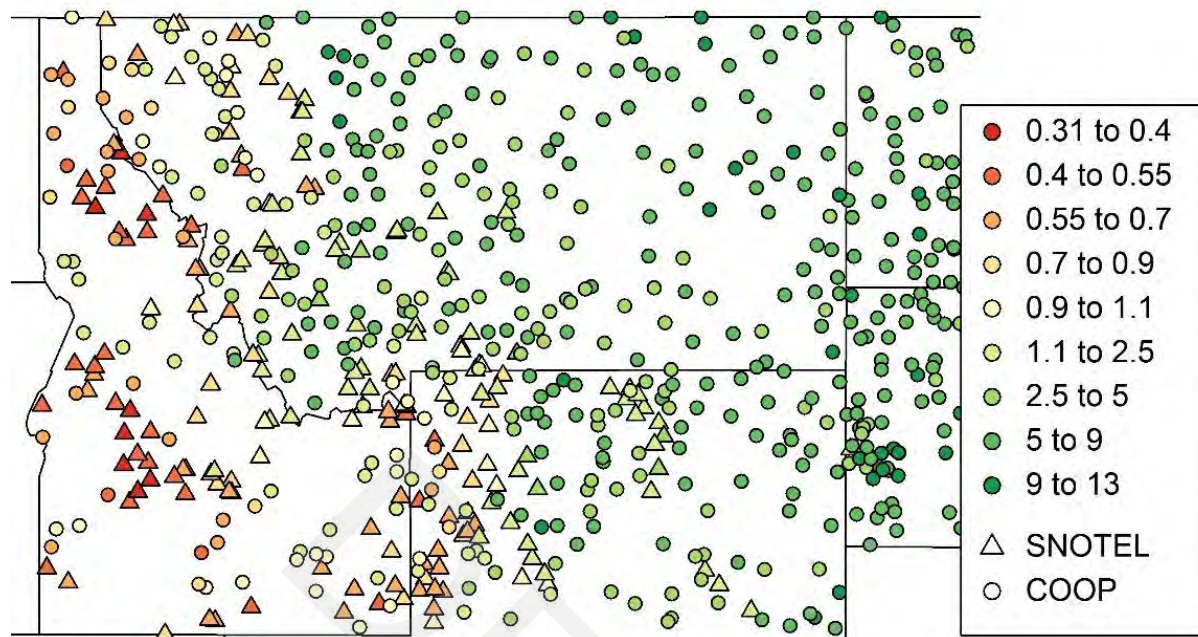


Figure 4.2—An index of precipitation seasonality in the Northern Rockies, a ratio of early summer (May-June) to winter (December-January) precipitation. Greener colors are wetter in May and June. July and August precipitation is low for most locations. Of note is the relative contribution of May through June precipitation in western Montana and central Idaho compared to mountains (SNOTEL sites) further south. There is also a notable difference in mountain versus local valley (COOP sites) seasonality.

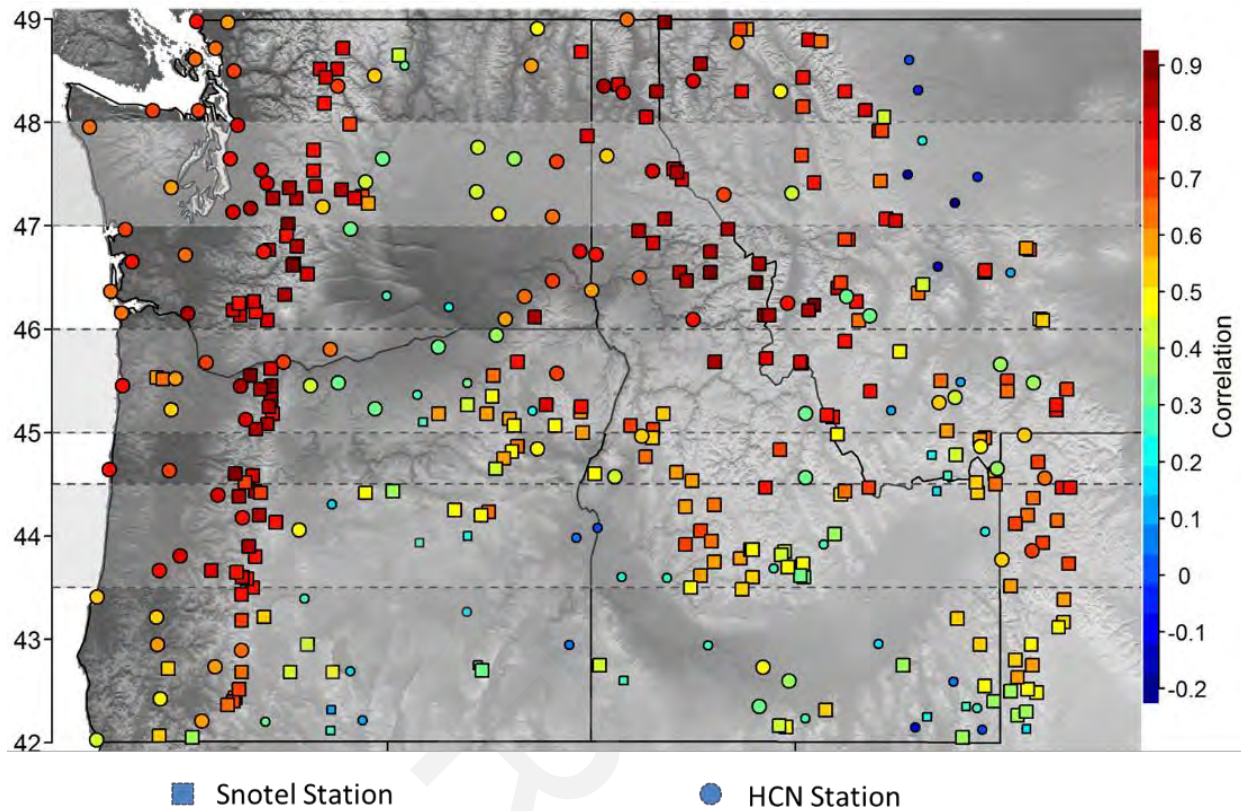


Figure 4.3—Correlation of winter precipitation to winter westerly wind speed across the Pacific Northwest (From Luce et al. 2013).

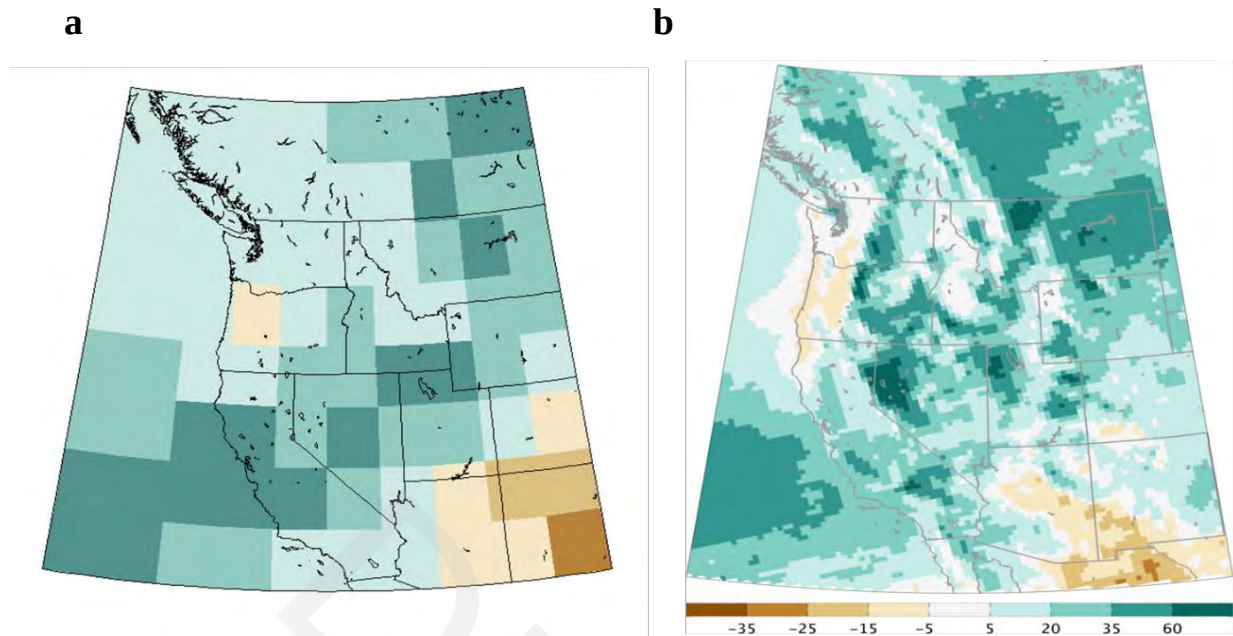


Figure 4.4—October through March precipitation change for 2041-2070 versus 1971-2000 as represented by a) a global circulation model (CanESM2) and b) a regional climate model with finer topographic detail.

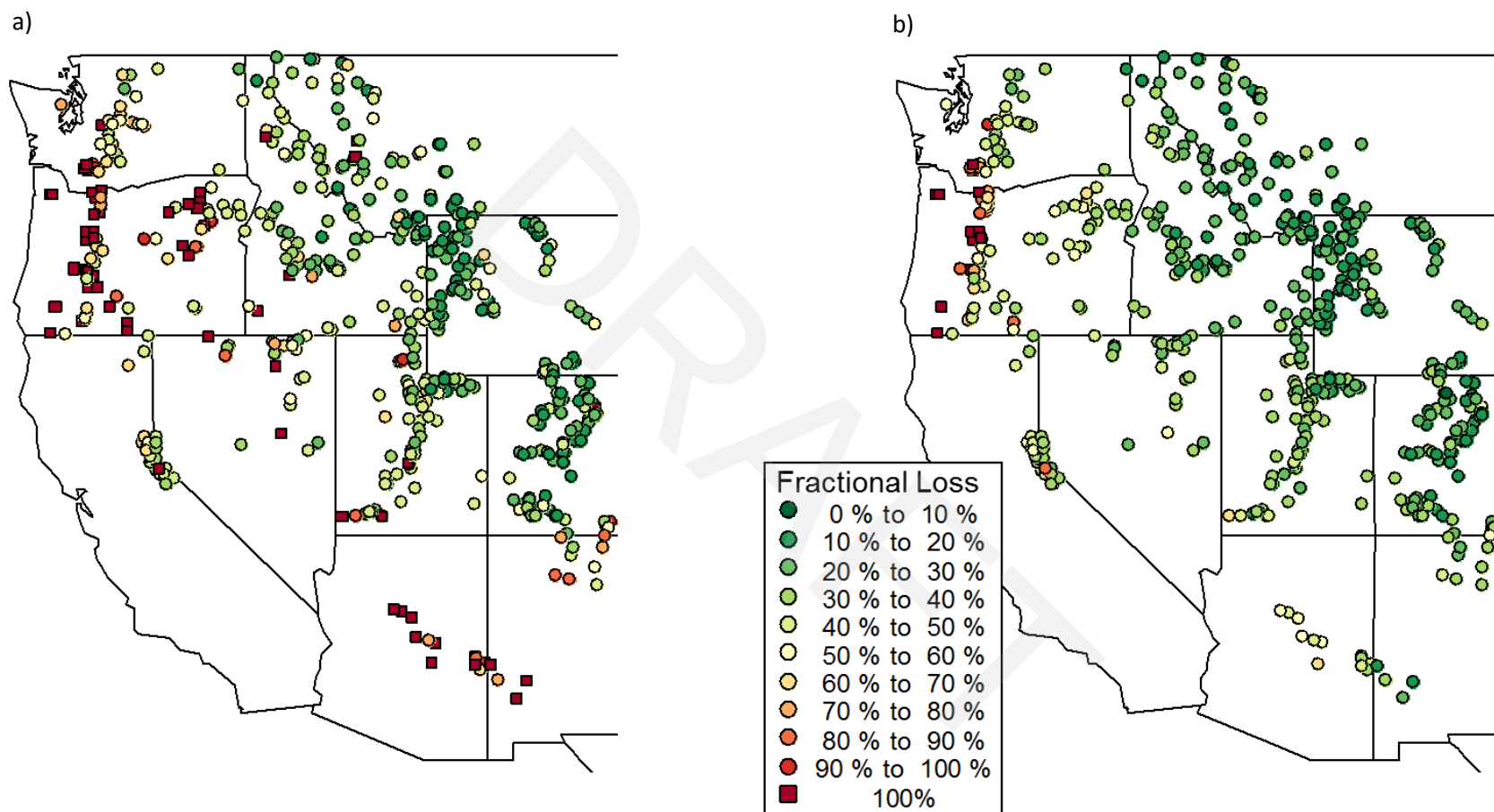
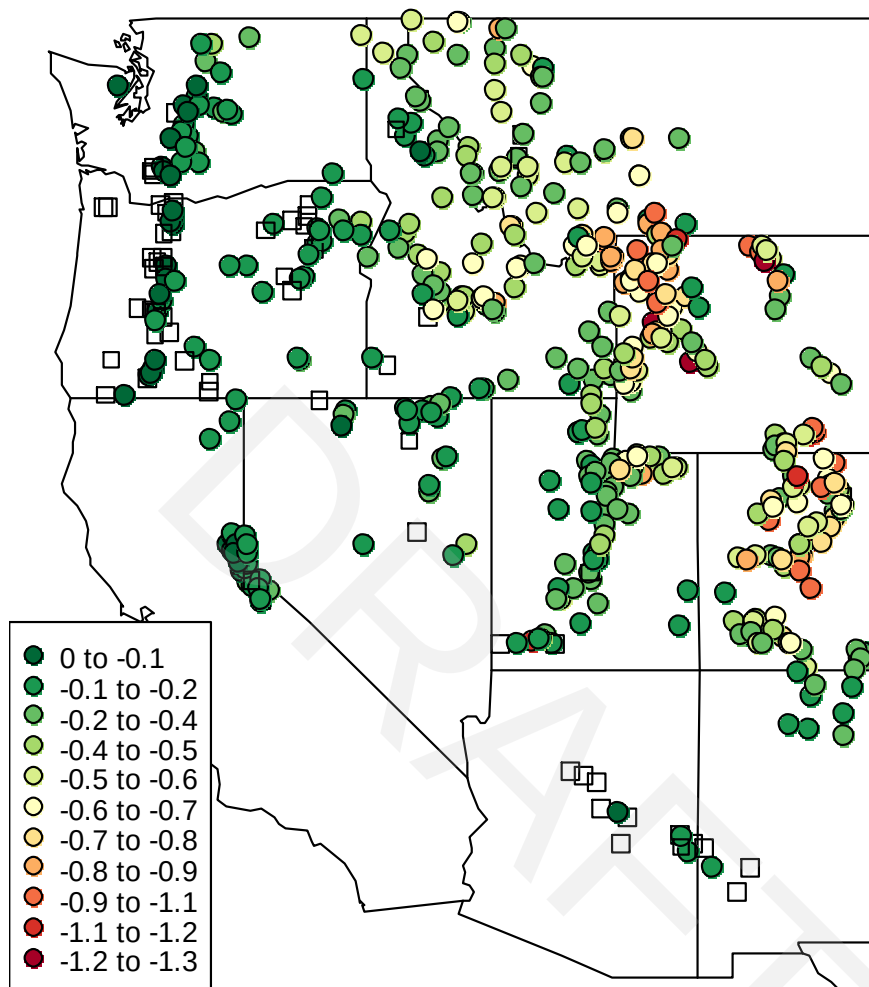


Figure 4.5—Estimated loss of a) April 1 snow water equivalent and b) mean snow residence time as related to warming of 5.4 °F (from Luce et al. 2014).

a)



b)

Figure 4.6—Uncertainty ratio for April 1 snow water equivalent. Orange to dark red sites are strongly influenced by precipitation in contrast to temperature. Thus, temperature based projections in those sites may be inaccurate if precipitation changes are large. At dark green (and white) sites, temperature effects will predominate, and precipitation changes in either direction are inconsequential.



1938 T. J. Hileman photo
Courtesy of GNP Archives



1981 Carl Key photo
USGS



1998 D. Fagre photo
USGS



2009 Lindsey Bengtson photo
USGS

Figure 4.7—Oblique view of Grinnell Glacier taken from the summit of Mount Gould, Glacier National Park (After Fagre 2005).

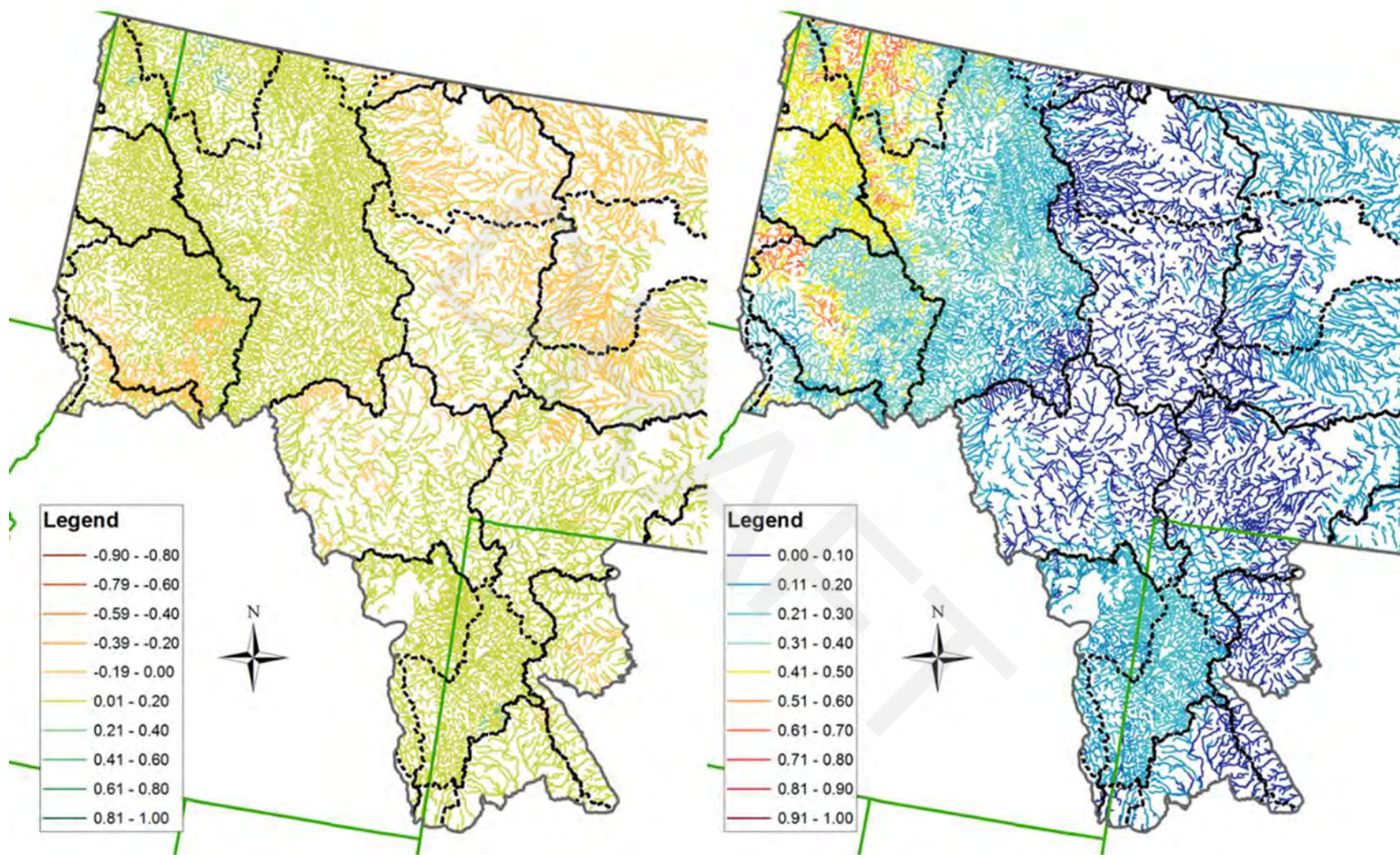


Figure 4.8—Projections for fractional change in mean annual flow for the 2080s compared to 1977-2006. The ensemble mean is on the left while the range between two disagreeing projections is shown on the right.

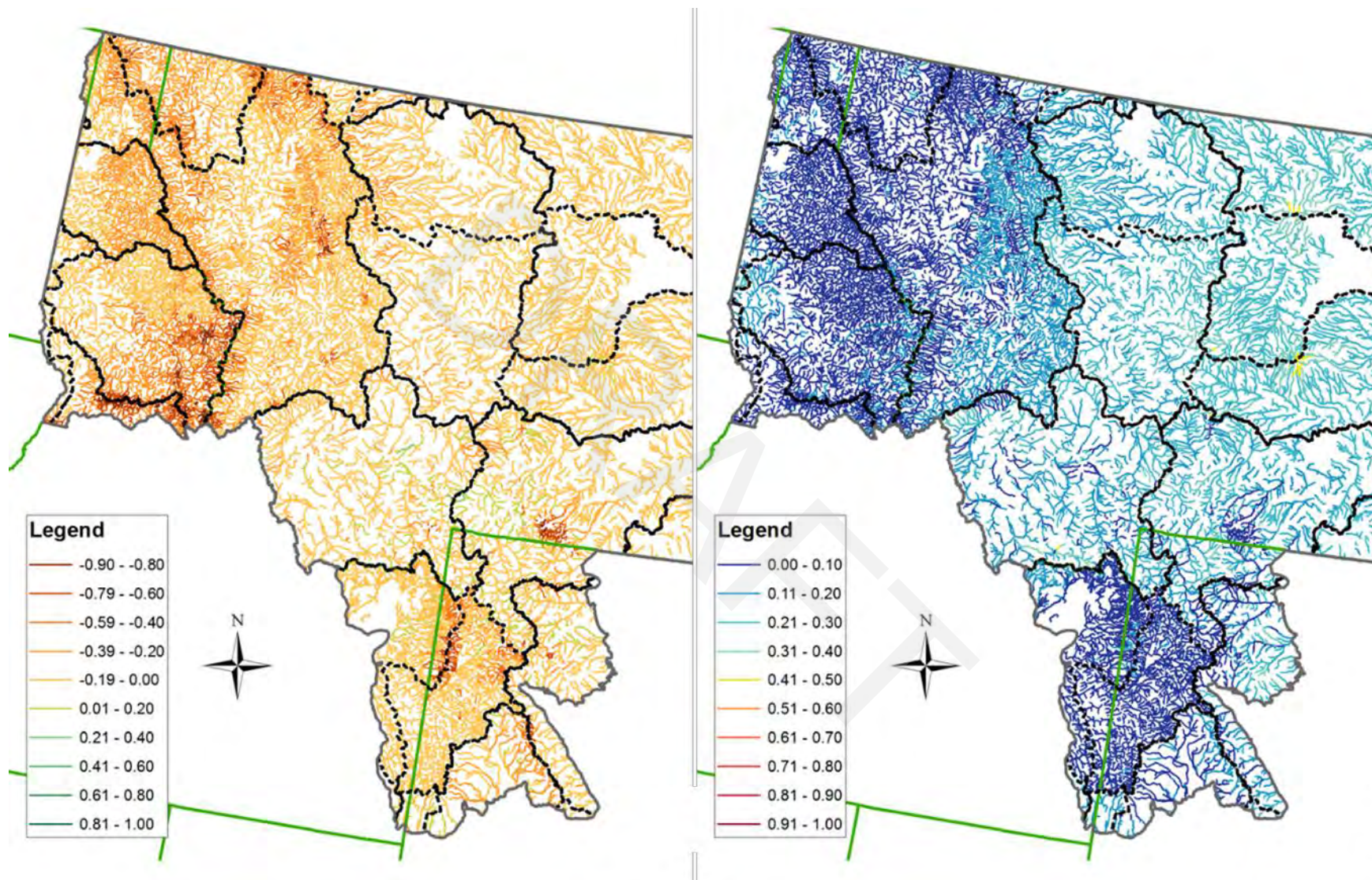


Figure 4.9—Projections for fractional change in mean summer flow (June-September) for the 2080s compared to 1977-2006. The ensemble mean is on the left while the range between two disagreeing projections is shown on the right.

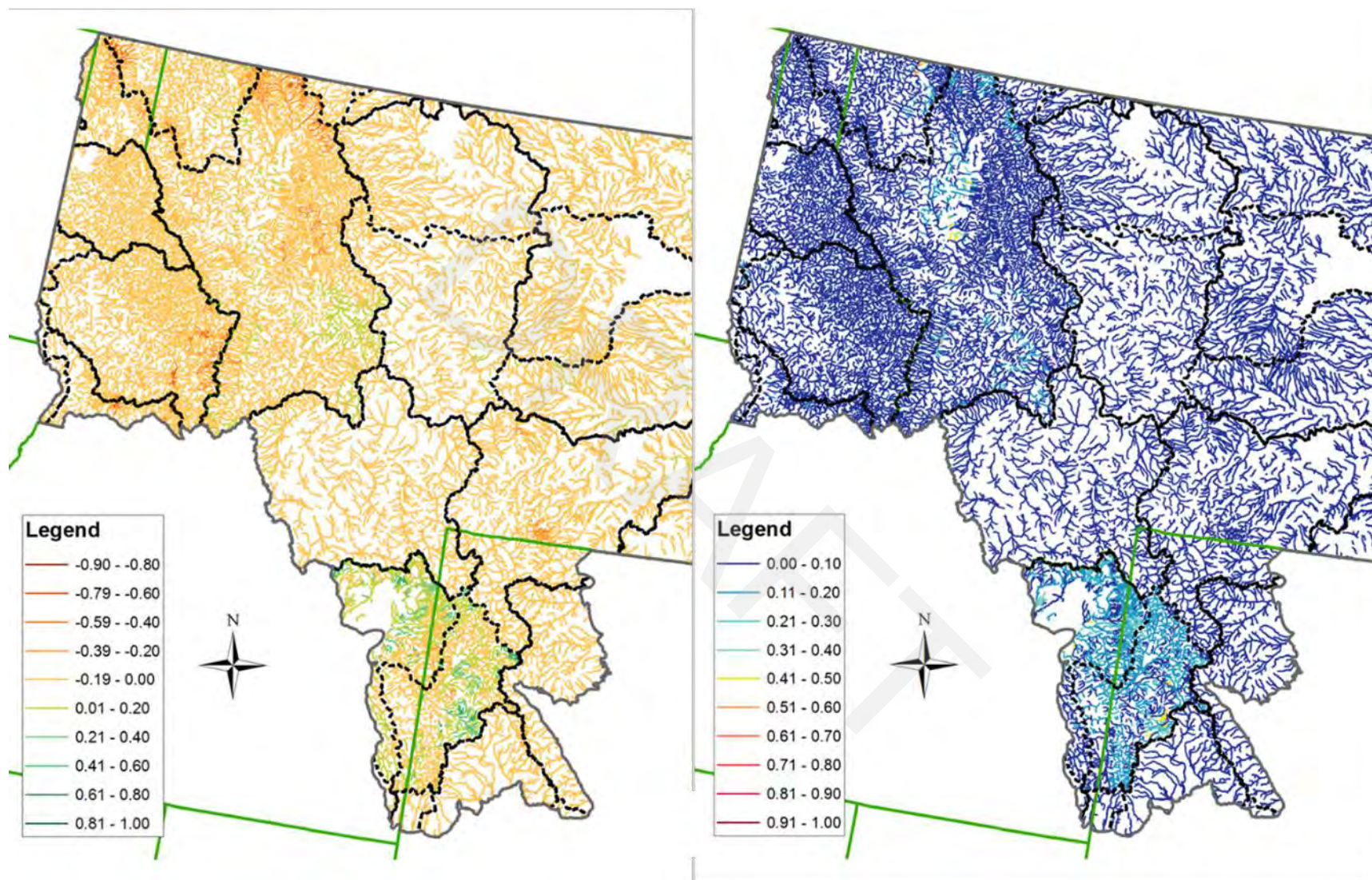


Figure 4.10—Projections for fractional change in minimum weekly flow with a 10-year return probability (7Q10) for the 2080s compared to 1977-2006. The ensemble mean is on the left while the range between two disagreeing projections is shown on the right.

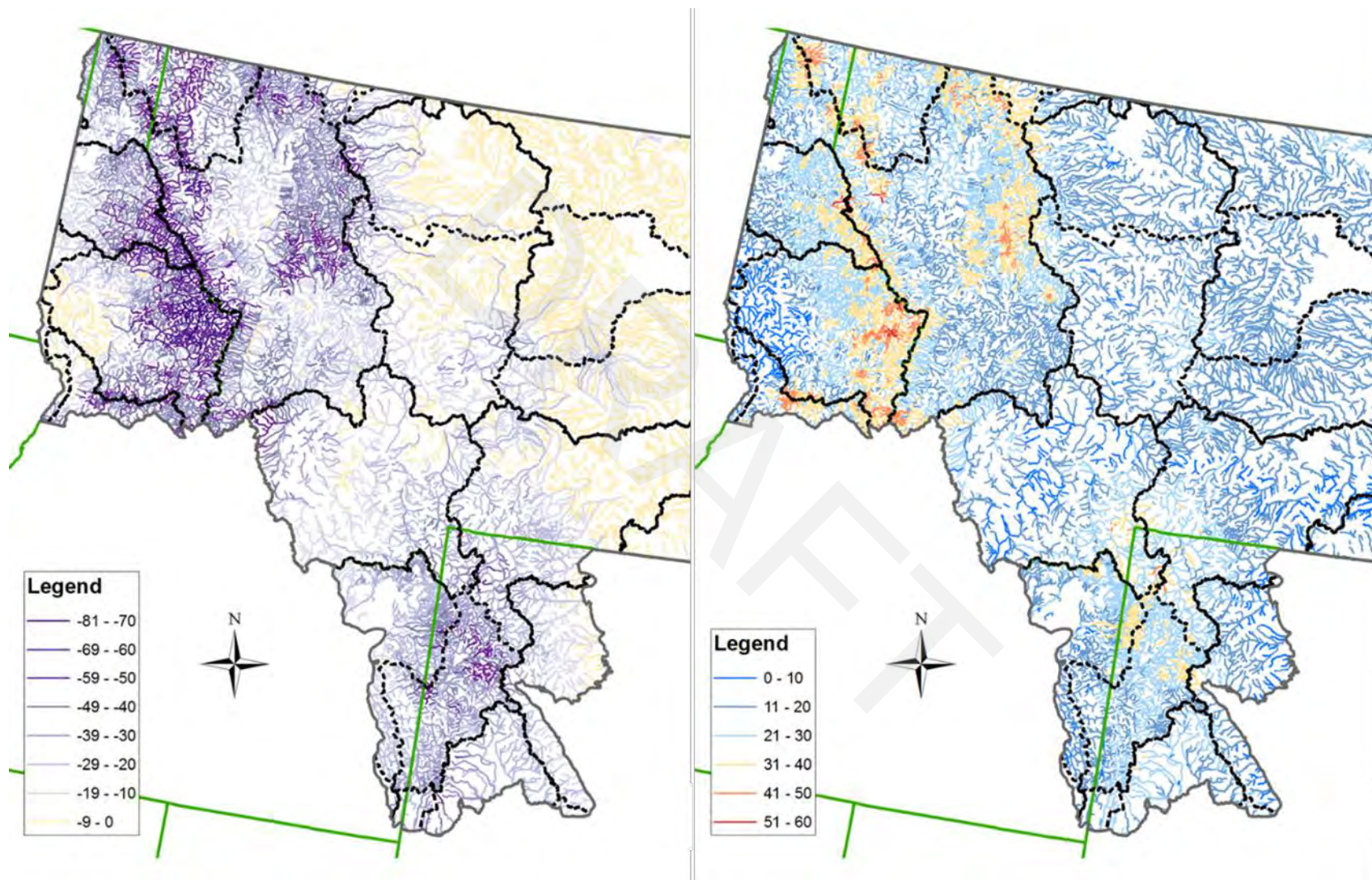


Figure 4.11—Projections for number of days of change in center of streamflow timing for the 2080s compared to 1977-2006. The ensemble mean is on the left while the range between two disagreeing projections is shown on the right.

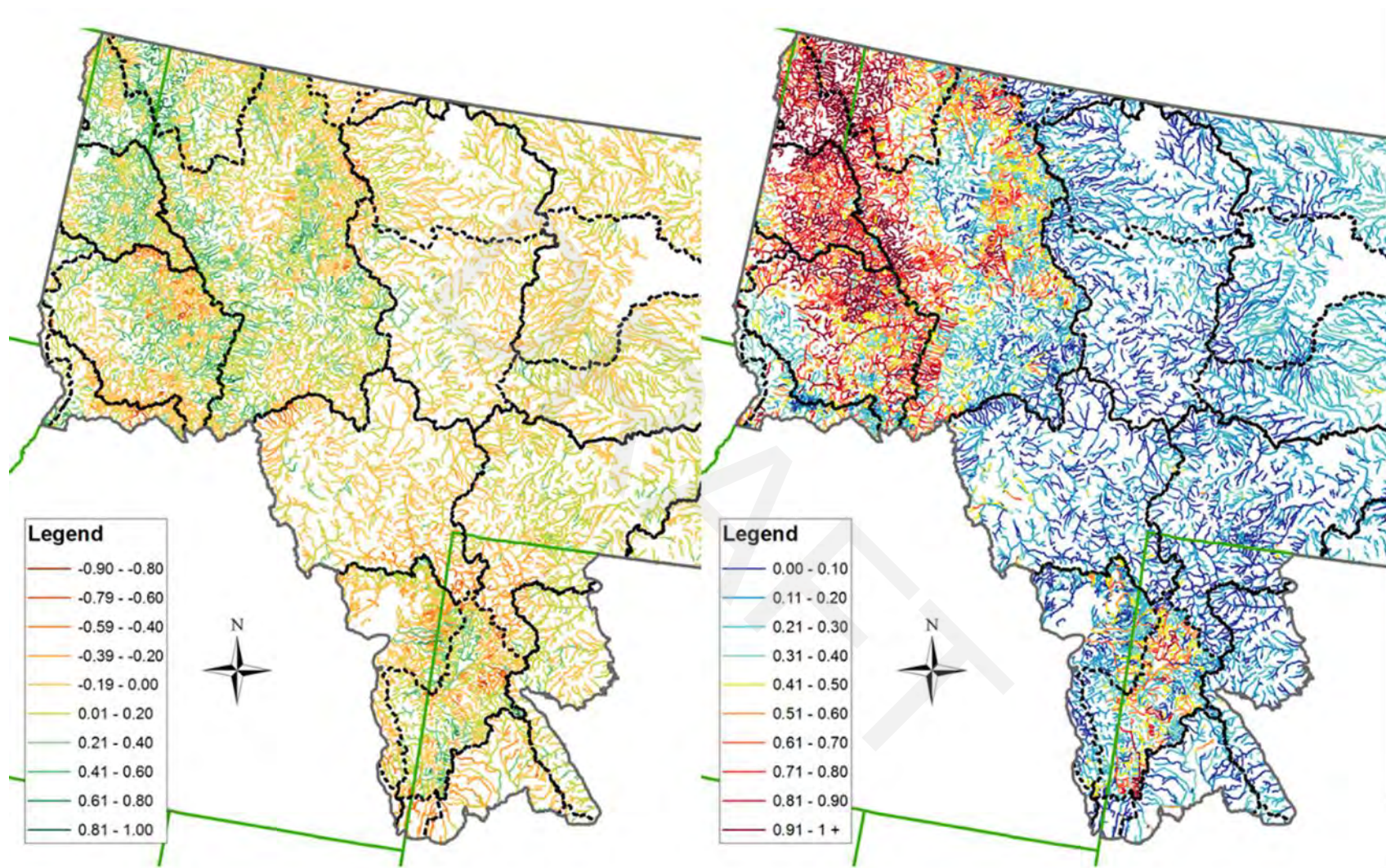


Figure 4.12—Projections for fractional change in 1.5-year flood magnitude (approximate “bankfull” flow) for the 2080s compared to 1977-2006. The ensemble mean is on the left while the range between two disagreeing projections is shown on the right.

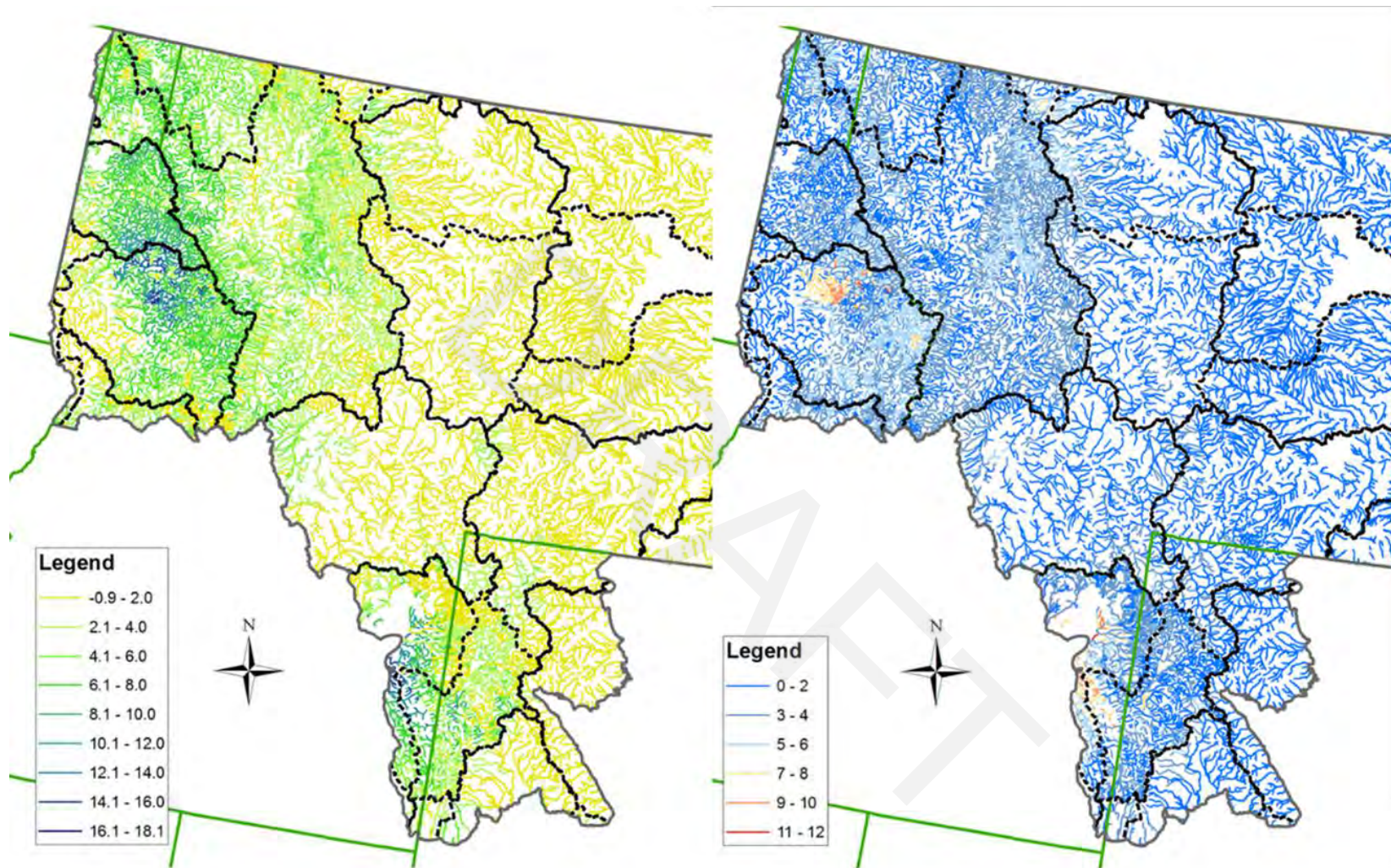


Figure 4.13—Projections for number of days in winter that exceed the 95th percentile flow in each year, an indicator of when floods are likely to happen, for the 2080s compared to 1977-2006. The value of this metric can take on values between 0 and 18.25, and the difference can take on the same range. The ensemble mean is on the left while the range between two disagreeing projections is shown on the right.



Figure 5.1—Northern Rockies Adaptation Partnership analysis area for cutthroat trout and bull trout, including the U.S. Forest Service Northern Region (white border). Bull trout range encompasses basins west of the Continental Divide and the St. Mary River basin (yellow dashed line), whereas historical cutthroat trout range includes most of the analysis area.

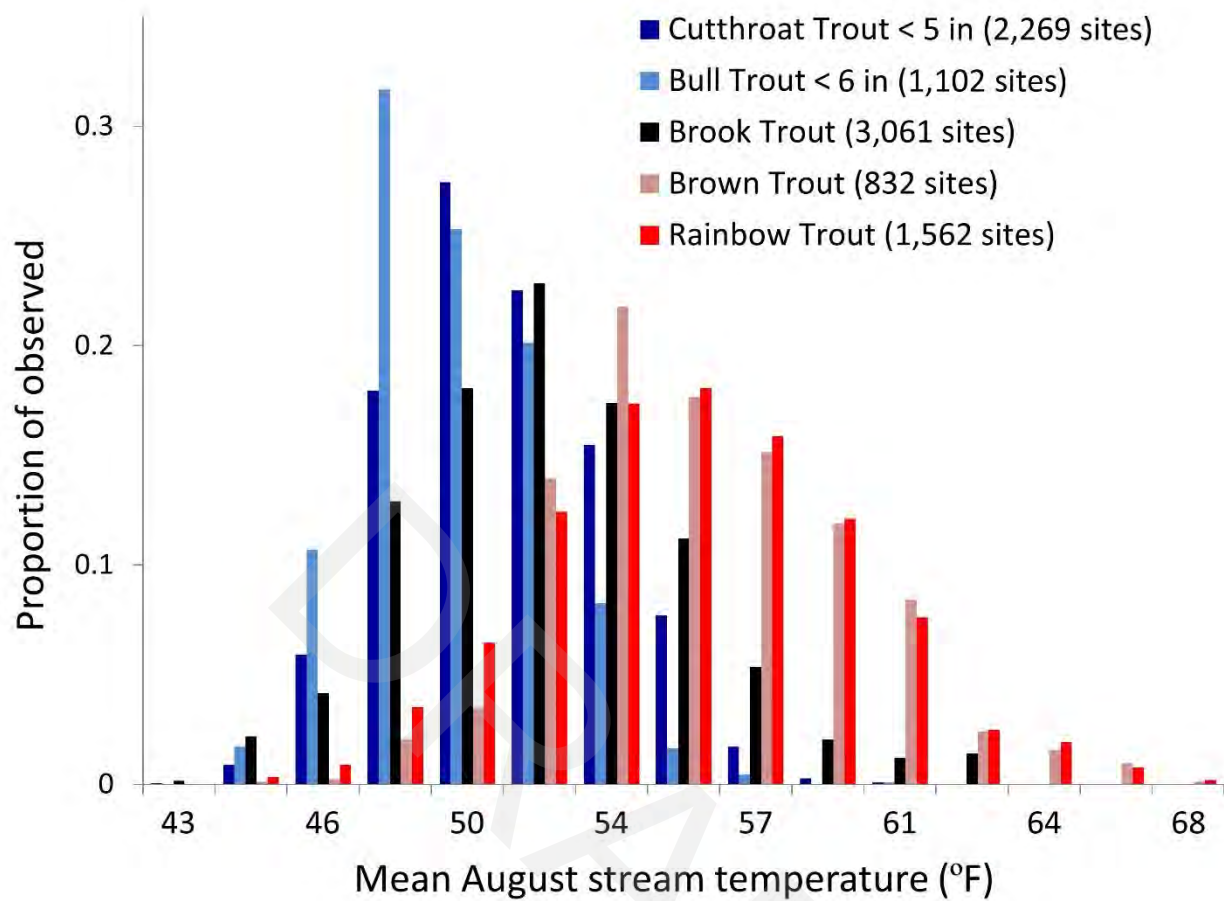


Figure 5.2—Presence of juvenile bull trout and cutthroat trout and all age classes of other trout species at sampling sites relative to temperature projections from the NorWeST baseline scenario of mean August temperature. Figure reproduced from Isaak et al. (2015).

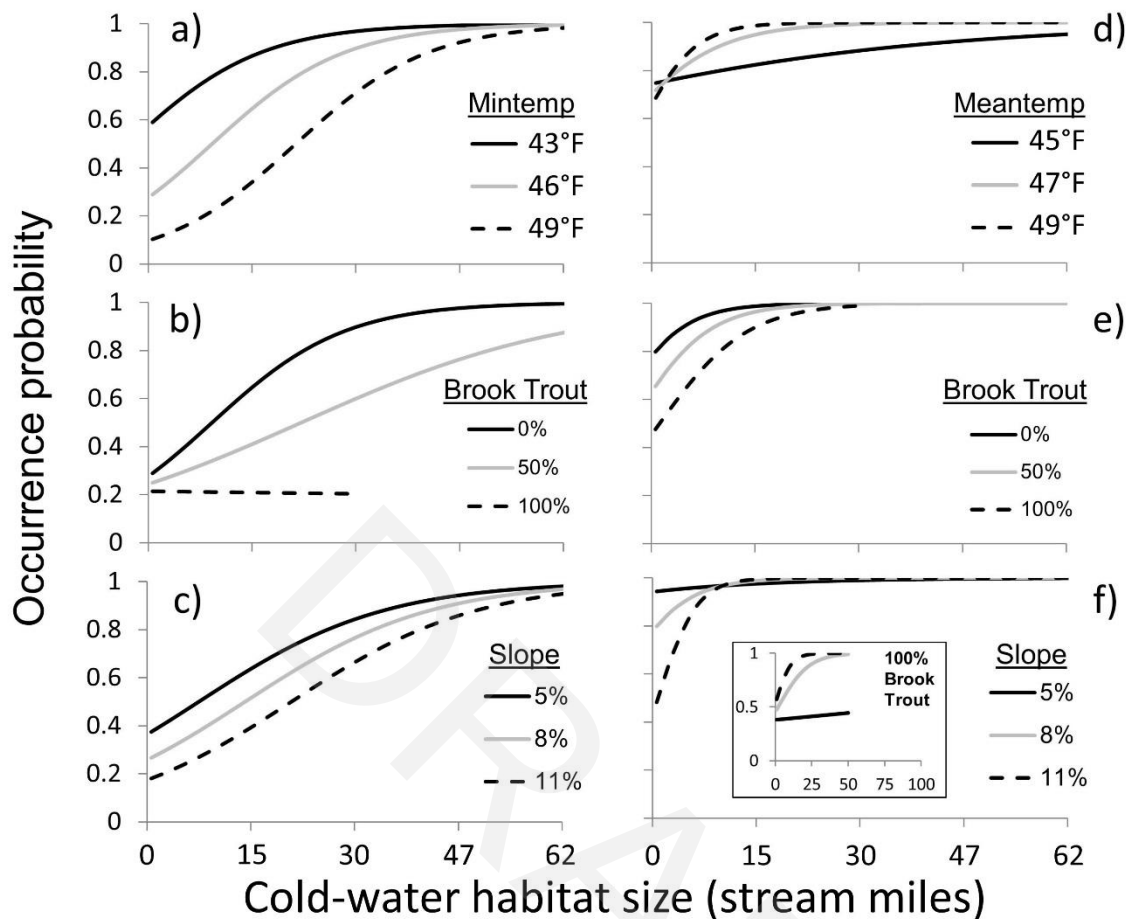


Figure 5.3—Relations between environmental covariates and probability of occupancy of juvenile native trout developed from 512 bull trout (a, b, c) and 566 cutthroat trout (d, e, f) cold-water habitats. Relations are conditioned on mean values of two independent variables not shown in a panel. An exception occurs for cutthroat trout with regard to stream slope (f) where brook trout values of 0% and 100% were used to highlight the interaction between these covariates. Figure reproduced from Isaak et al. (2015).

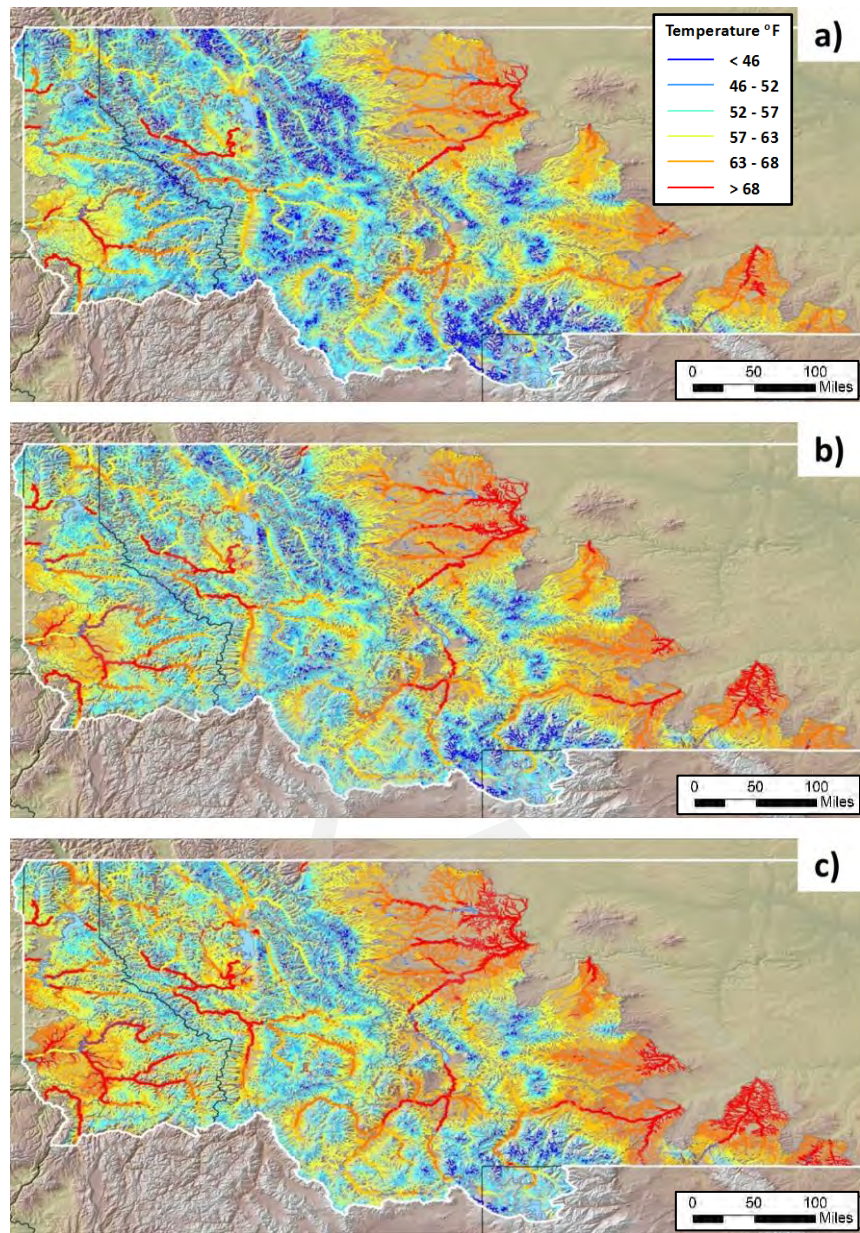


Figure 5.4—NorWeST August mean stream temperature maps interpolated from 11,703 summers of monitoring data at 5,461 unique stream sites across the 114,000 mi of streams in the analysis area. Map panels show conditions during baseline (a, 1980s), moderate (b, 2040s), and extreme change scenarios (c, 2080s). Networks were trimmed to represent potential fish-bearing streams by excluding reaches with slopes greater than 15 percent and Variable Infiltration Capacity model summer flows less than $0.20 \text{ ft}^3 \text{ s}^{-1}$. High-resolution digital images of these maps and ArcGIS databases with reach-scale predictions are available at the NorWeST website (<http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html>).

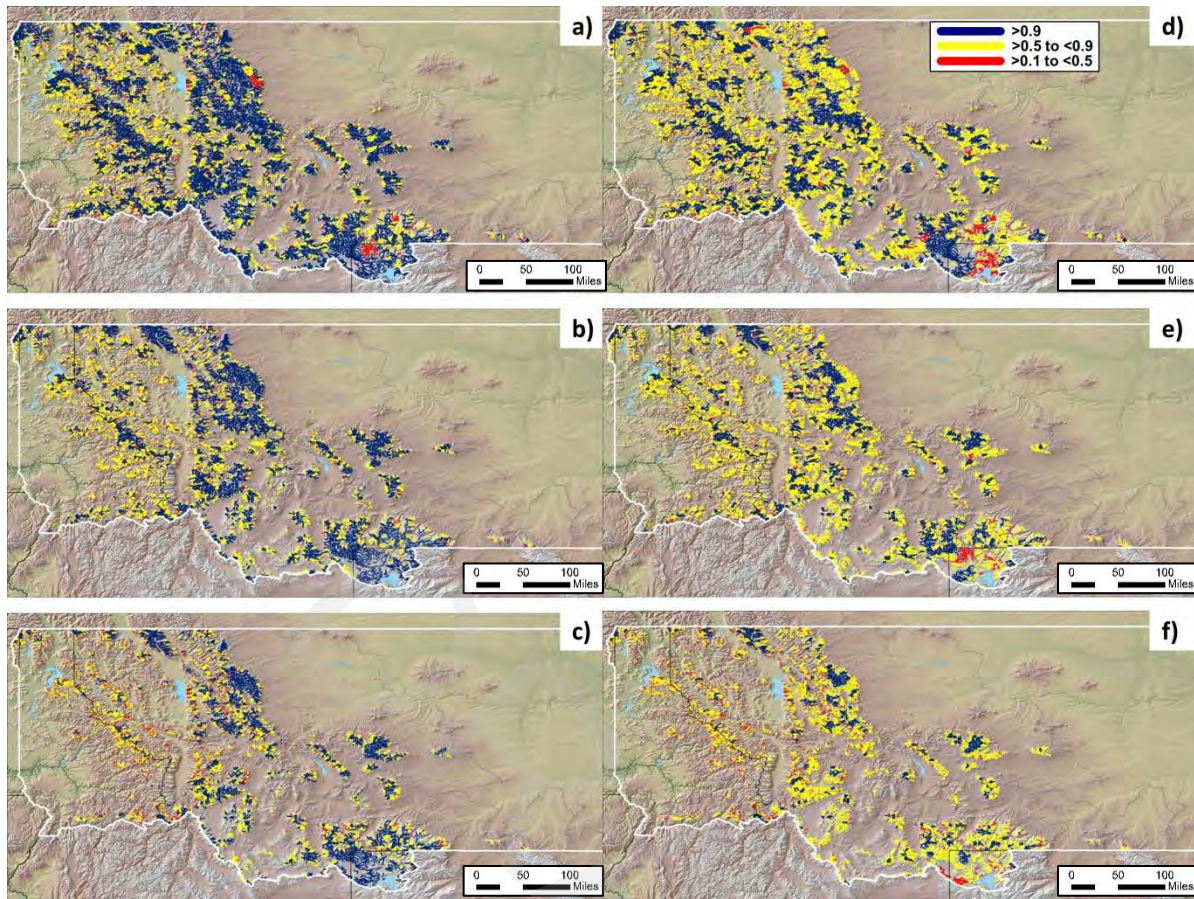


Figure 5.5—Distribution of cold-water habitats with probabilities of occupancy greater than 0.1 for juvenile cutthroat trout during baseline (a and d, 1980s), moderate change (b and e, 2040s), and extreme change scenarios (c and f, 2080s). Panels a–c illustrate occupancy when brook trout are absent. Panels d–f illustrate occupancy when brook trout prevalence is 50 percent. High-resolution digital images and ArcGIS databases of these maps with stream-specific projections are available at the Climate Shield website (<http://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield/maps.html>).

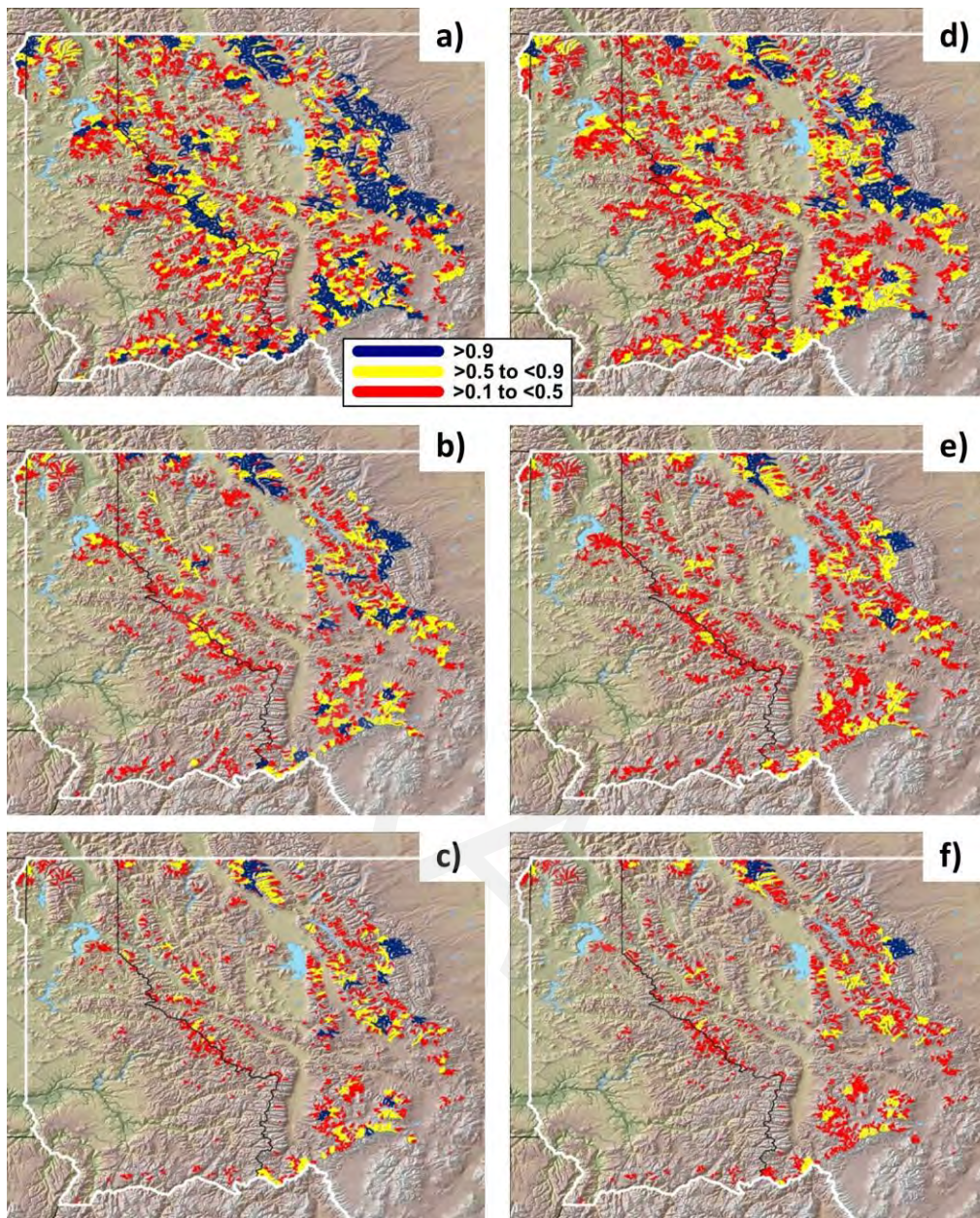


Figure 5.6—Distribution of cold-water habitats with probabilities of occupancy greater than 0.1 for juvenile bull trout during baseline (a and d, 1980s), moderate change (b and e, 2040s), and extreme change scenarios (c and f, 2080s). Panels a–c illustrate occupancy when brook trout are absent. Panels d–f illustrate occupancy when brook trout prevalence is 50 percent. High-resolution digital images and ArcGIS databases of these maps with stream-specific predictions are available at the Climate Shield website (<http://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield/maps.html>).

Climate Shield Cold-Water Habitats for Juvenile Bull Trout

Scenario: 1980s, 0% Brook Trout

NorWeST Unit: SpoKoot

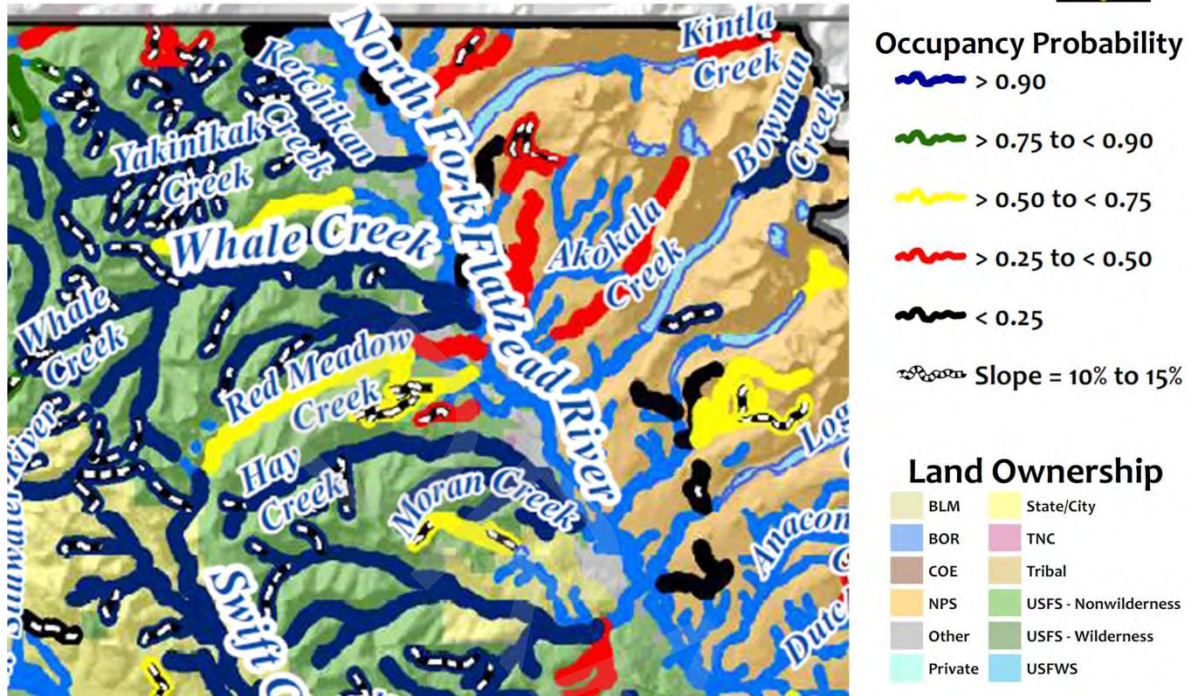


Figure 5.7—Example of a detailed Climate Shield map available at the project website that shows probabilities of juvenile bull trout occupancy in cold-water habitats during the 1980s baseline period in the North Fork Flathead River basin. Maps with identical formats for three climate periods and five brook trout invasion scenarios are available as .pdf and ArcGIS files for all bull trout and cutthroat trout streams across the northwestern United States.

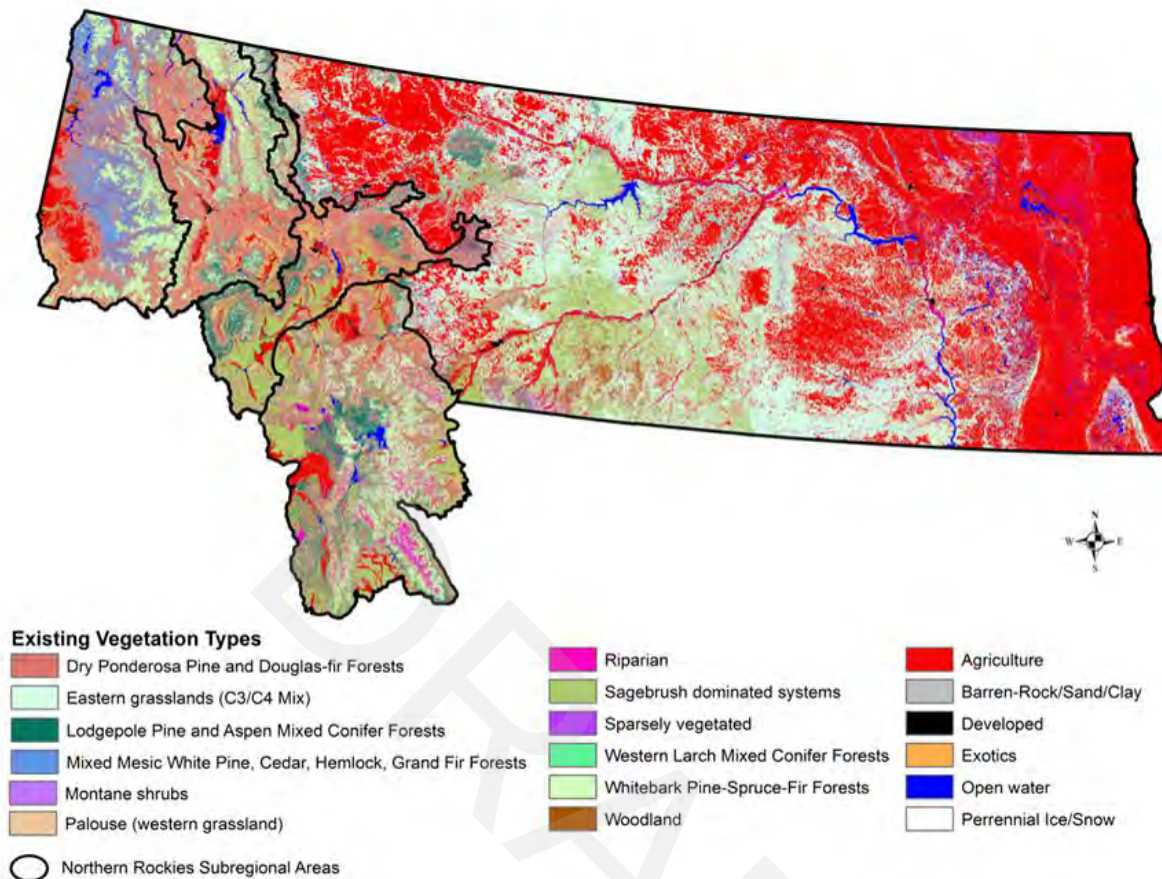


Figure 6.1—The Northern Rockies (NR) assessment area that includes the Northern Region of the U.S. Forest Service and the Greater Yellowstone Area (Yellowstone National Park and surrounding areas). Presented are existing vegetation types by the five geographic sub-areas used to stratify assessments in this report. This map was created from the LANDFIRE Existing Vegetation Type map by aggregating the National Vegetation Classification Standard vegetation types into a set of vegetation types that has some meaning across the NR at this coarse scale. This map is intended to convey current vegetation of the NR.

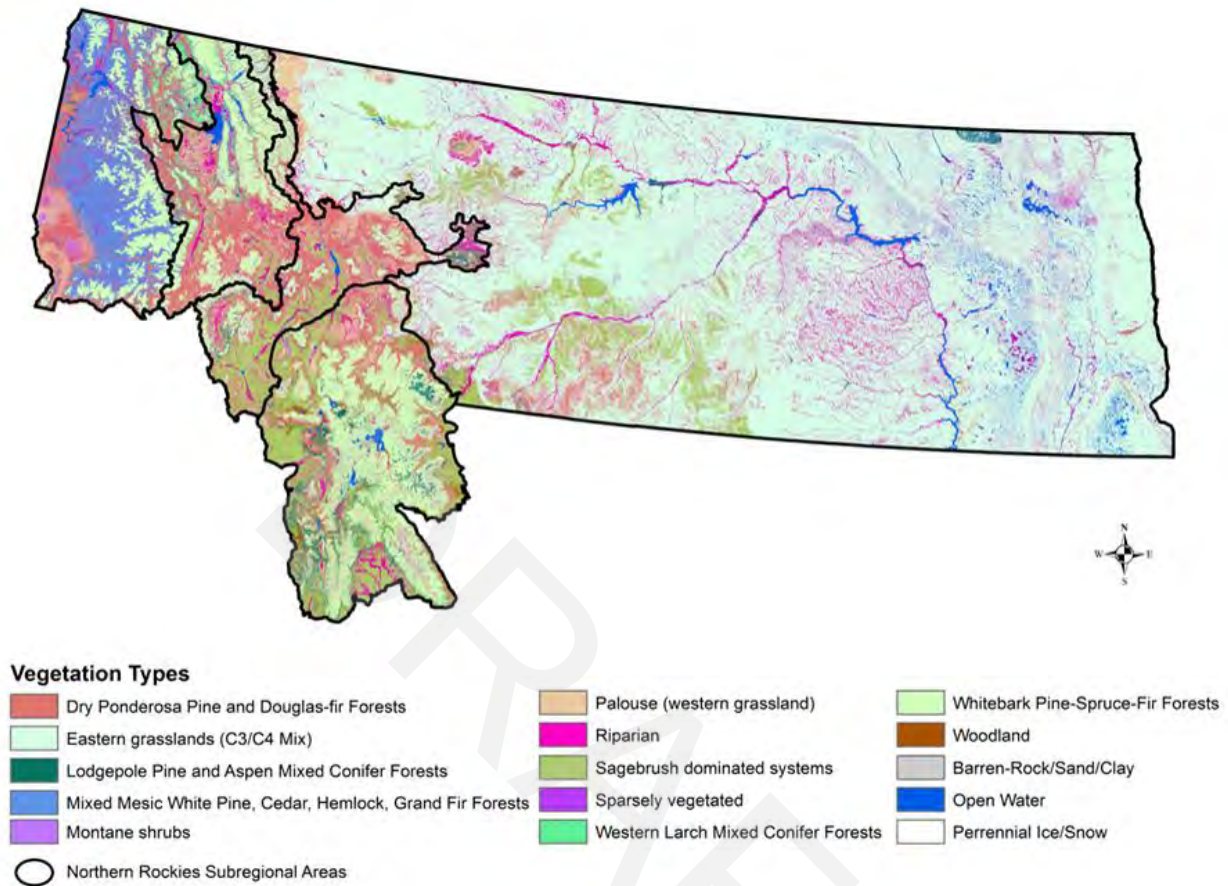


Figure 6.2—Potential vegetation types for the entire NRAP assessment area by the five geographic sub-areas. This map was created from the LANDFIRE Biophysical settings map by aggregating the National Vegetation Classification Standard vegetation types into a set of vegetation types that has some meaning across the NR at this coarse scale.

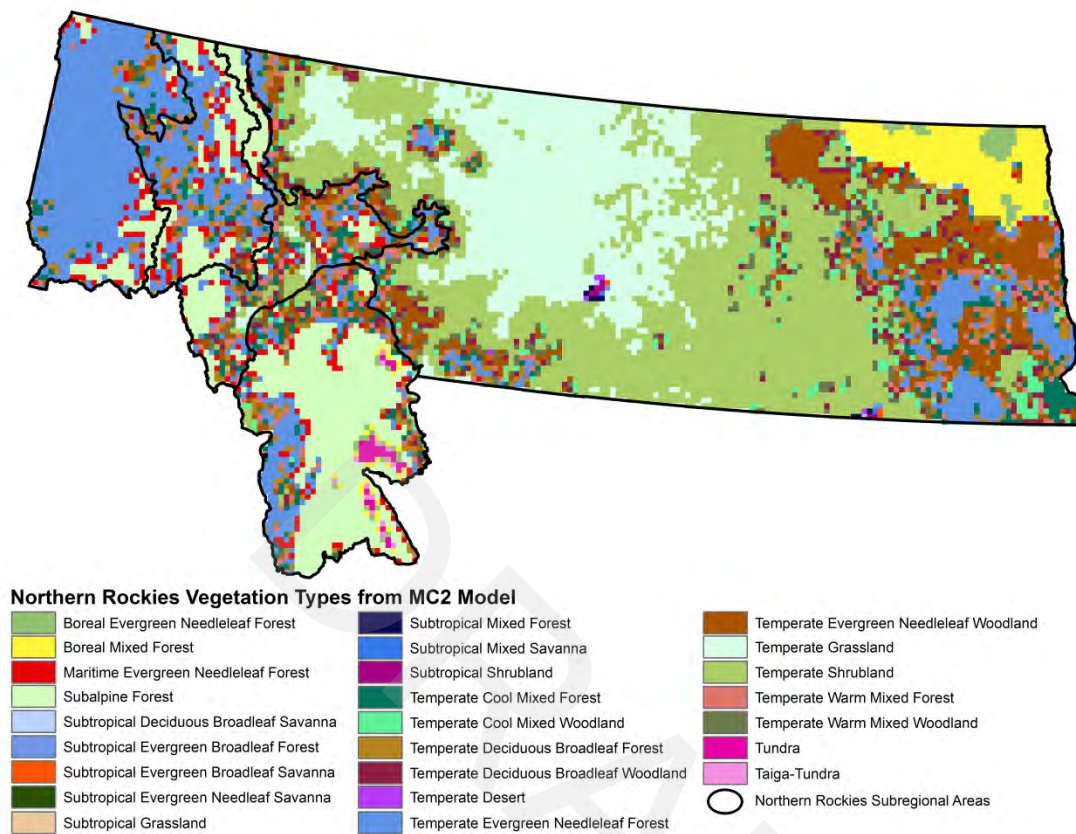


Figure 6.3—The MC2 vegetation types for the assessment area by the five geographic sub-areas. This map was created from a MC2 modeling effort (see appendix 6A).

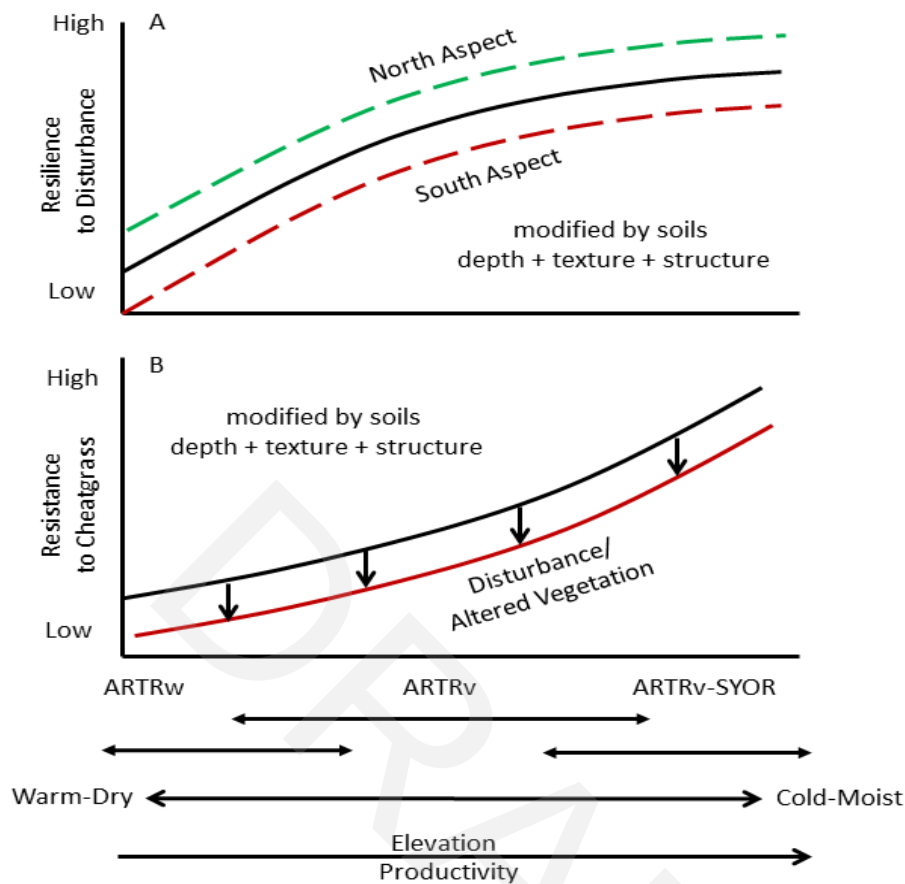


Figure 7.1—Resilience to disturbance (A) and resistance to cheatgrass (B) over a typical temperature/precipitation gradient in the cold desert. Dominant ecological sites occur along a continuum that includes Wyoming big sagebrush on warm and dry sites, to mountain big sagebrush on cool and moist sites, to mountain big sagebrush and root-sprouting shrubs on cold and moist sites. Resilience increases along the temperature/precipitation gradient and is influenced by site characteristics like aspect. Resistance also increases along the temperature/precipitation gradient and is affected by disturbances and management treatments that alter vegetation structure and composition and increase resource availability. Modified from Chambers et al. (2014). ARTRw = Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*); ARTRv = mountain big sagebrush (*A. tridentata* ssp. *vaseyana*); SYOR = mountain snowberry (*Symphoricarpos oreophilus*)

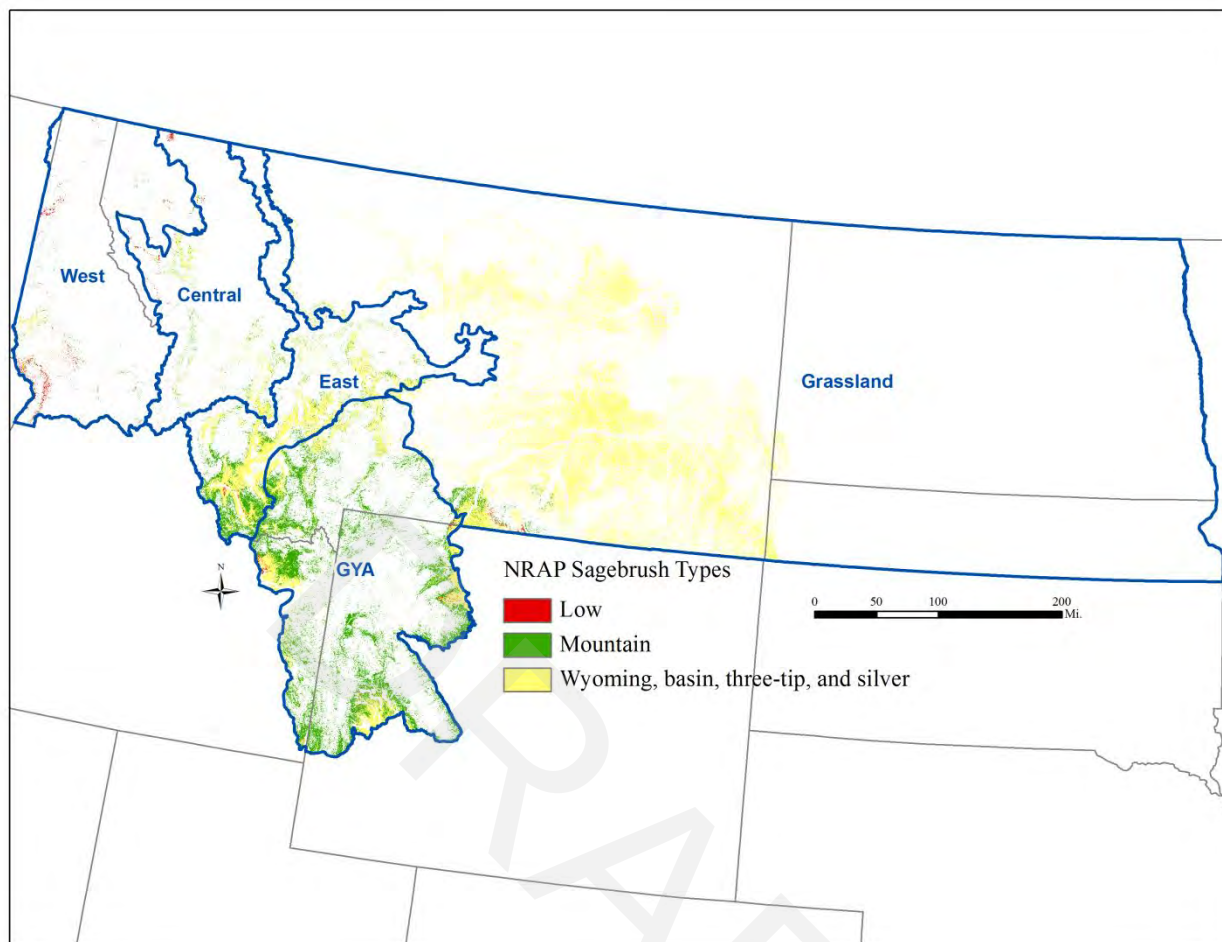


Figure 7.2—Estimated distribution of various sagebrush vegetation classes in the Northern Rockies.

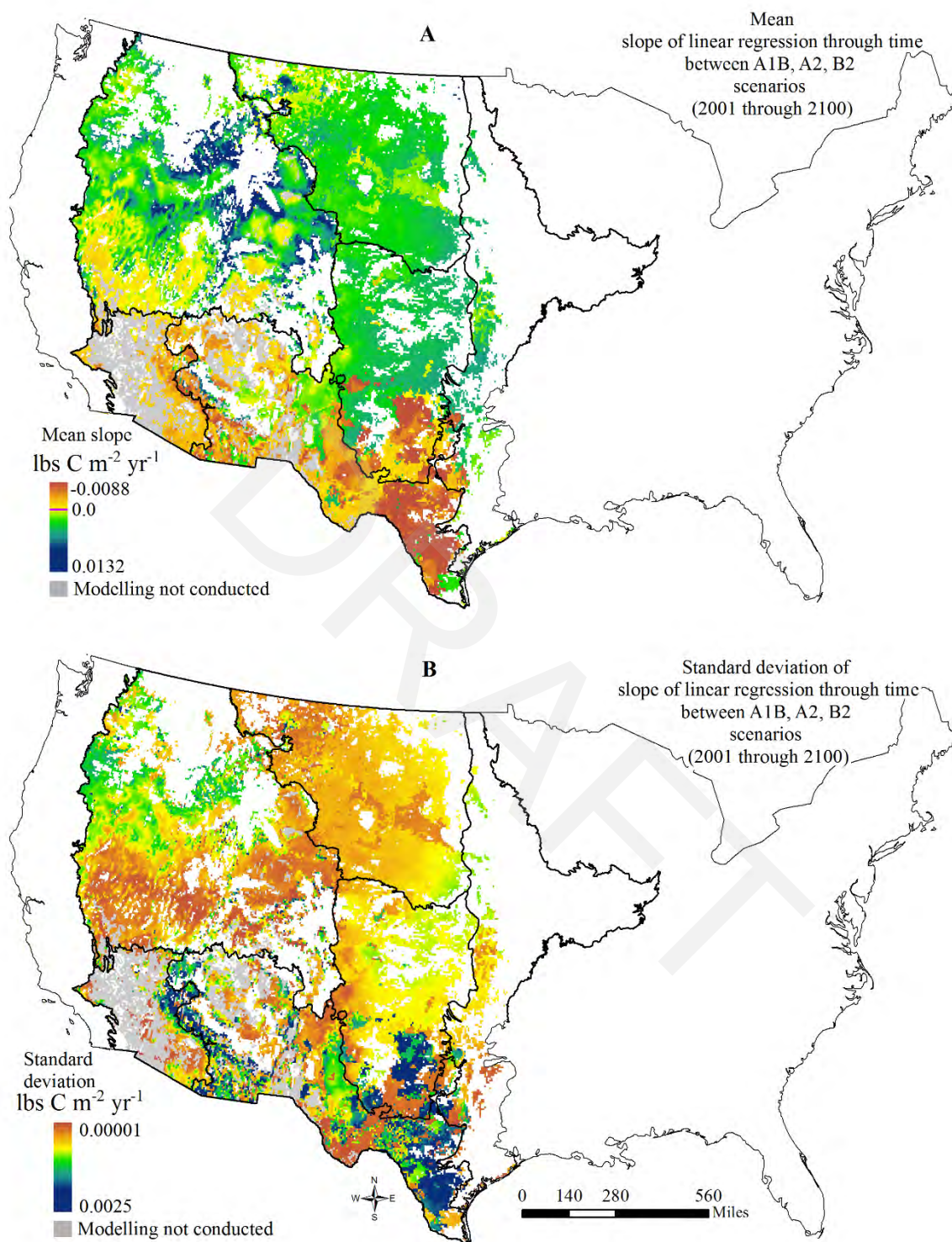


Figure 7.3—Mean slope of linear regression of the net primary productivity trend for the B2, A1B, and A2 emission scenarios (models averaged here include: GCGM2, HadCM3, CSIRO, MK2, MIROC3.2)(A) and standard deviation of the mean slope of linear regression of the net primary productivity trend for the same scenarios (B). From Reeves et al. (2014).



Figure 7.4—Conifer encroachment, predominantly ponderosa pine into a montane grassland, including the ubiquitous graminoid rough fescue. (Photo by Mary Manning, Forest Service, U.S. Department of Agriculture)

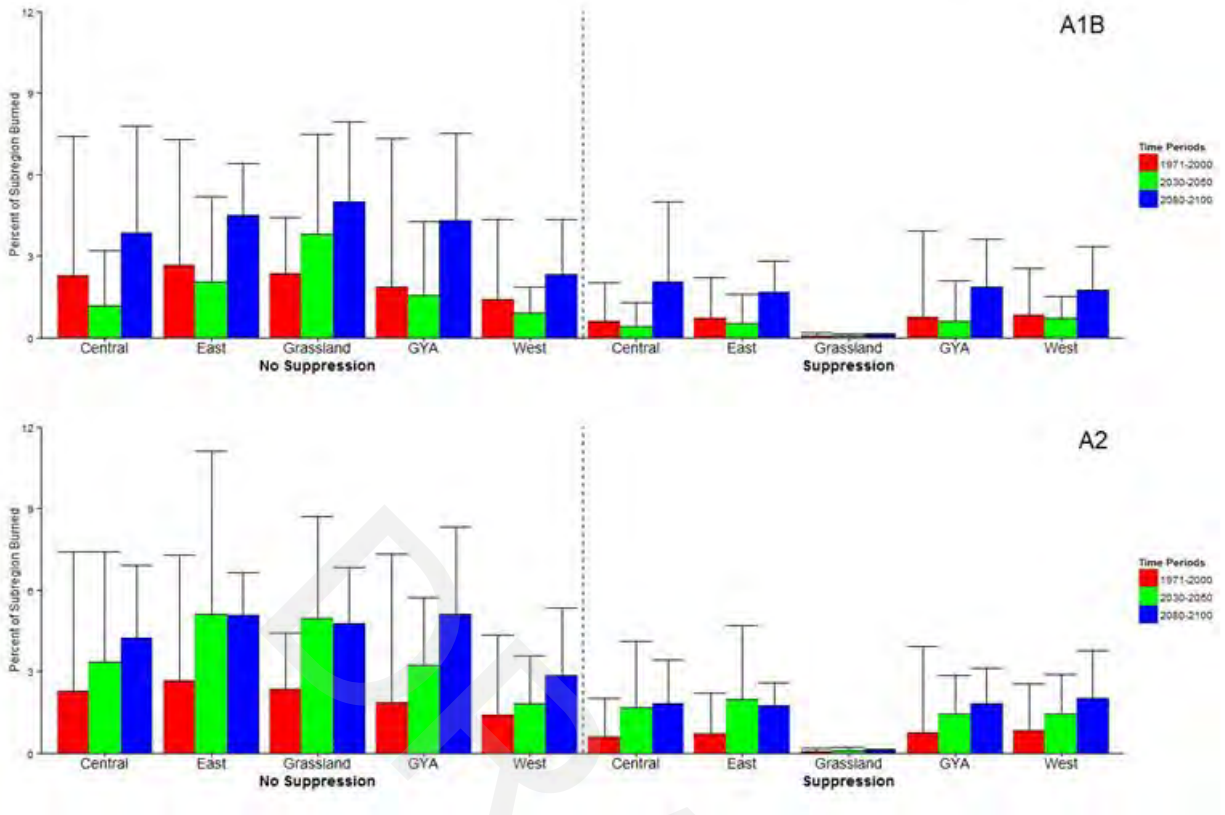


Figure 7.5—Mean and standard deviation of percent of subregions burned across three time spans (historic, 2030-2050, 2080-2100) and without/with fire suppression.

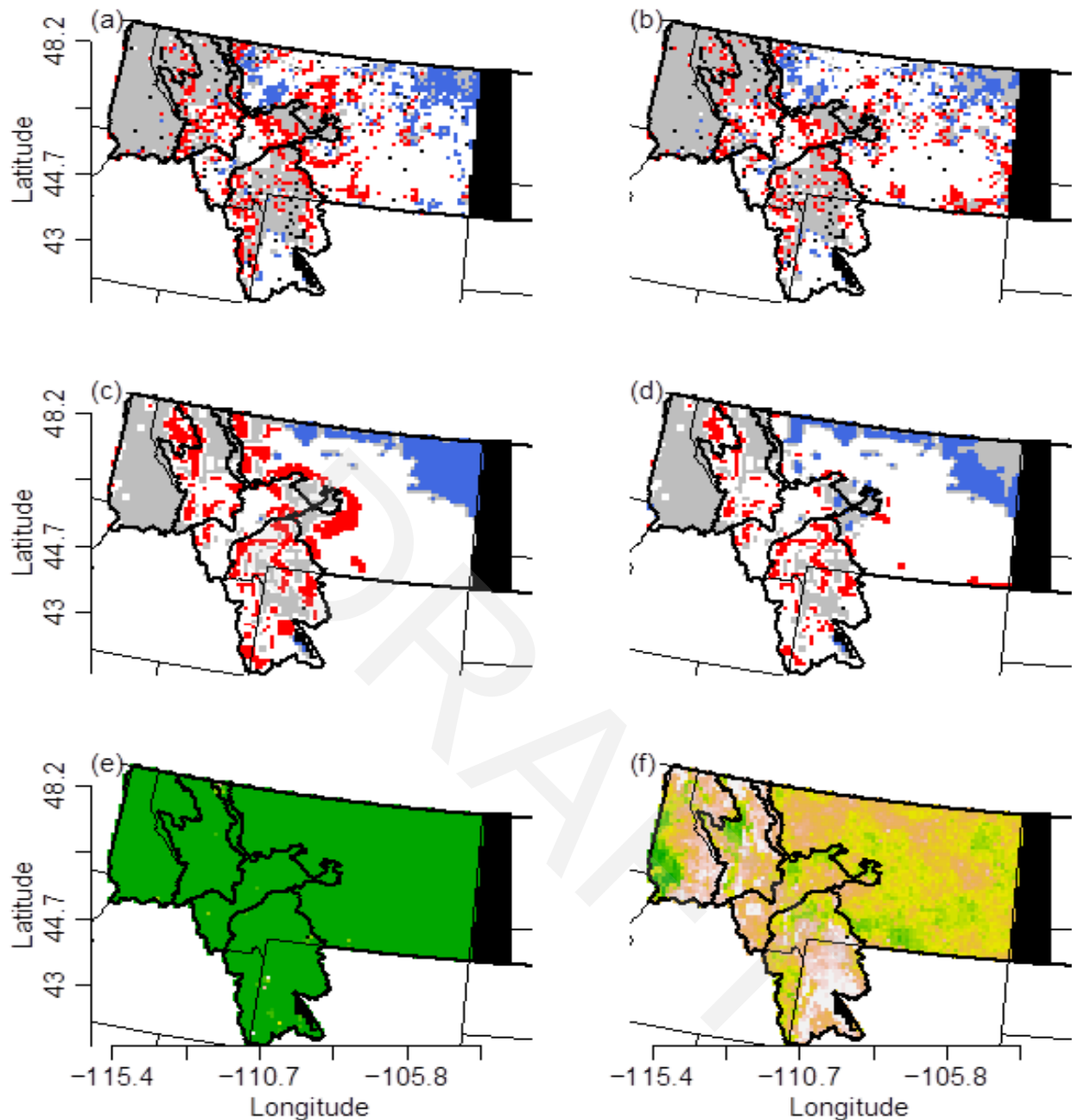


Figure 7.6—Change in big sagebrush habitat suitability (a-d) based on species distribution models using climate (c)-(d) or ecohydrology (a)-(b), along with germination (e) and seedling survival potential (f) for NR (outlined in bold). Projected change in big sagebrush habitat suitability is between 1970-1999 climate and future A2 scenario (a)-(c) and B1 scenario (b)-(d) 2070-2099 emission scenarios. Red cells indicate areas of decrease in big sagebrush habitat suitability, blue cells indicate areas of increase, white cells indicate stable areas, and gray cells indicate absence of big sagebrush. Maps of germination (e) and seedling survival (f) represent current conditions and are summarized as fraction of years with successes: red (0, no years with success), tan (>0), green (1, every year with success). Black cells indicate data not available (Schlaepfer et al. 2012).

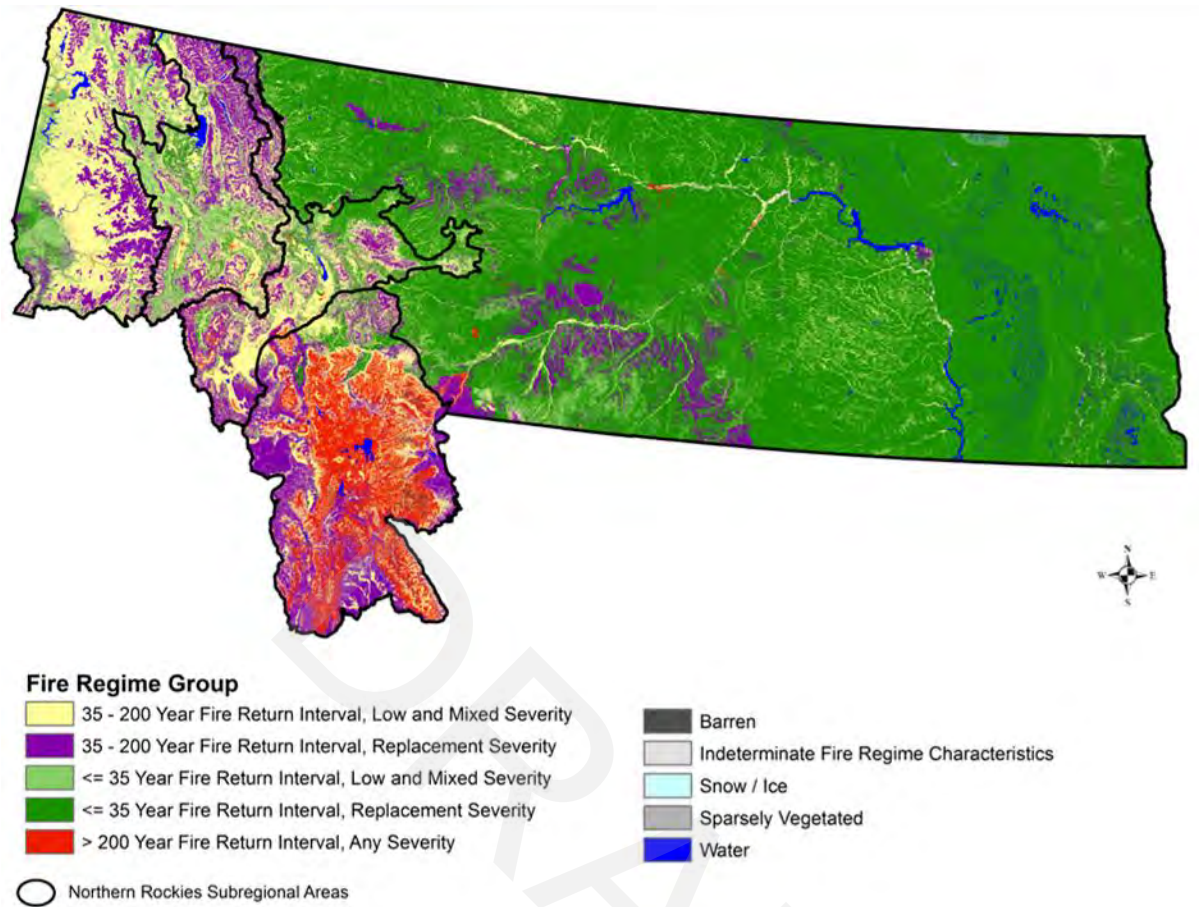


Figure 8.1—Fire regime groups for the Northern Rockies, LANDFIRE mapping program. The fire regime group layer characterizes the presumed historical fire regimes within landscapes based on interactions among vegetation dynamics, fire spread, fire effects, and spatial context. See <http://www.landfire.gov/NationalProductDescriptions12.php>.

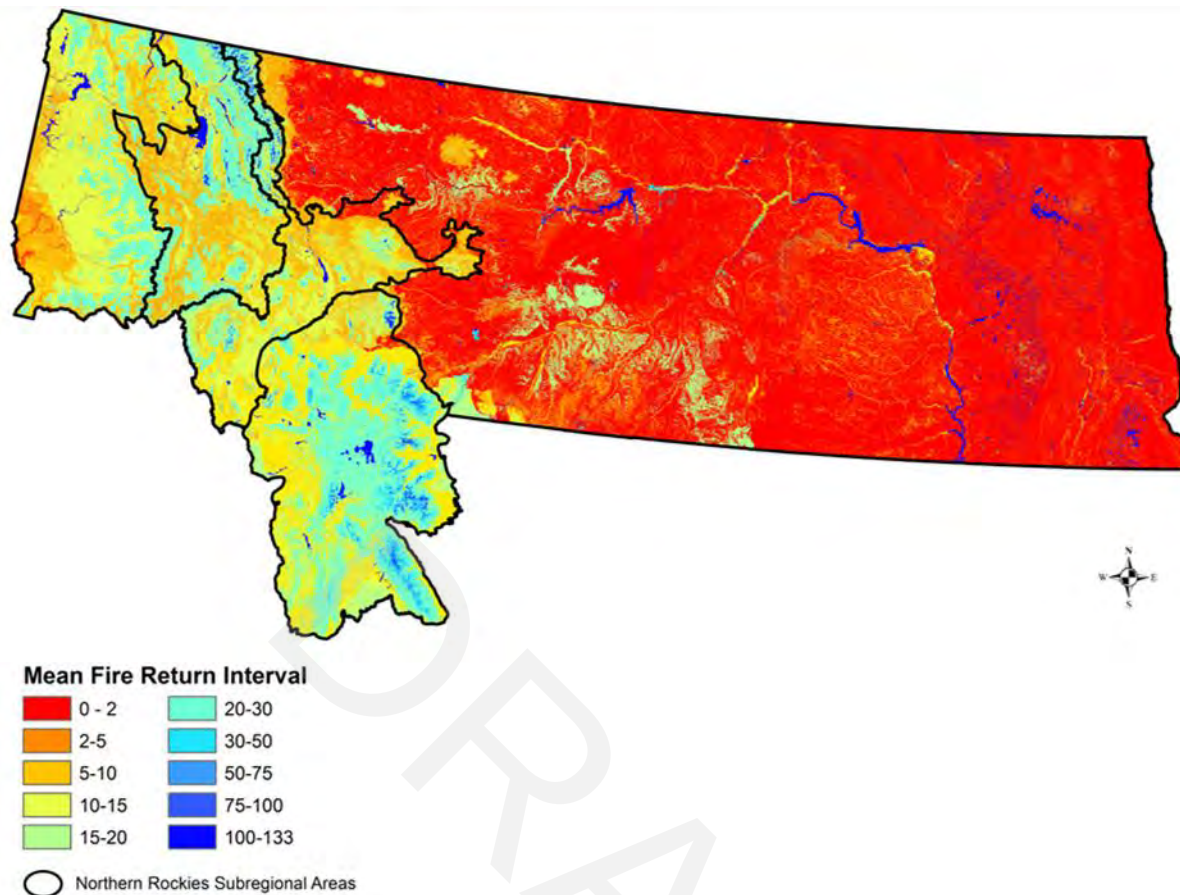


Figure 8.2—Mean fire return interval for the Northern Rockies, LANDFIRE mapping program. The mean fire return interval layer quantifies the average period between fires under the presumed historical fire regime. See <http://www.landfire.gov/NationalProductDescriptions13.php> for more information.

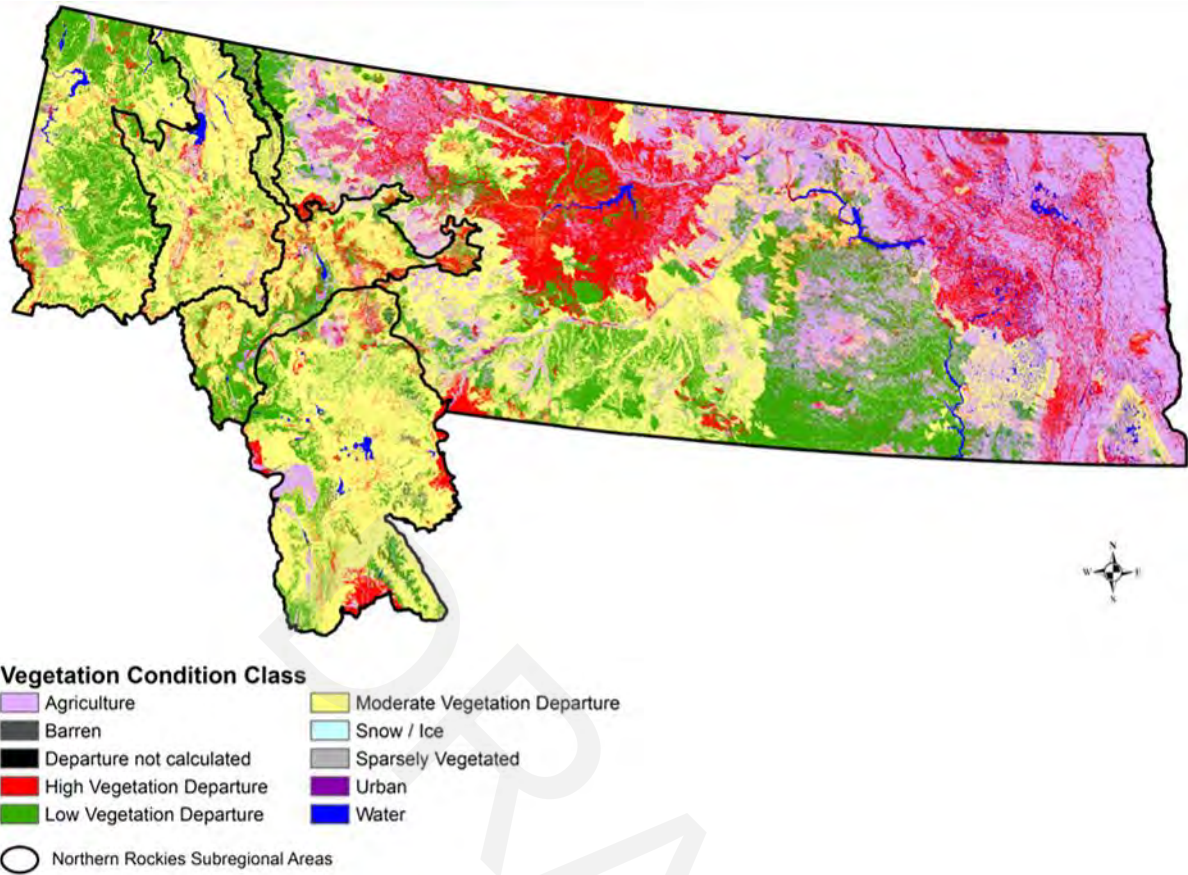


Figure 8.3—Vegetation condition class for the Northern Rockies, LANDFIRE mapping program. The vegetation condition class layer quantifies the amount that current vegetation has departed from the simulated historical vegetation reference conditions. See <http://www.landfire.gov/NationalProductDescriptions10.php>.

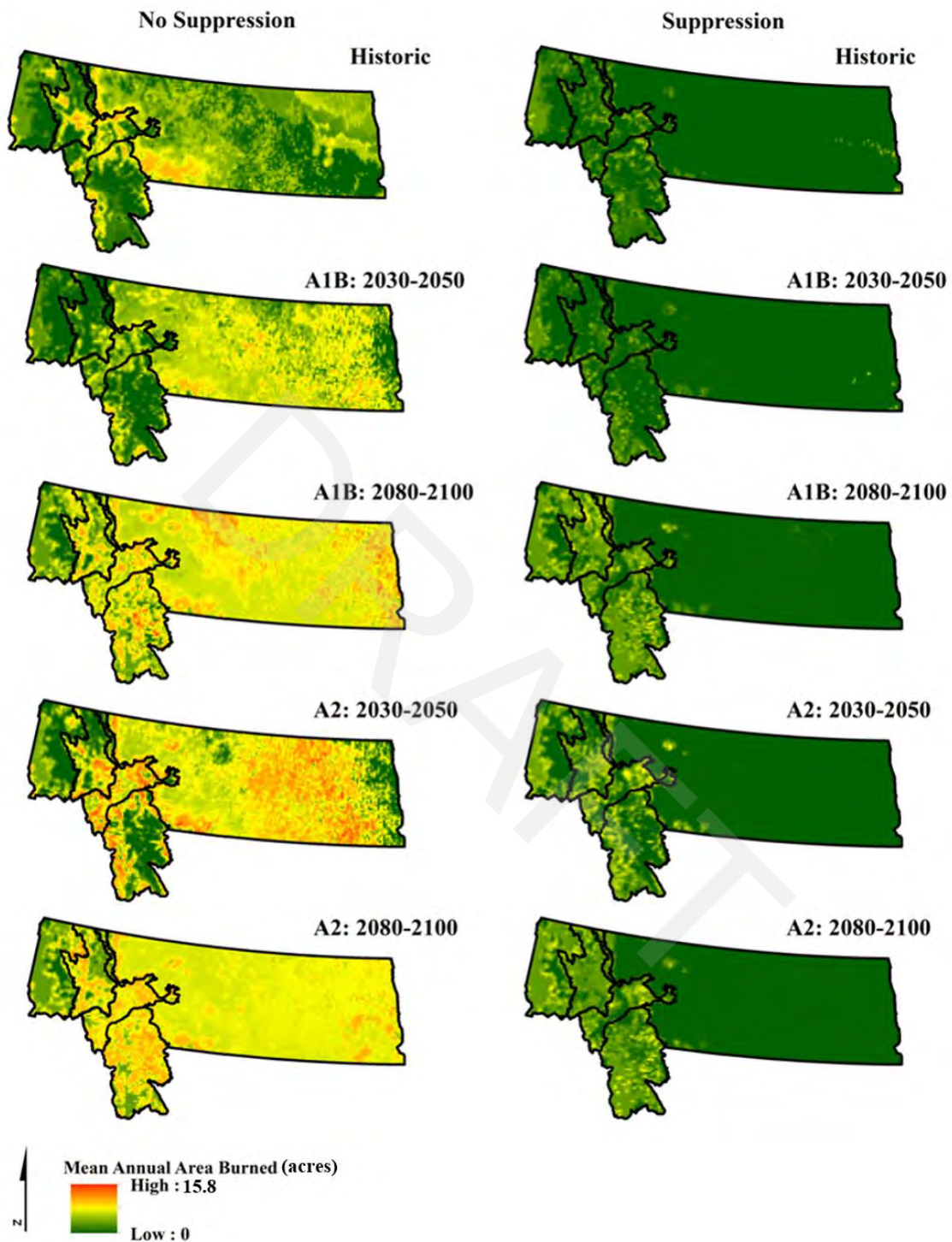


Figure 8.4—Changes in mean annual area burned (ha) for current levels of fire suppression and no fire suppression, A1B (moderate) and A2 (hgh) emission scenarios, and for the time periods 2030-2050 and 2080-2100, as projected by the MC2 dynamic global vegetation model (Bachelet et al. 2003).

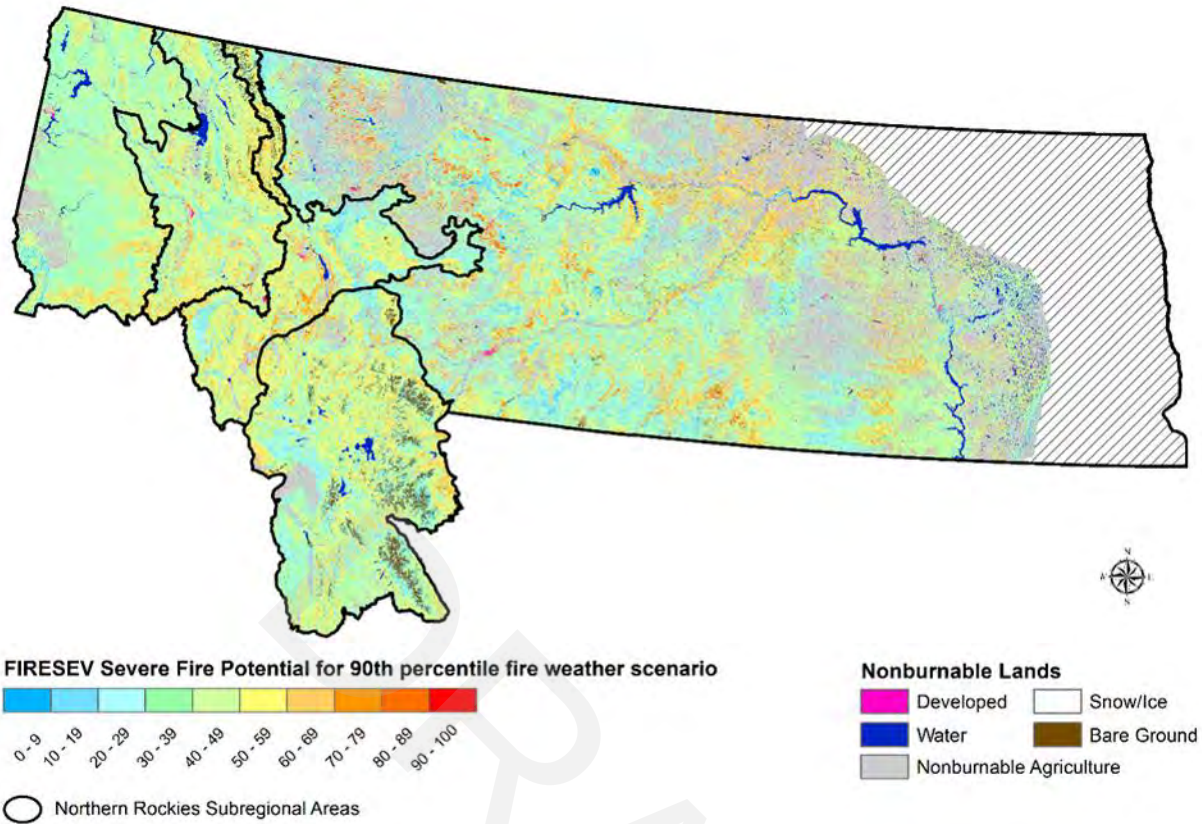


Figure 8.5—Severe fire potential (probability) for 90th percentile fire weather scenario, with non-burnable areas added in from the LANDFIRE 2008 Fire Behavior Fuel Model layer (Dillon et al. 2011).

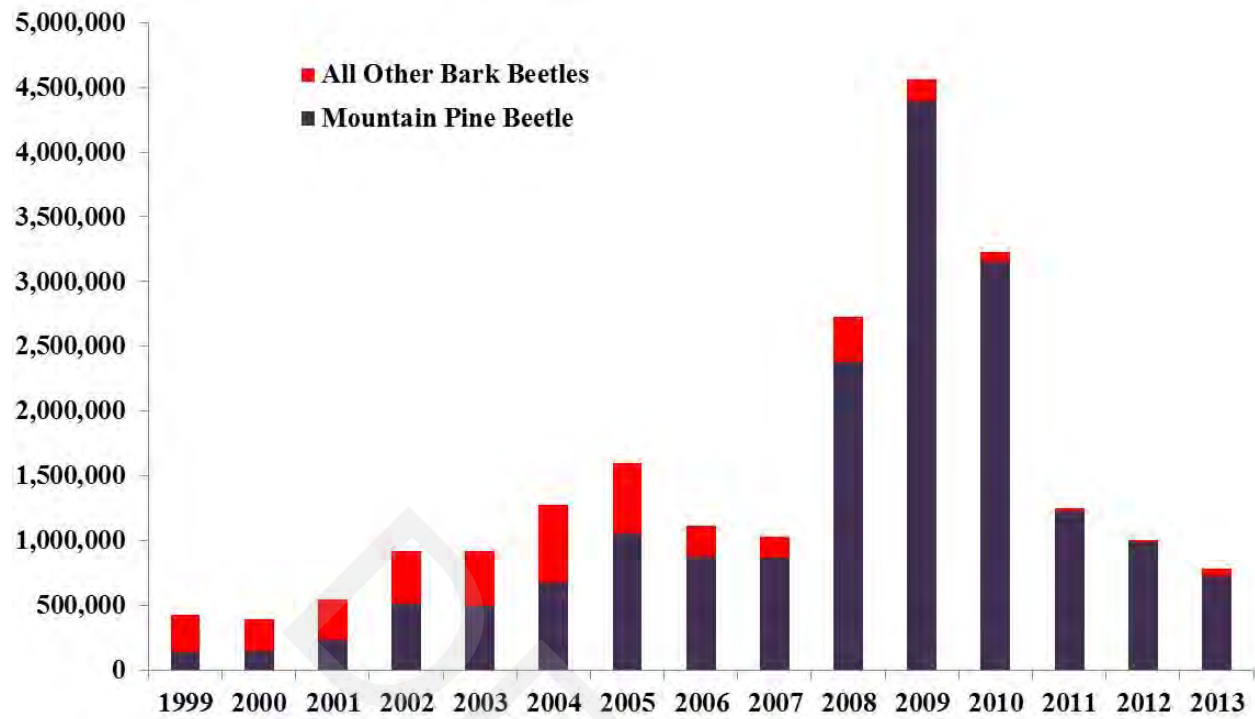


Figure 8.6—Area (acres) affected by bark beetles in the U.S. Forest Service Northern Region. Data based on Forest Health Protection aerial detections surveys.

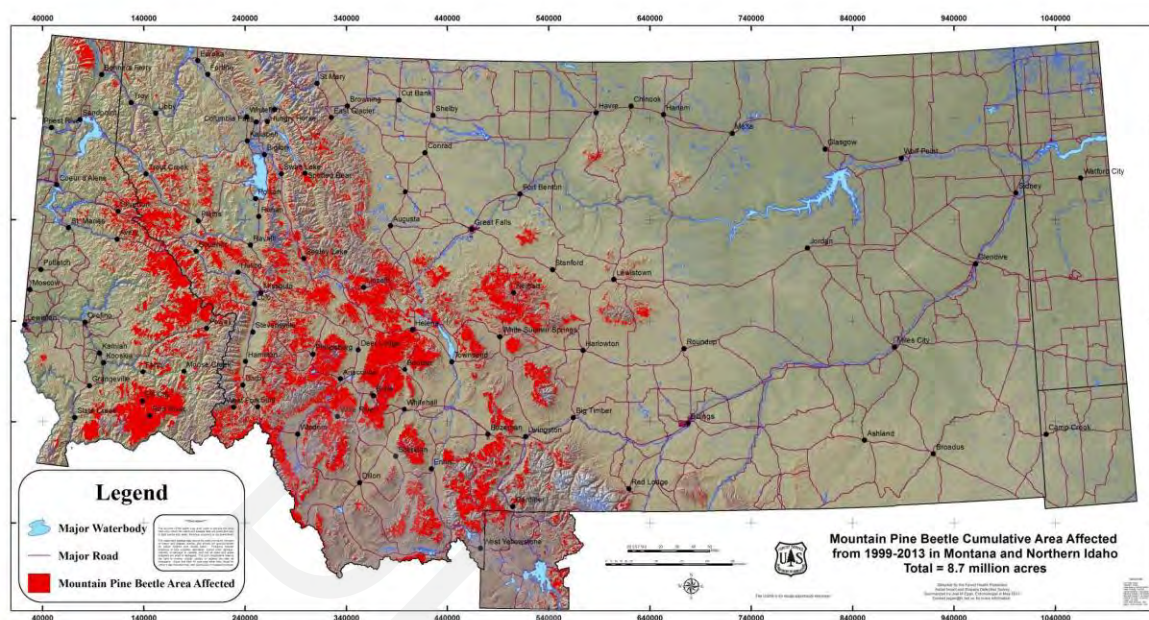


Figure 8.7—Cumulative area affected by mountain pine beetle between 1999 and 2013 in the Northern Rockies. Data based on Forest Health Protection aerial detection surveys.

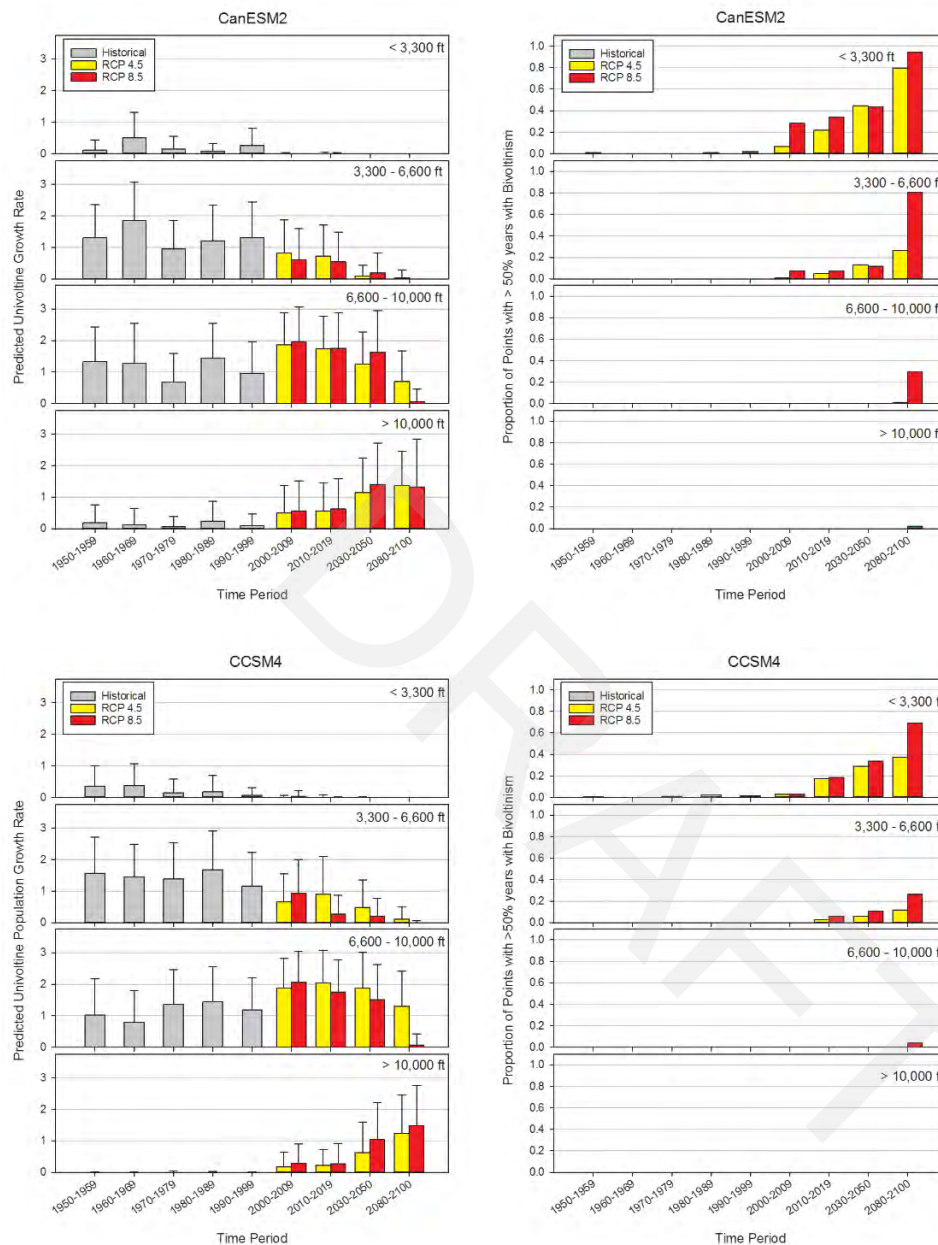


Figure 8.8—Left panel: projected mountain pine beetle (MPB) population growth rate (mean, standard deviation) of univoltine populations (one generation per year) over decades (historical) and 20-year periods (projected) from 1950 to 2100. Shown are the mean and standard deviation among locations of decadal (historic) and 2-decadal (projected) growth rates. Right panel: proportion of simulation points in which bivoltinism (two generations in one year) is projected for more than 50 percent of years in each time period. Projections are based on a temperature-dependent model of MPB development and population growth (Powell and Bentz 2009) using temperatures from the CanESM2 and CCSM4 GCMs and two emission scenarios (Representative Concentration Pathways [RCP] 4.5 and 8.5). Model output is shown by elevation category (in feet). Simulation points are geographic locations of downscaled temperatures where pines occur (sample size = 17,616).

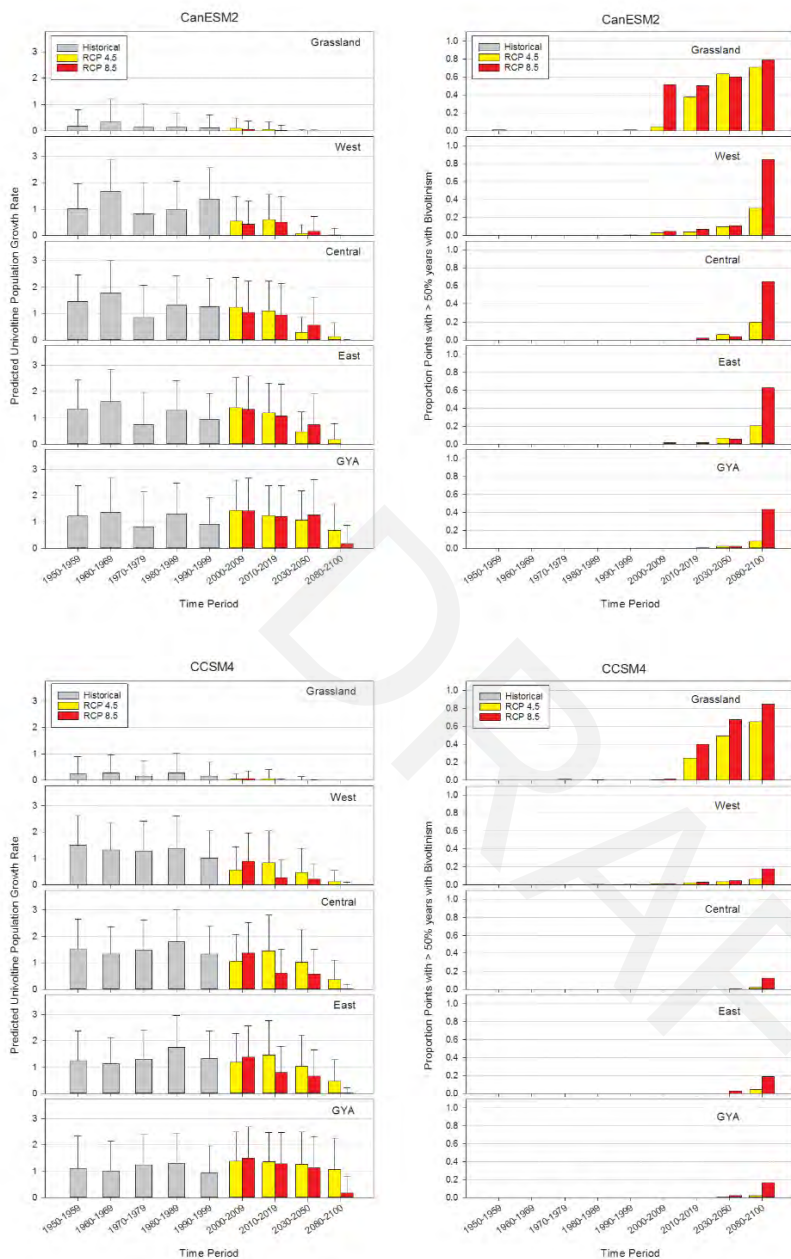


Figure 8.9—Left panel: Predicted mountain pine beetle (MPB) population growth rate (mean, standard deviation) of univoltine populations (one generation per year) over decades (historical) and 20 year periods (projected) from 1950 to 2100. Shown are the mean and standard deviation among locations of decadal (historic) and 2-decadal (projected) growth rates. Right panel: proportion of simulation points where bivoltinism (i.e., two generations in one year) is projected for more than 50 percent of years in each time period. Predictions are based on a temperature-dependent model of MPB development and population growth (Powell and Bentz 2009) using temperatures from the CanESM2 and CCSM4 GCMs and two emission scenarios (RCP 4.5, RCP 8.5). Model output is shown by Northern Rockies Adaptation Partners (NRAP) subregion. Simulation points are geographic locations of downscaled temperatures where pines occur (sample size = 17,616).

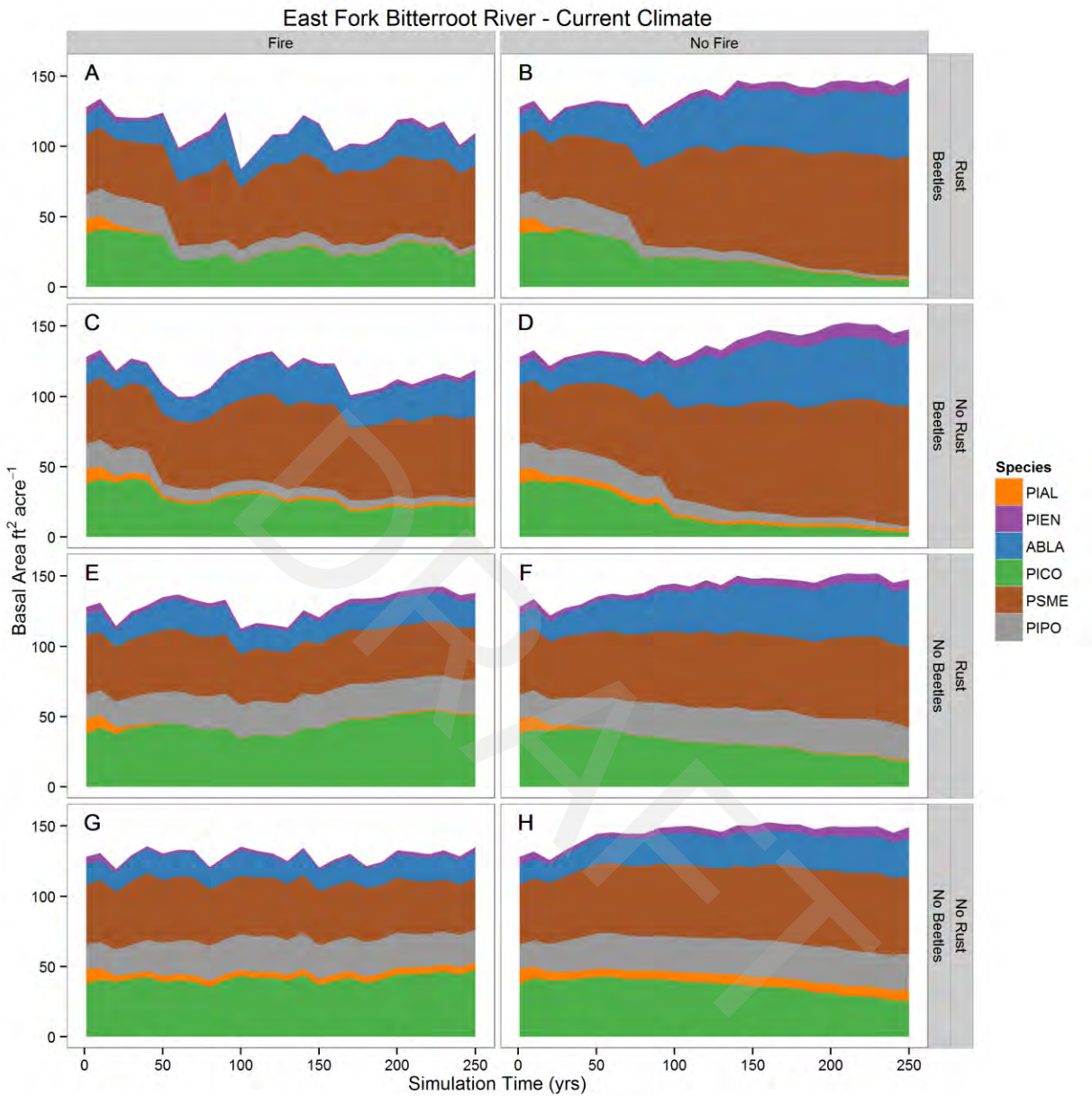


Figure 8.10—Landscape composition of species cover types using the plurality of basal area for *current climate* for the East Fork of the Bitterroot River landscape with all combinations of fire, white pine blister rust (WPBR), and mountain pine beetle (MPB): (A) fire, WPBR, and MPB, (B) no fire, WPBR, MPB, (C) fire and MPB, (D) MPB only, (E) fire and WPBR, (F) WPBR only, (G) fire only, and (H) no disturbances. Species: PIAL-whitebark pine, PIEN-Engelmann spruce, ABLA = subalpine fir, PICO-lodgepole pine, PSME-Douglas-fir, and PIPO-ponderosa pine. Produced using the FireBGCv2 mechanistic ecosystem-fire process model (Keane et al. 2015).

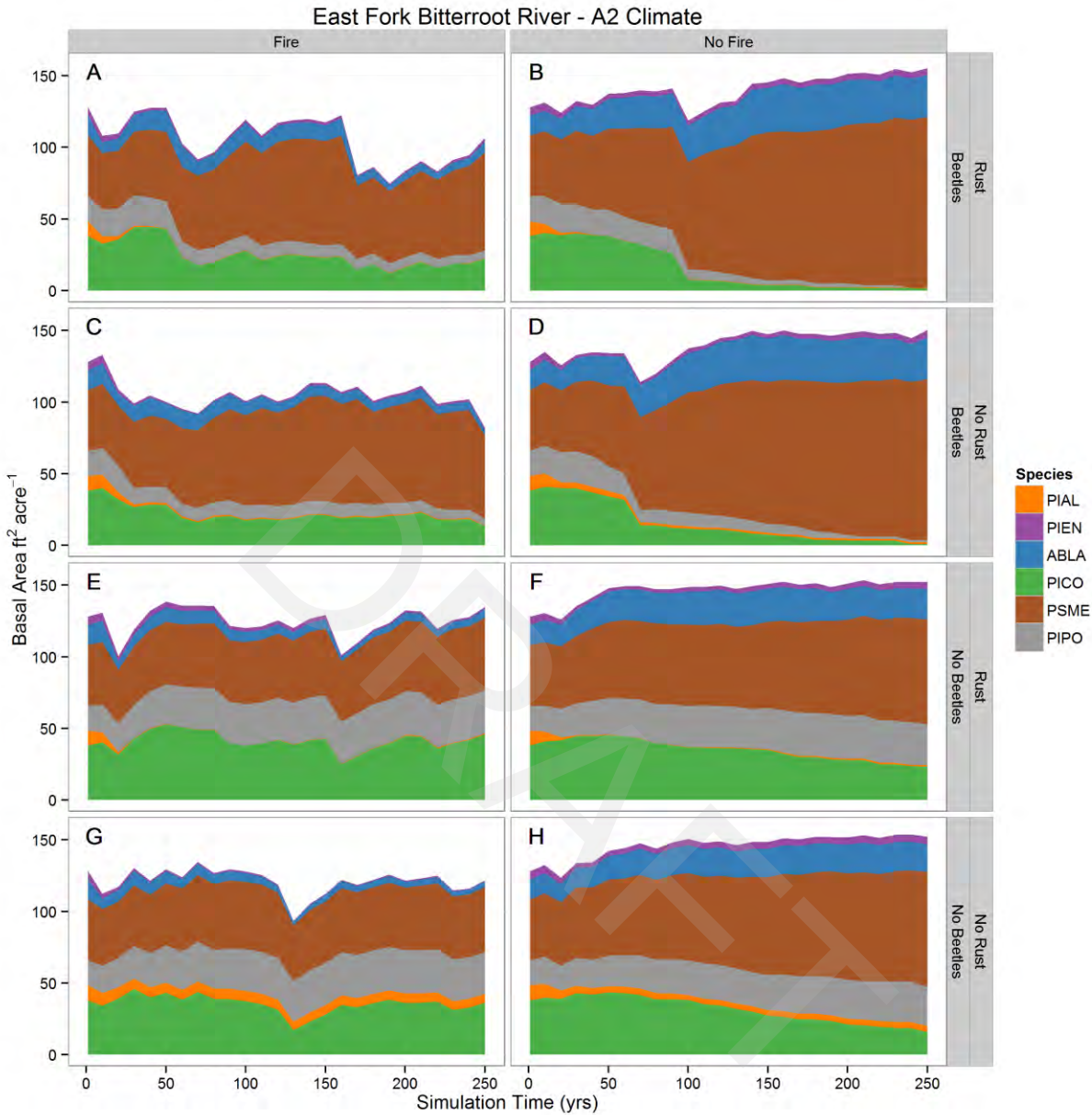


Figure 8.11—Landscape composition of species cover types using the plurality of basal area for a warmer climate (A2 emission scenario) for the East Fork of the Bitterroot River landscape with all combinations of fire, white pine blister rust (WPBR), and mountain pine beetle (MPB): (A) fire, WPBR, and MPB, (B) no fire, WPBR, MPB, (C) fire and MPB, (D) MPB only, (E) fire and WPBR, (F) WPBR only, (G) fire only, and (H) no disturbances. Species: PIAL = whitebark pine, PIEN = Engelmann spruce, ABLA = subalpine fir, PICO = lodgepole pine, PSME = Douglas-fir, and PIPO = ponderosa pine. Produced using the FireBGCv2 mechanistic ecosystem-fire process model (Keane et al. 2015).

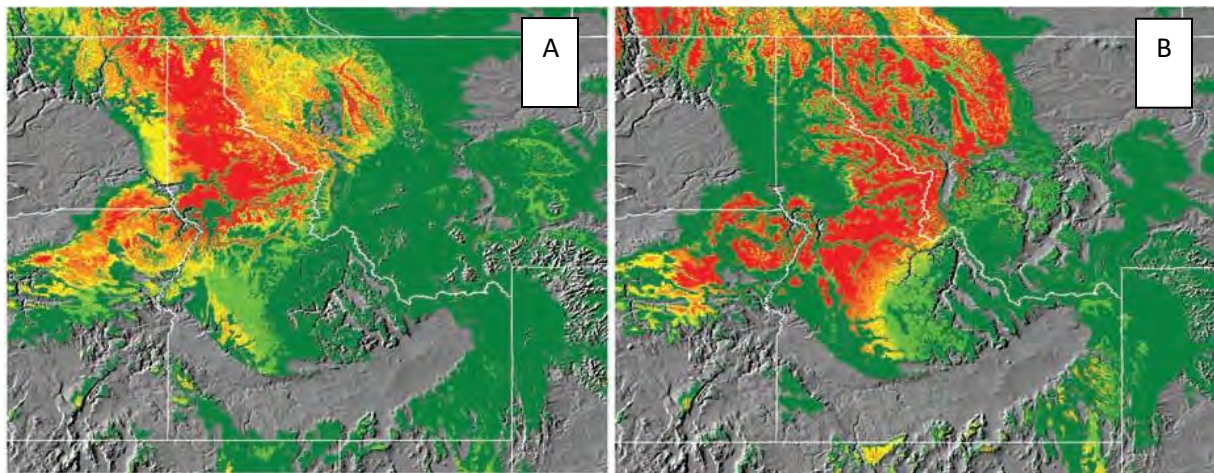


Figure 8.12—Modeled (A) current and (B) future (year 2060) climate space for *Armillaria solidipes* (Klopfenstein et al. 2009). Colors represent the number of tree votes cast, analogous to the probability of occurrence. Yellow = 50 to 75 votes, red = 76 to 100 votes.

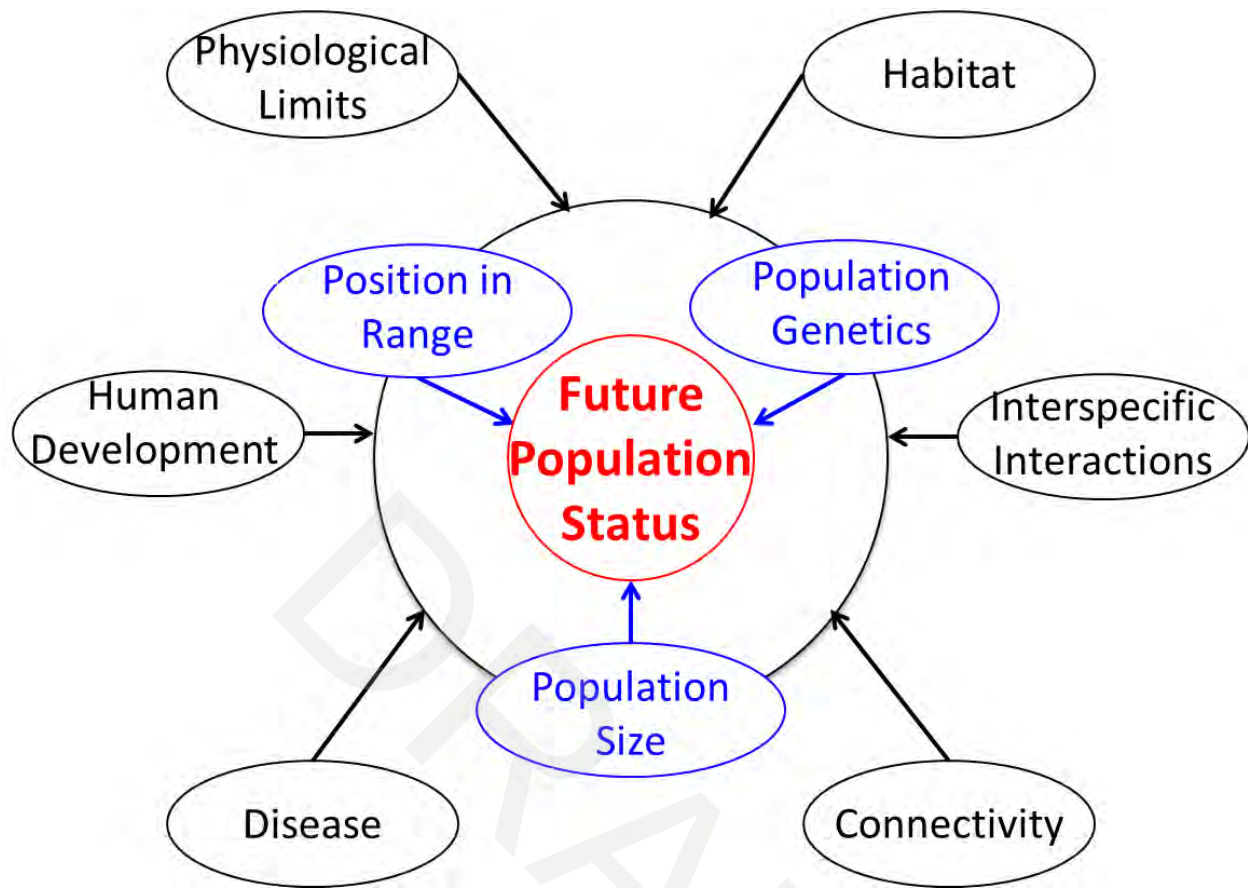


Figure 9.1—Visual summary of workshop discussions on the influence of climate on wildlife populations in the Northern Rockies Adaptation Partnership. Pathways of climate influence (black) interact with population characteristics (blue) to affect the future population status (red). A given pathway affects multiple species, and multiple pathways affect a given species.



Figure 9.2—Canada lynx have snow-specific adaptations (oversized feet, long legs, and a thin, light skeleton), and snowshoe hares dominate their diets. Snowshoe hares undergo seasonal pelage changes from brown to white, and the effectiveness of this strategy depends on synchrony with snow cover. A mismatch between the hare's fur color and its environment would make it more vulnerable to predation by lynx. (Left photo by Milo Burcham, right photo by L. Scott Mills)



Figure 9.3—Maintenance and restoration of American beaver populations are an adaptation tactic for maintaining water on the landscape. Although beavers are not particularly climate sensitive themselves, the structures beavers create and their effects on aquatic habitats and floodplains may help to ameliorate the effects of climatic change on cold-water fish species and other aquatic organisms. (Photo by E. Himmel, National Park Service)



Figure 9.4—The American pika is a small lagomorph that collects grass and herbs throughout the summer as winter food and remains active throughout the winter. It depends on the relatively warm subnivean environment associated with deep winter snowpack. (Photo by Jim Jacobson)



Figure 9.5—Ungulates generally respond favorably to wildfires that create patchy habitat, especially if forage availability improves, as shown in this photo of an elk browsing adjacent to a recently burned lodgepole pine forest. (Photo by Jeff Henry, National Park Service)



Figure 9.6—Since climate change is expected to reduce the extent of mature sagebrush through increased wildfire, sagebrush-obligate species such as Brewer's sparrow (shown here) and greater sage-grouse may have less nesting habitat in the future. (Photo by Paul Higgins, www.utahbirds.org)



Figure 9.7—Warmer air temperature and less snowpack are expected to decrease the presence of shallow water during the summer, reducing habitat for the Columbia spotted frog (shown here) and western toad. Higher water air and water temperatures may also increase infections from amphibian chytrid fungus. (Photo by Roger Myers, Alaska Department of Fish and Game)

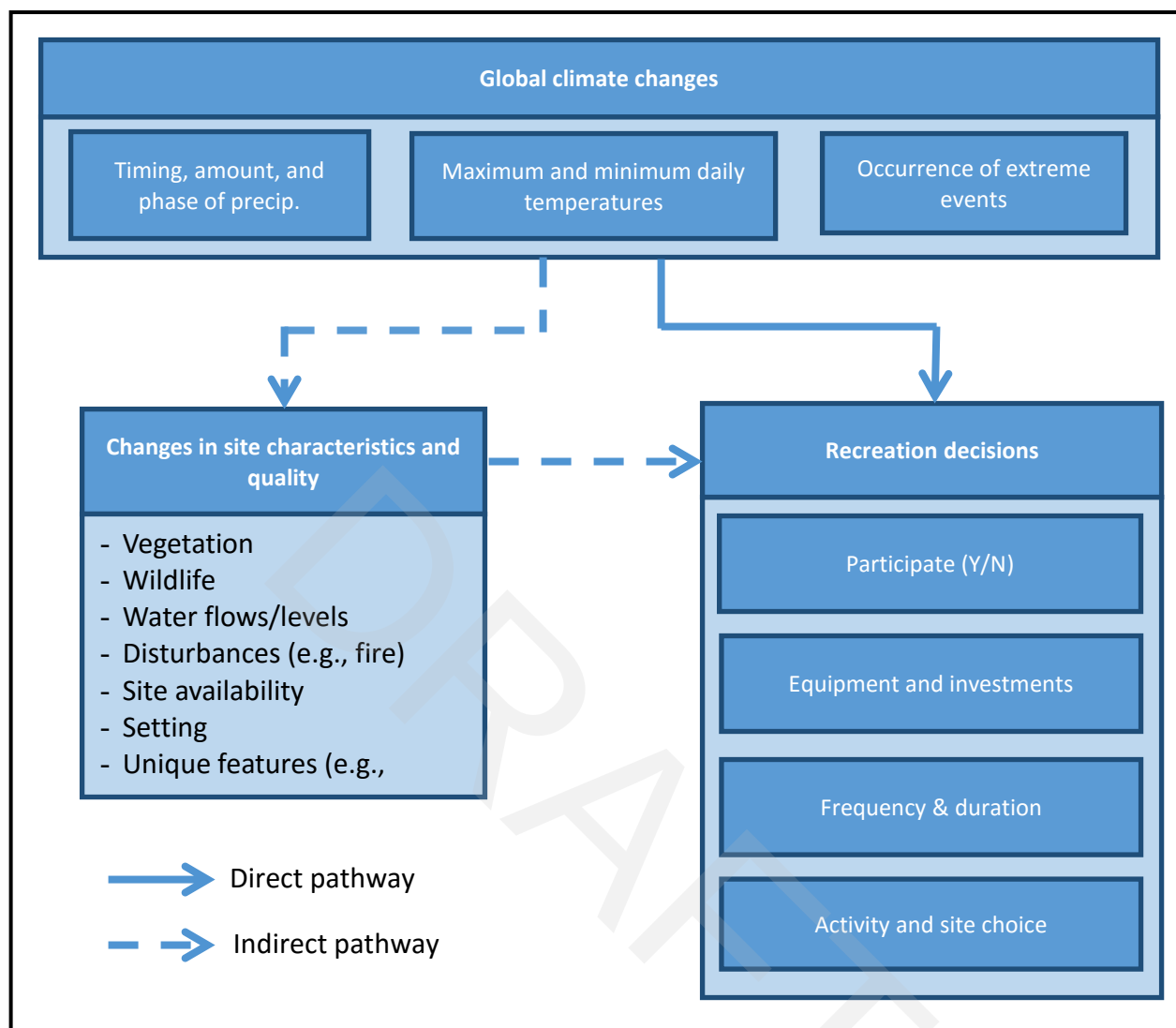


Figure 10.1—Direct and indirect effects of climate on recreation decisions.

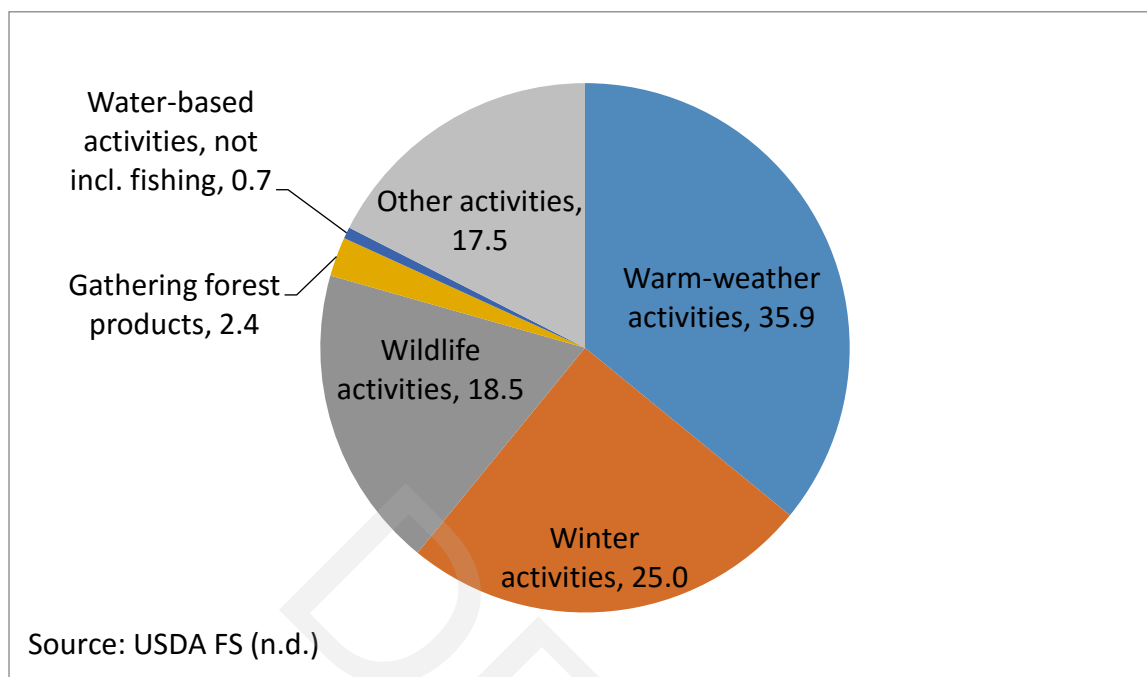


Figure 10.2—Percent of total national forest visits by climate-sensitive primary activity (Source: USDA FS n.d.)



Figure 10.3—Expectations for extent and severity of wildfires in a warmer climate will create forest conditions that may be less desirable for hiking and other recreational activities. (Photo courtesy of Dave Pahas, <http://IdahoAlpineZone.com>)



Figure 10.4—Cross-country skiing at lower elevation locations (shown here in the Beaverhead-Deerlodge National Forest) may be vulnerable as snowpack decreasee in future decades. (Photo courtesy of U.S. Forest Service)



Figure 10.5—Algal blooms, shown here in Hayden Lake, Idaho, may become more common in a warmer climate. These conditions are undesirable for water-based recreation and some fish species. (Photo courtesy of Panhandle Health District)

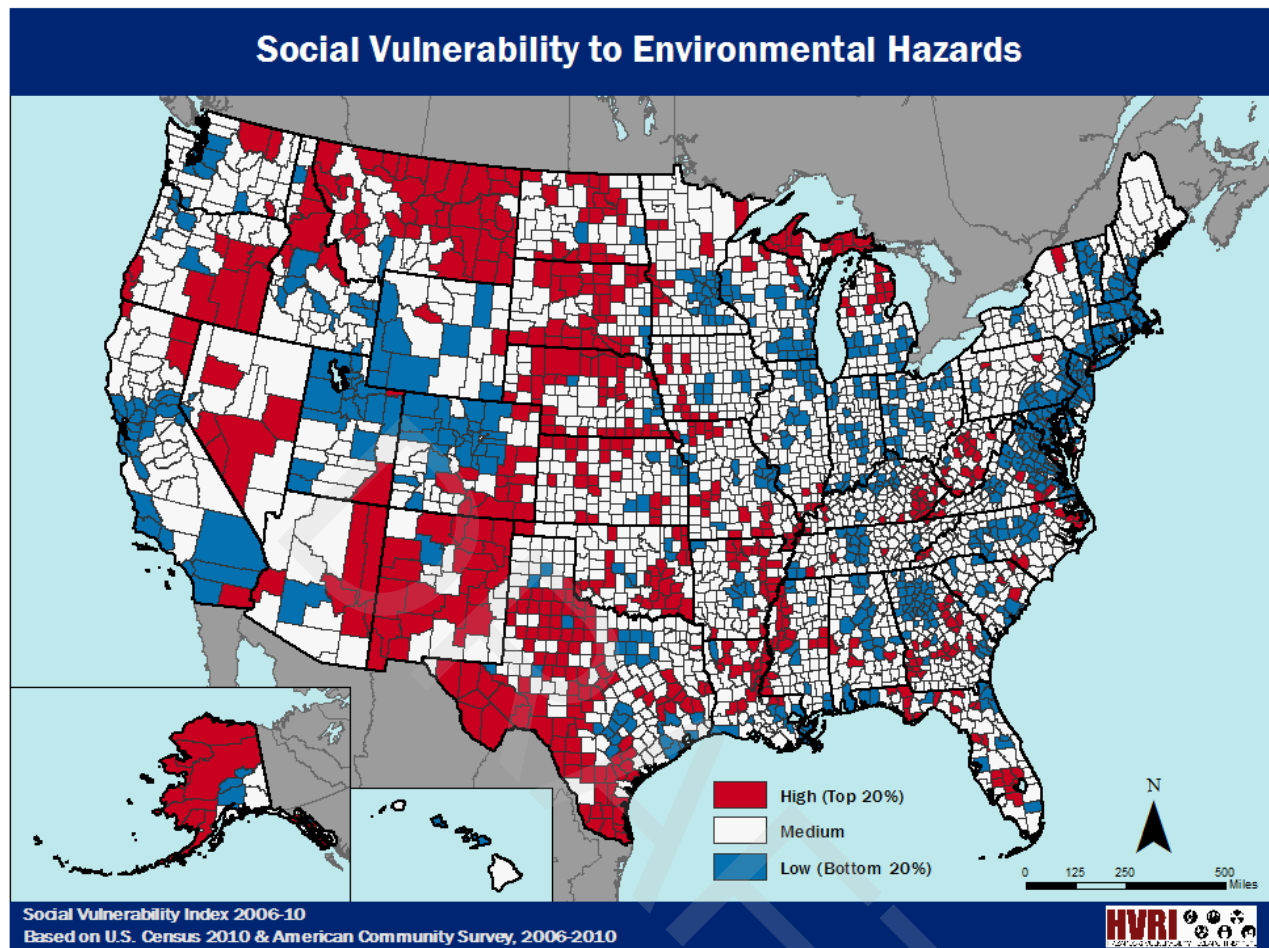
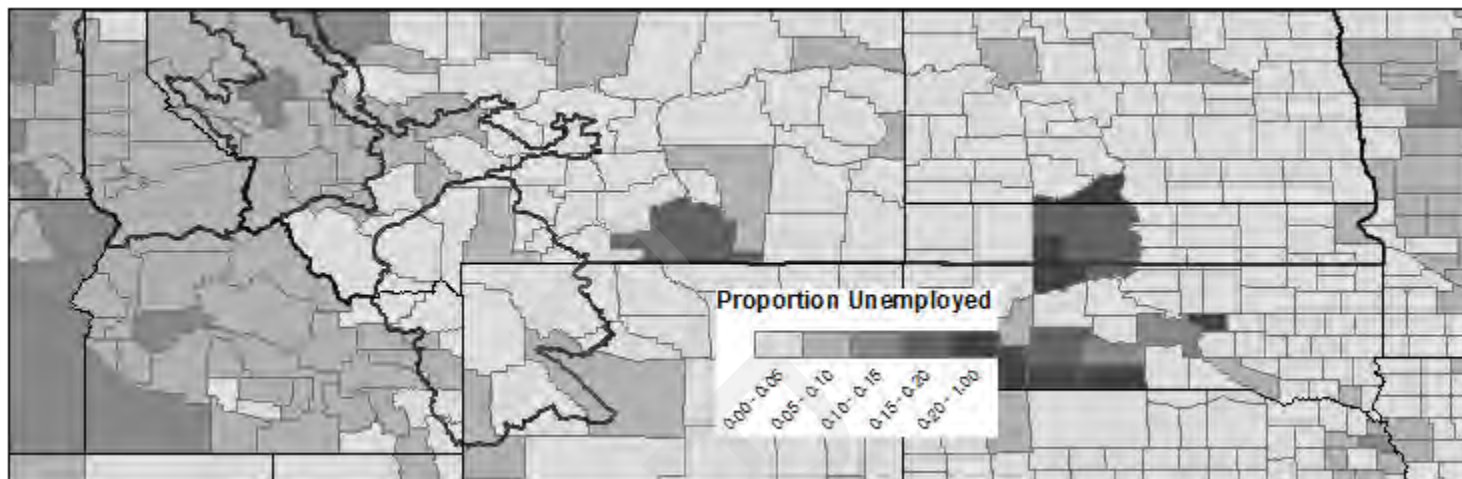
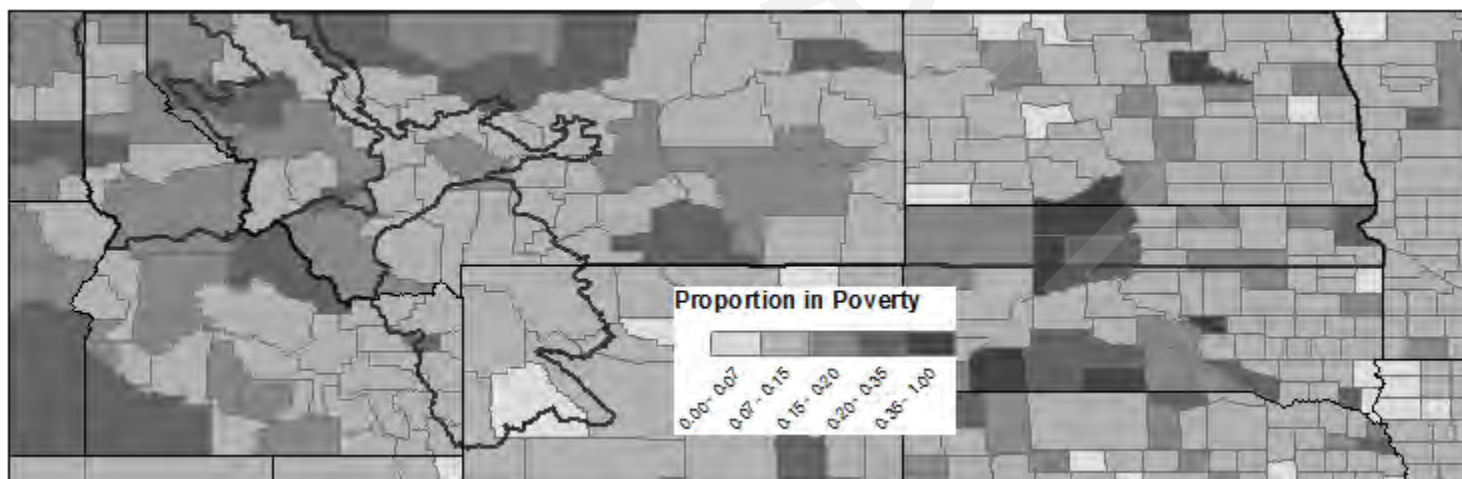


Figure 11.1— The Social Vulnerability Index (SoVI) to environmental hazards for U.S. counties (managed and updated by the Hazards and Vulnerability Research Institute at the University of South Carolina; Cutter et al. 2003). The SoVI is based on 11 underlying factors identified to affect social vulnerability: personal wealth, age, density of the built environment, single-sector economic dependence, housing stock and tenancy, race, ethnicity, occupation, and infrastructure dependence. For each county in the U.S., scores based on these 11 factors are summed to form a composite vulnerability score. To highlight counties with the most “extreme” scores, composite scores are then converted to standard deviations and mapped.

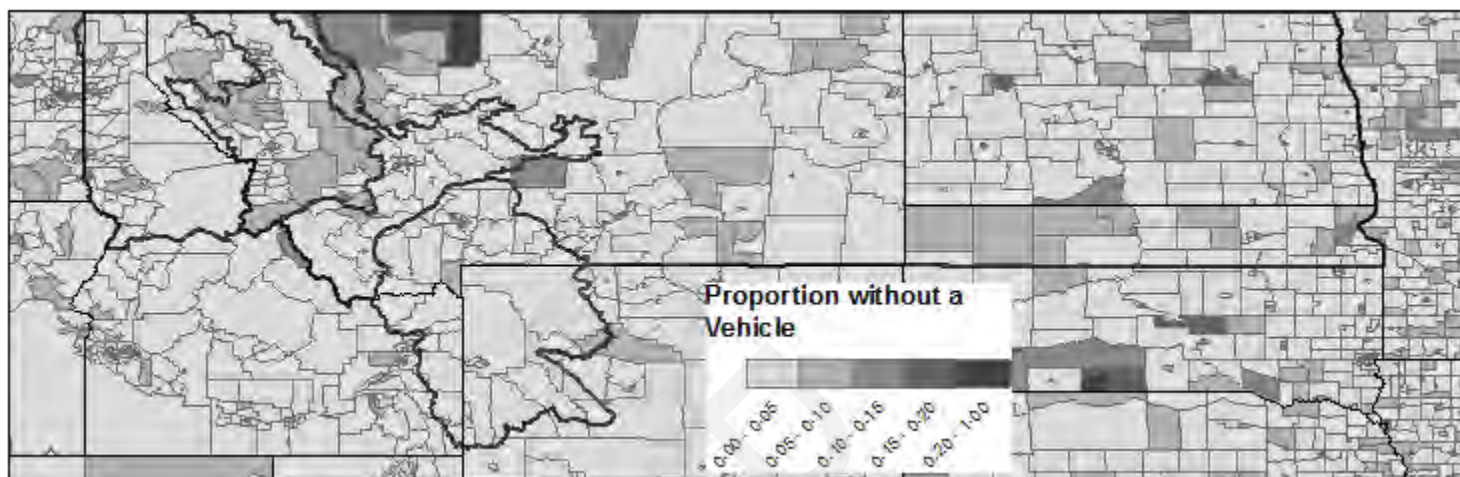
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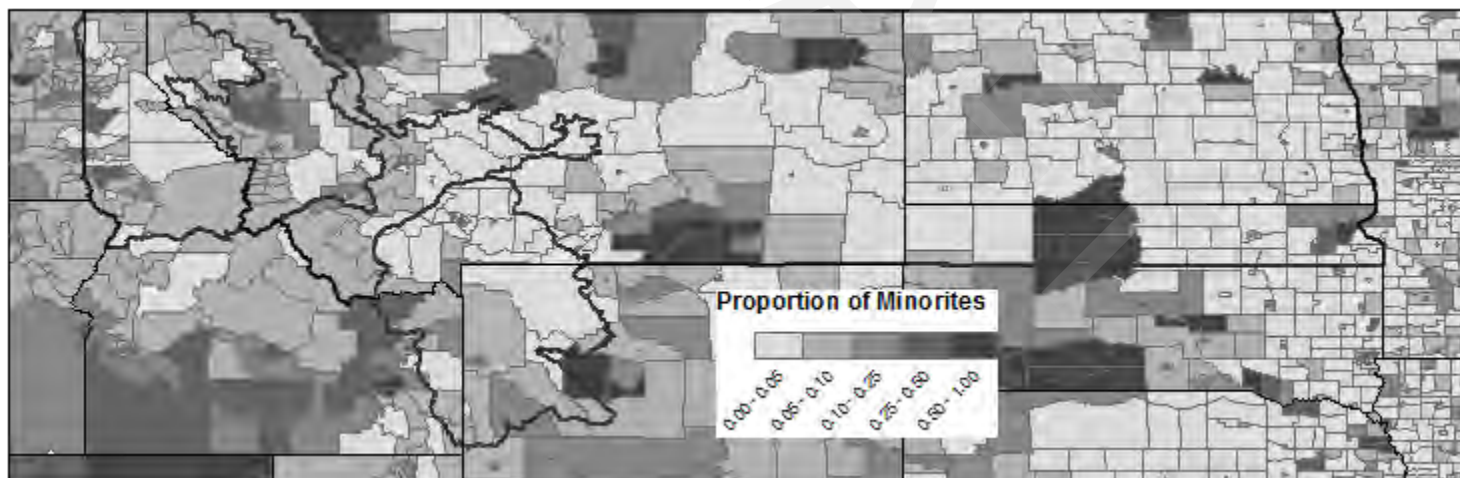
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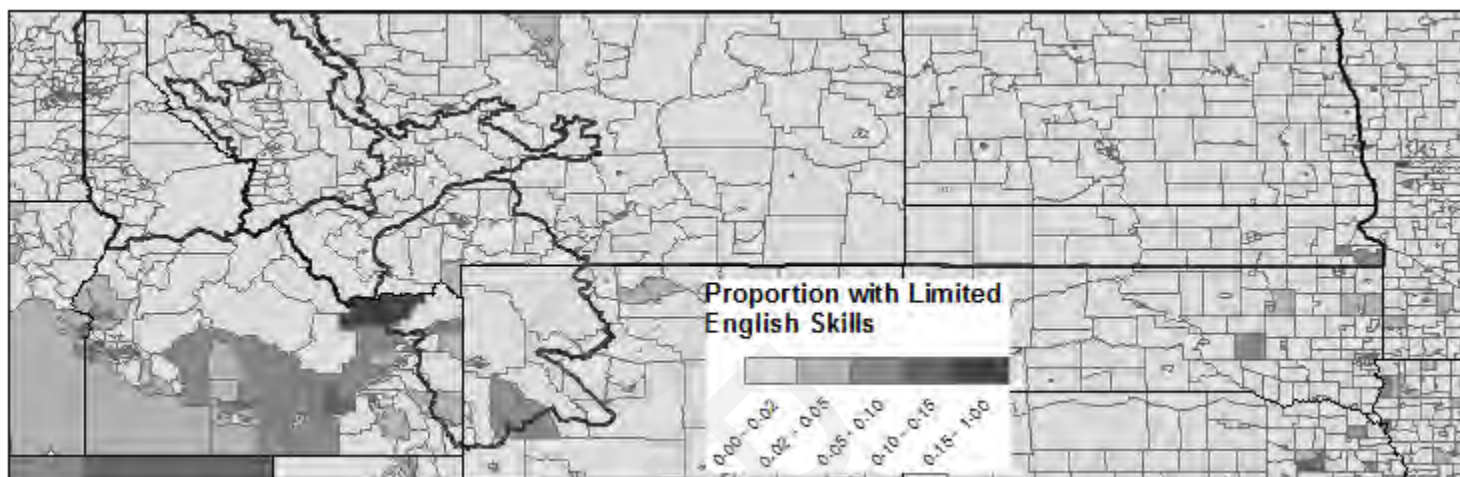
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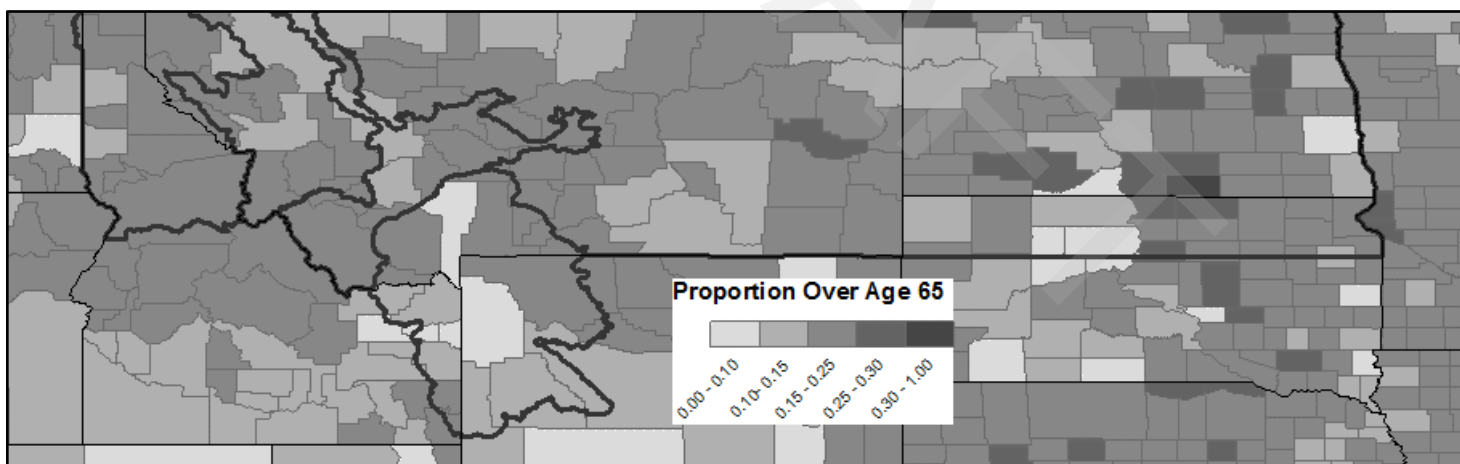


Figure 11.2—Demographic information for the Northern Rockies region, including proportion unemployed (a), proportion in poverty (b), proportion without a vehicle (c), proportion of minorities (d), proportion with limited English skills (e), and proportion over age 65 (f).

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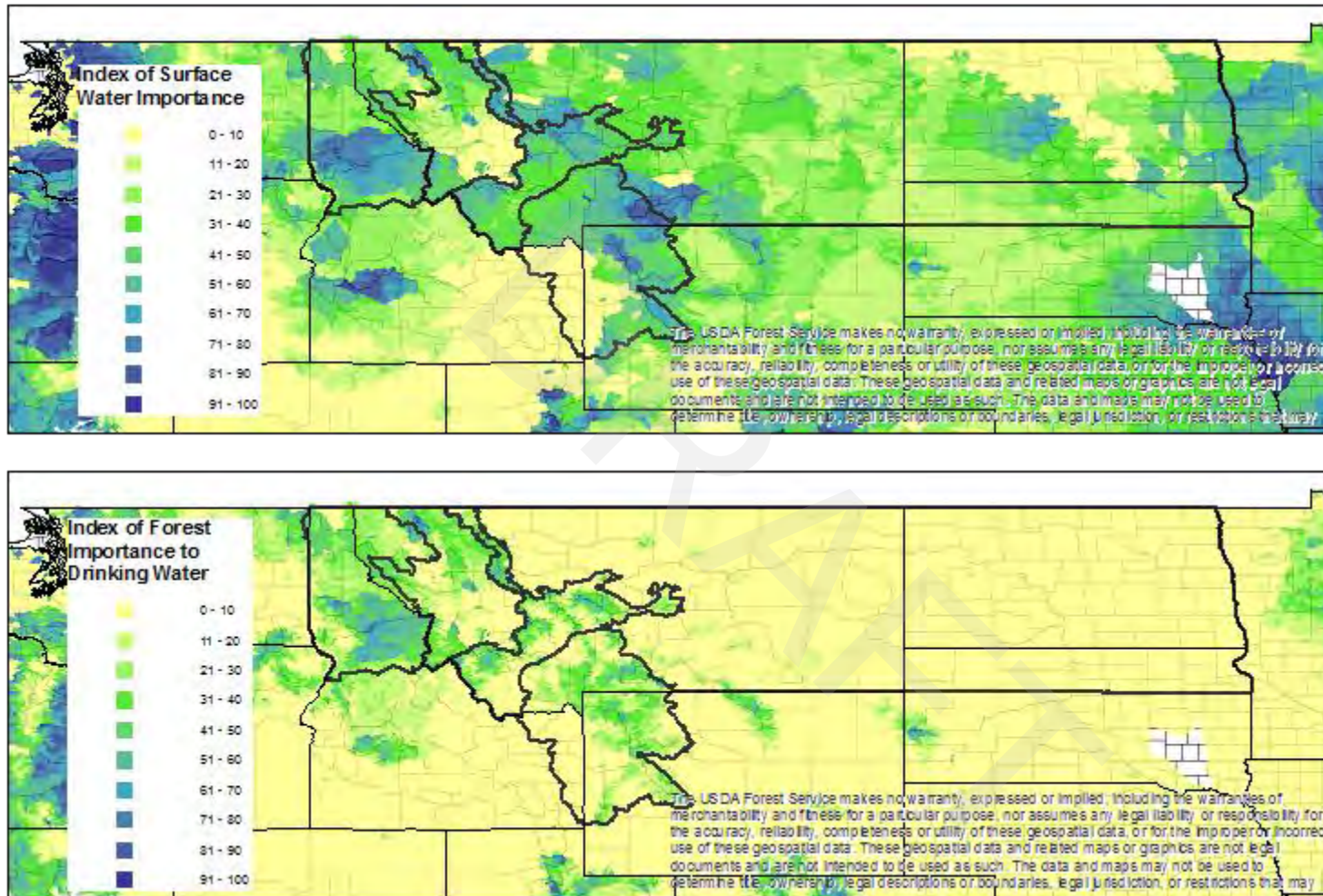


Figure 11.3—Forests to Faucets data showing the relative importance of surface water for municipal water supply (top) and forests for maintaining watershed health (bottom). The index depends on both the amount of water coming off forests and the population served by that water. Higher numbers indicate higher levels of importance (from Weidner and Todd 2011).

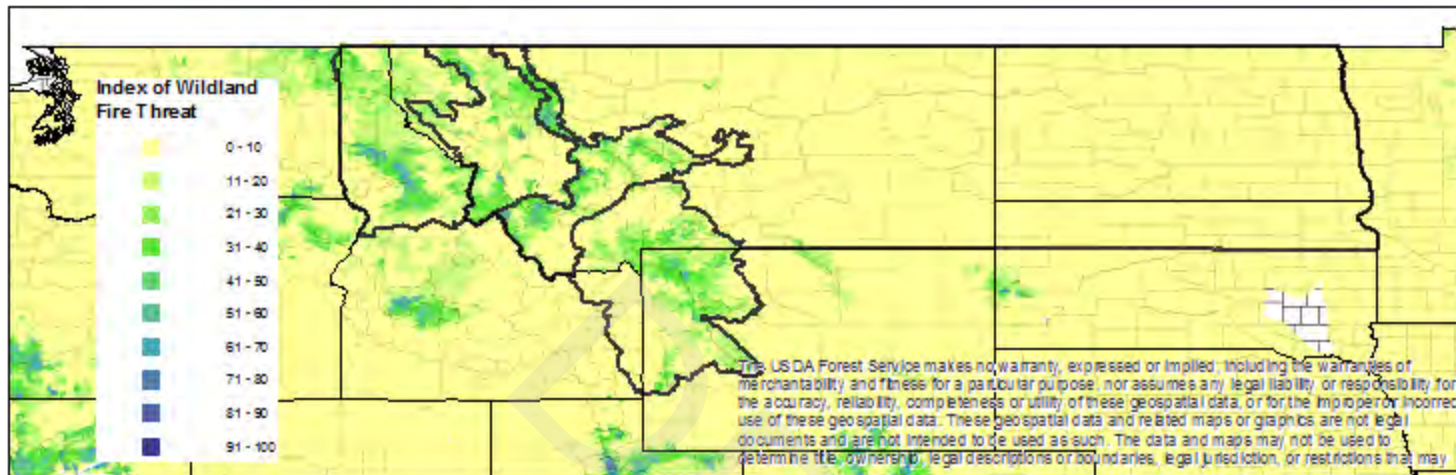


Figure 11.4—Wildland fire threat to forests and importance to surface drinking water. Higher numbers indicate higher risk of wildland fire (from Weidner and Todd 2011).

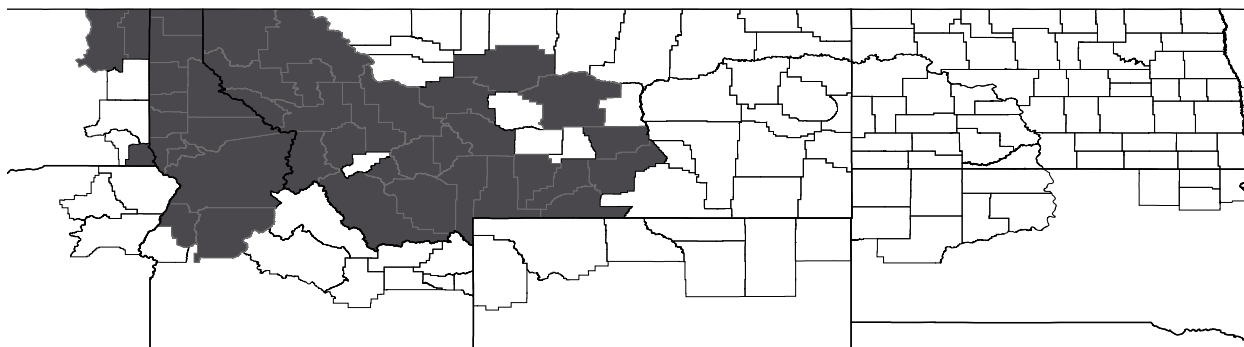


Figure 11.5—Primary area where timber is processed from national forests in the U.S. Forest Service Northern Region.

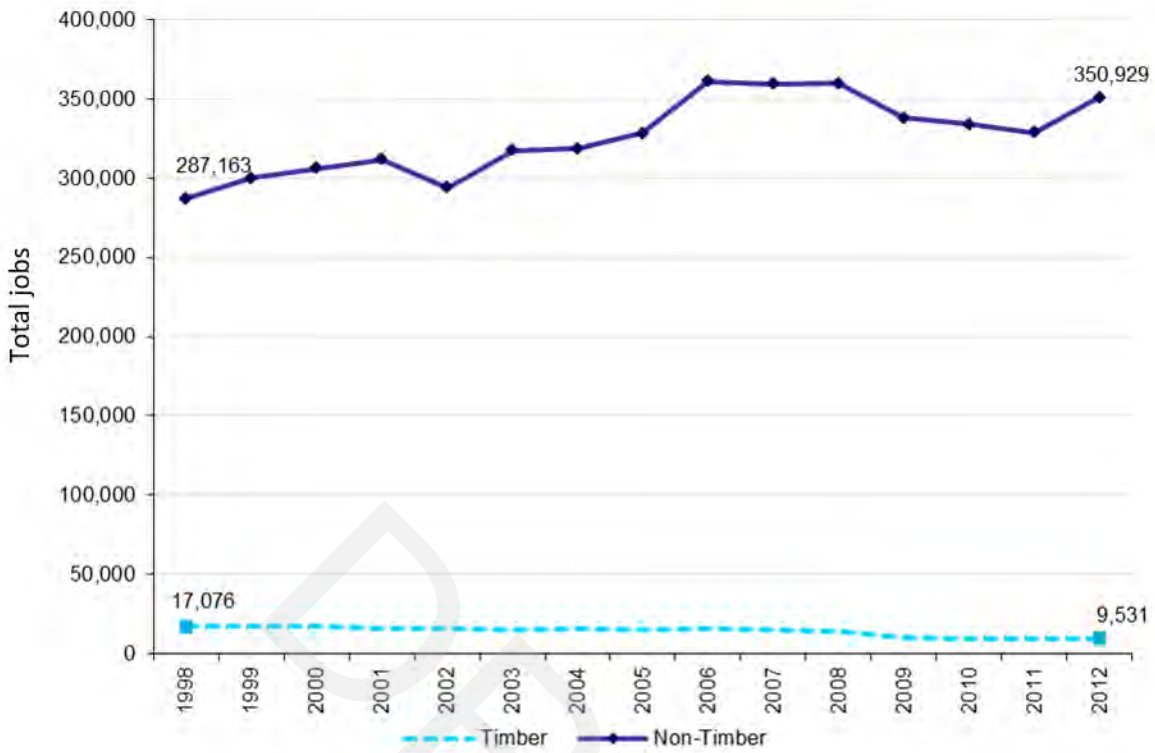


Figure 11.6—Total jobs in timber and non-timber for national forests in the U.S. Forest Service Northern Region (from U.S. Department of Commerce 2014).

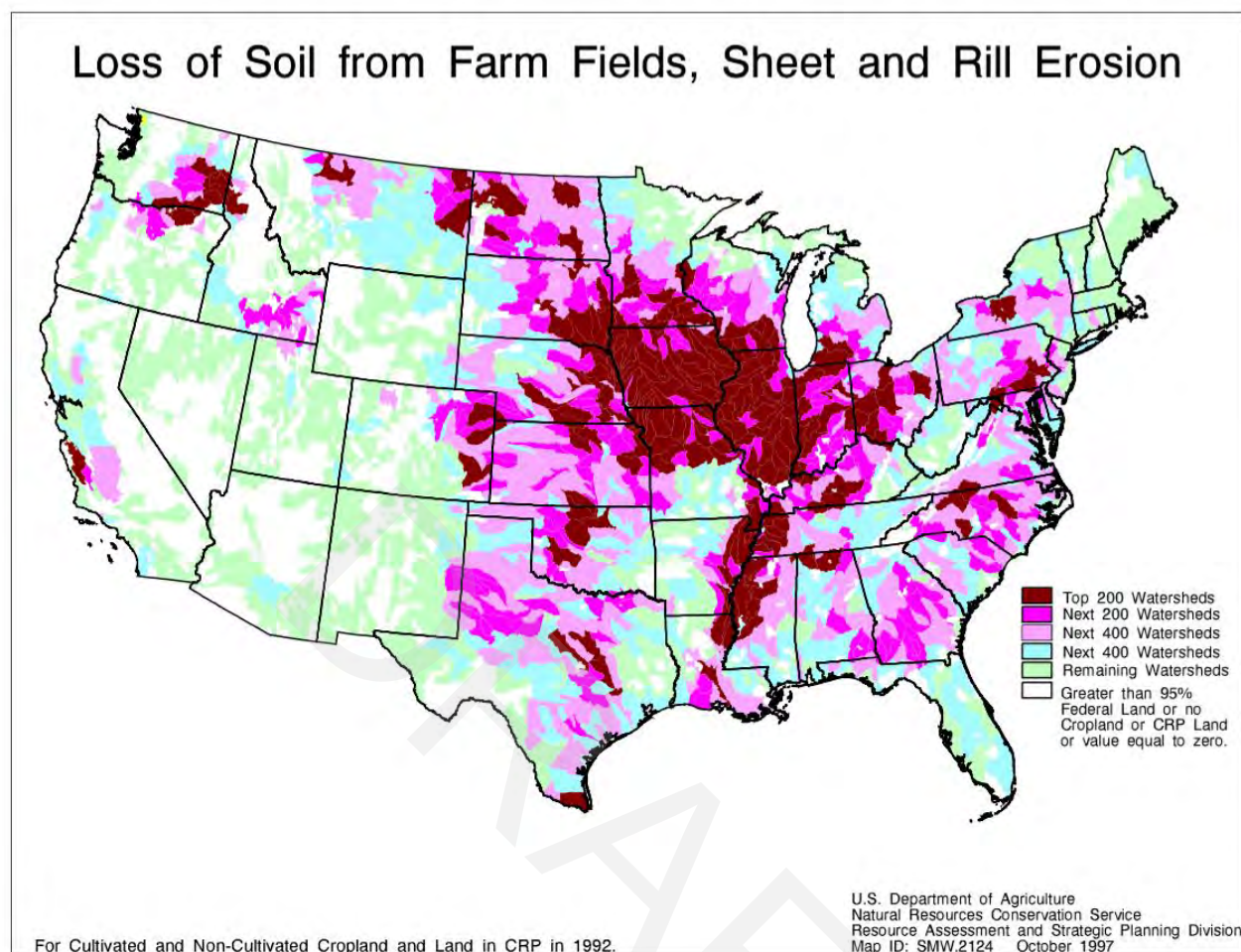


Figure 11.7—Ranking of watersheds in U.S. by their potential for soil loss from sheet and rill erosion (from U.S. Department of Agriculture, Natural Resources Conservation Service, http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/home/?cid=nrcs143_014067).

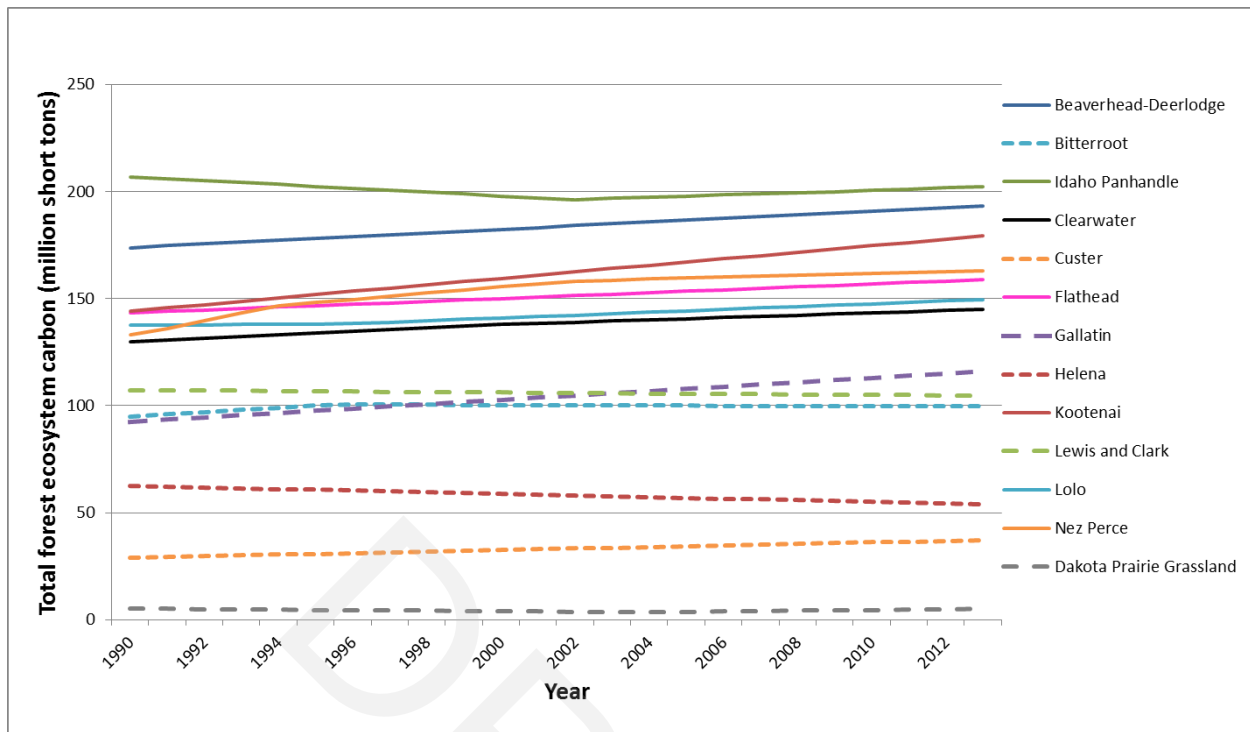


Figure 11.8—Total forest ecosystem carbon for the national forests and grassland in the Northern Region from 1990 to 2013.

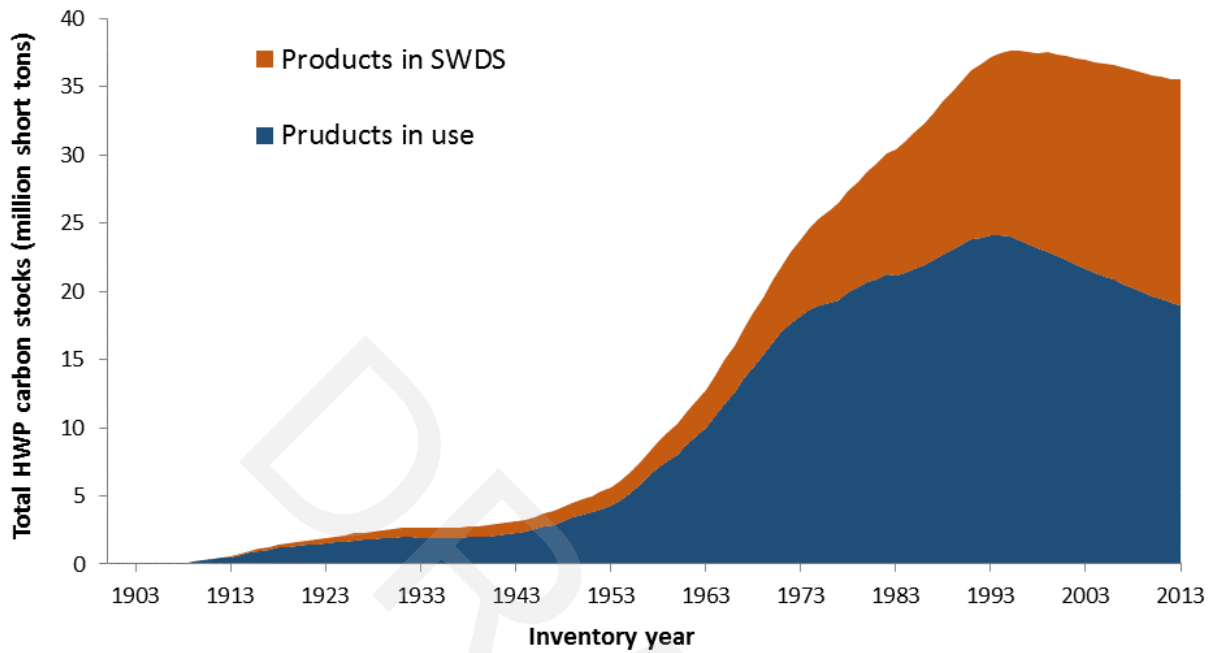


Figure 11.9—Cumulative total carbon stored in harvested wood products (HWP) manufactured from the Northern Region timber. Carbon in HWP includes both products that are still in use and carbon stored at solid waste disposals sites (SWDS), including landfills and dumps (Stockmann et al. 2014).



Figure 12.1—Prehistoric stone cairn exposed by wildfire in Custer National Forest. Intense wildfires, suppression, and rehabilitation activities annually affect hundreds of cultural resources in the Northern Rockies. (Photo by Halcyon LaPoint, Custer-Gallatin National Forest)



Figure 12.2—Prehistoric artifacts exposed in soil-deflated surface caused by drought conditions. Exposed artifacts are vulnerable to illegal collecting and livestock trampling. (Photo by Carl Davis, U.S. Forest Service)



Figure 12.3—Post-wildfire debris flow that obliterated or covered cultural resources in Meriwether Canyon, Helena National Forest. Early, intense spring runoff events may become more common in the future. (Photo by Carl Davis, U.S. Forest Service)



Figure 12.4—Melting perennial ice patches expose prehistoric artifacts in Custer-Gallatin National Forest. These high-elevation locations document activities by Native American groups in the recent and distant past. (Photo by Craig Lee, Montana State University)



Figure 12.5—Whitebark pine mortality may affect the integrity and status of cultural sites, such as the Lewis and Clark Pass cultural landscape and National Register District shown here. Significant landscape change may also affect indigenous peoples and local communities who use the area and its resources. (Photo by Sara Scott, Montana Department of Fish, Wildlife, and Parks)



Figure 12.6—Installing emergency roof supports in the main lodge, OTO Dude Ranch, Custer-Gallatin National Forest. Routine and emergency projects to stabilize, protect, and maintain historic buildings are likely to increase in a warmer climate. (Photo by Marcia Pablo, Custer-Gallatin National Forest)

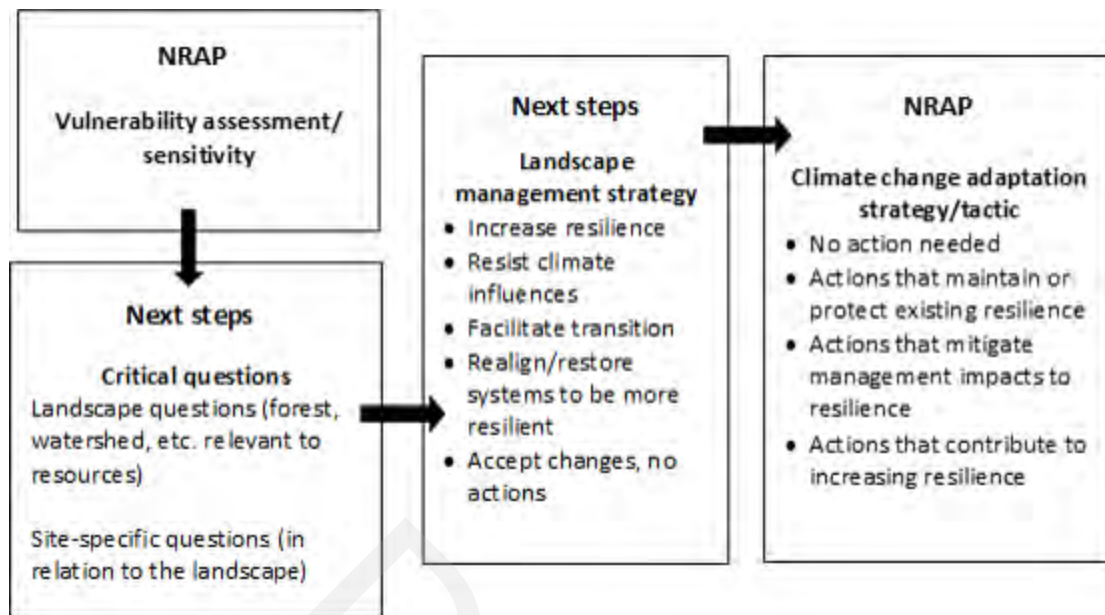


Figure 13.1—General framework for use of the Northern Rockies Adaptation Partnership vulnerability assessment and adaptation strategies and tactics to ask critical questions and develop a landscape management strategy.

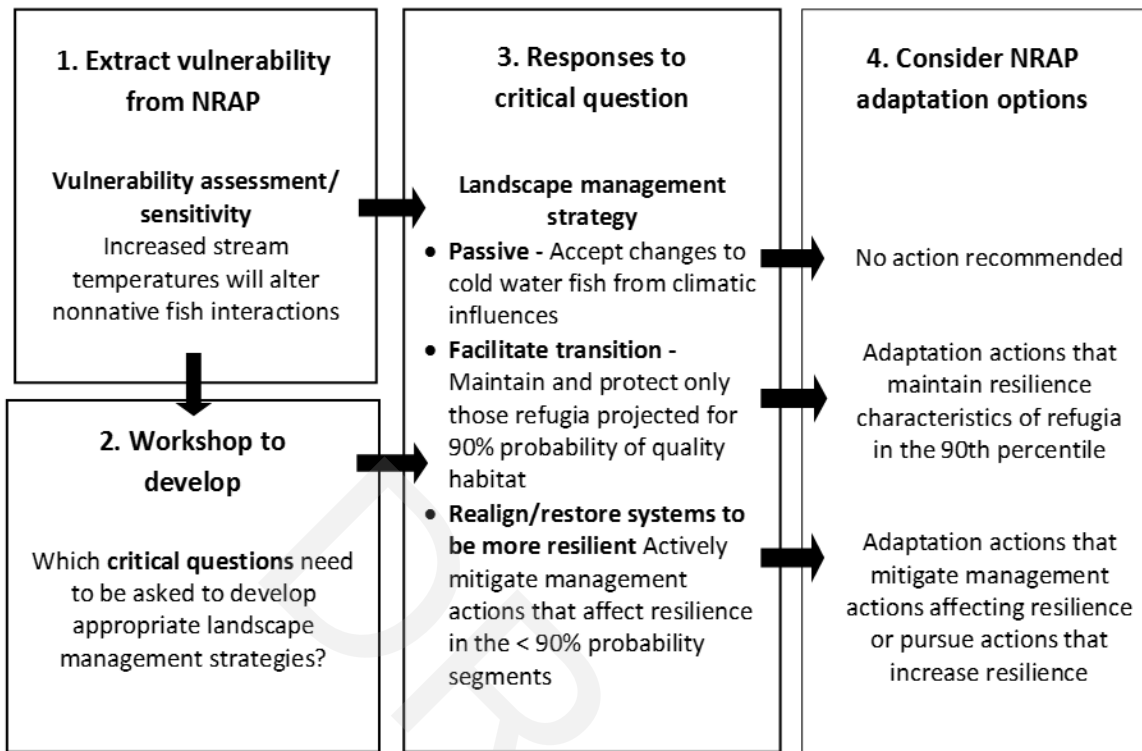


Figure 13.2—Example of how a workshop can be conducted to answer critical questions and develop a landscape management strategy for cold-water fish

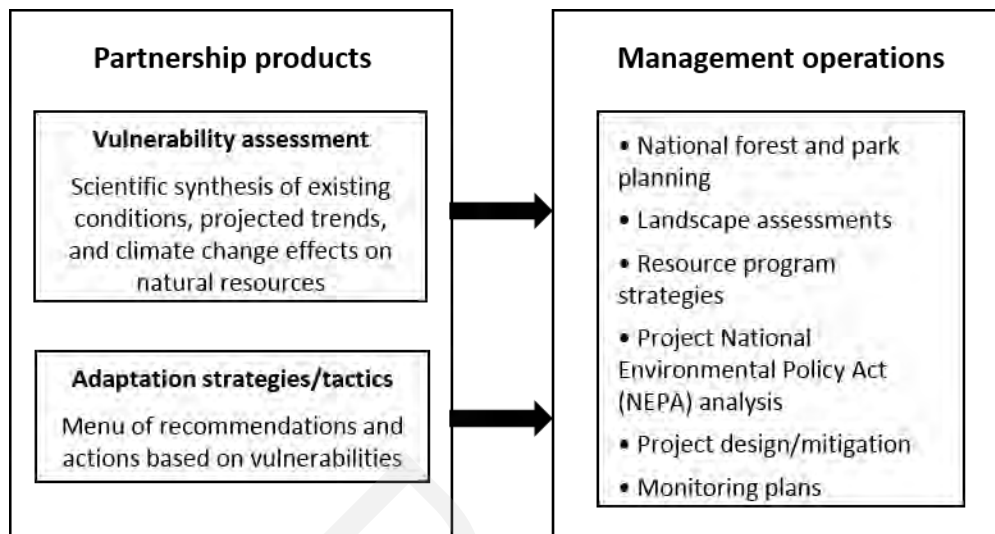


Figure 13.3—Example applications of Northern Rockies Adaptation Partnership products to land management operations.

Boxes

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Box 3.1—Comparing CMIP3 and CMIP5 for temperature and precipitation projections for Oregon and Washington

Model evaluation

One way to evaluate a model's "skill" is to have it simulate (recreate) past climate and compare those results to observed climate. Both CMIP3 and CMIP5 models reproduce important characteristics of climate in the NRAP region fairly well, including wet winters, dry summers, annual temperature, and a 20th century warming trend (~1.4 °F per century). However, both CMIP3 and CMIP5 models are wetter on an annual basis than observations (Mote and Salathé 2010, Rupp et al. 2013).

Future temperature

- CMIP5 climate experiments based on RCP 4.5 and RCP 8.5 are warmer for the NRAP region, on average, than the CMIP3 scenarios based on SRES-B1 and SRES-A2.
- Most of the difference in temperature projections can be explained through increased forcing between the two sets of emissions/concentration scenarios, rather than modifications to the models between CMIP3 and CMIP5.

Future precipitation

- CMIP3 and CMIP5 both project a slightly wetter future on average by mid-21st century.
- CMIP3 and CMIP5 both project slightly drier summers and slightly wetter conditions the rest of the year.
- High natural variability in precipitation masks differences between CMIP3 and CMIP5.

Box 3.2—Summary: Climatic variability and change for the Northern Rockies Adaptation Partnership region

- The mountainous West, Central, East, and Greater Yellowstone Ecosystem subregions sit at the boundary between the warm, wet, maritime airflows from the Pacific Ocean, and the cooler, drier airflows from Canada. The Grassland subregion is influenced primarily by the cooler, drier airflows from Canada.
- Climatic variability in the mountainous areas of Idaho, Montana, and the Greater Yellowstone Ecosystem is strongly influenced by interactions with topography, elevation, and aspect.
- Historically, the coolest areas are found in the Greater Yellowstone Ecosystem, and the warmest areas are associated with grasslands in central Montana and into South Dakota and North Dakota.
- By the 2040s, mean annual monthly temperatures are projected to increase in the NRAP region. The warmest areas continue to be associated with central Montana. For the Grassland subregion, projections show a pattern of drier west and wetter east, with the mean of climate models showing a slight increase in the wetter eastern area.
- Projections for precipitation suggest a very slight increase in the future. Precipitation projections, in general, have much higher uncertainty than those for temperature.
- Seasonally, projected winter maximum temperature begins to rise above freezing (32 °F) in the mid-21st century in several of the subregions.
- Projected climate was derived from climate models in the Coupled Model Intercomparison Project version 5 (CMIP5) database, which was used in the most recent Intergovernmental Panel on Climate Change reports.
- Some chapters in this publication draw from existing scientific literature that used climate projections from the 2007 IPCC reports (CMIP3 database). In the mid- 21st century (2040-2060), CMIP3 and CMIP5 temperature projections are similar, whereas CMIP5 precipitation projections are slightly wetter than those in CMIP3.

Box. 3.3—Summary: Historical and projected climate for the NRAP Western subregion

- Climatologically, this mountainous region sits at the boundary between warm, wet, maritime airflows from the Pacific Ocean, and cooler, drier airflows from Canada.
- Changes in climate affecting mountain snowpack will have important hydrological implications.
- Over the historical period of record (1895-2012), the annual mean monthly minimum temperature increased by about 3.0 °F, while the annual mean monthly maximum temperature increased by about 0.6 °F. During the same period, annual mean monthly precipitation increased slightly, by an average of about 0.1 per month.
- Temperature is projected to increase 5-10 °F by 2100, including increases in both the annual mean monthly minimum and annual mean monthly maximum.
- Mean monthly maximum and minimum temperatures are projected to increase for all seasons. The mean monthly minimum temperature (spring and autumn) and the mean monthly maximum temperature (winter) may rise above freezing.
- Seasonal precipitation is projected to be slightly wetter in winter and spring, slightly drier in summer.

Box. 3.4—Summary: Historical and projected climate for the NRAP Central subregion

- Climatologically, this mountainous region sits at the boundary between warm, wet, maritime airflows from the Pacific Ocean, and cooler, drier airflows from Canada.
- Changes in climate affecting mountain snowpack will have important hydrological implications.
- Over the historical period of record (1895-2012), the annual mean monthly minimum temperature increased by about 2.6 °F, while the annual mean monthly maximum temperature increased by about 1.3 °F.
- By 2100, temperature is projected to increase 6-12 °F for the annual mean monthly minimum, and 5-11 °F for the annual mean monthly maximum.
- Mean monthly maximum and minimum temperatures are projected to increase for all seasons. The mean monthly minimum temperature (spring and autumn) and the mean monthly maximum temperature (winter) may rise above freezing.
- Seasonal precipitation is projected to be slightly wetter in winter and spring, slightly drier in summer.

Box. 3.5—Summary: Historical and projected climate for the NRAP Eastern subregion

- Climatologically, this mountainous region sits at the boundary between warm, wet, maritime airflows from the Pacific Ocean, and cooler, drier airflows from Canada.
- Changes in climate affecting mountain snowpack will have important hydrological implications.
- Over the historical period of record (1895-2012), the annual mean monthly minimum temperature increased by about 2.2 °F, while the annual mean monthly maximum temperature increased by about 1.8 °F. During the same period, annual mean monthly precipitation was unchanged.
- By 2100, temperature is projected to increase 6-11 °F for the annual mean monthly minimum, and 5-11 °F for the annual mean monthly maximum.
- Mean monthly maximum and minimum temperatures are projected to increase for all seasons. The mean monthly minimum temperature (spring and autumn) and the mean monthly maximum temperature (winter) may rise above freezing.
- Seasonal precipitation is projected to be slightly wetter in winter and spring, slightly drier in summer.

Box. 3.6—Summary: Historical and projected climate for the NRAP Greater Yellowstone subregion

- In the Greater Yellowstone Ecosystem subregion, climatic variability is strongly influenced by interactions with topography, elevation, and aspect.
- Over the historical period of record (1895-2012), the annual mean monthly minimum temperature increased by about 2.9 °F, while the annual mean monthly maximum temperature increased by about 1.2 °F.
- By 2100, temperature is projected to increase 5-10 °F for the annual mean monthly minimum, and 7-12 °F for the annual mean monthly maximum.
- Annual mean monthly precipitation is projected to increase slightly by 2100, although projections for precipitation have high uncertainty compared to temperature.
- Projected winter maximum temperature is projected to increase above freezing in the mid-21st century. Projected summer temperature is projected to increase 5 °F by 2060 and 10 °F by 2100.

Box. 3.7—Summary: Historical and projected climate for the NRAP Grassland subregion

- Warming trends indicate that future climate will be similar to the area south of this region.
- Even with little or no change in precipitation, there is the potential for summer drying or drought due to the increased heat and increased evapotranspiration.
- Early snow melt from the west will imply changes in streamflow, with implications for streamflow and temperature, therefore reservoir management and stream ecology.
- There is a pattern of a drier west and wetter east, with the average of climate models showing a slight shift for more of the wetter east.

DRAFT

Box 5.1—Effects of Climate Change on Arctic Grayling

Arctic grayling (*Thymallus arcticus*) are a salmonid species native to Arctic Ocean drainages in North America and northern Eurasia, and Pacific Ocean basins in Alaska and British Columbia, with two disjunct inland groups in Michigan (now extinct) and the upper Missouri River basin in Montana and Wyoming (Kaya 1992, Scott and Crossman 1998). Within its range in Montana and Wyoming, grayling was represented by four adfluvial (lake living, stream spawning) populations in the Red Rock and Big Hole River basins, and by fluvial populations widely but irregularly distributed in the Missouri River basin above the Great Falls (USFWS 2014). Relative to this historical distribution, the current range and abundance of Arctic grayling have decreased greatly. Lacustrine populations are more common recently because of introductions inside and outside its historical range (Kaya 1992). Declines of riverine populations were caused by habitat degradation and fragmentation, inundation by reservoirs, overharvest, and interactions with nonnative fish, particularly rainbow trout, brook trout, and brown trout (Kaya 1992). The distinct population segment in the upper Missouri River basin was petitioned for listing under the ESA, but has not been listed (USFWS 2014). Recent activities focused on increasing instream flows, improving habitat connectivity, supplementing existing populations, and founding new populations (some in historically fishless lakes) appear to have arrested declines in most grayling populations in this basin (USFWS 2014).

Arctic grayling are regarded as a cold-water species (Elliott and Elliott 2010). Grayling life histories are often characterized by extensive movements to habitats for growth, reproduction, and overwintering, especially in riverine systems (Northcote 1995). Access to thermal refugia may be important to population persistence at the southern extreme of its range; many of the fluvial systems that retain grayling in the upper Missouri River basin are heavily influenced by groundwater inputs (USFWS 2014). Although the thermal preferences of this species are uncertain, the upper thermal limits of grayling in the Big Hole River basin are comparable to those of cutthroat trout (Johnstone and Rahel 2003; Lohr et al. 1996; Wagner et al. 2001).

The influence of climate change on Arctic grayling is uncertain, because data are lacking on this topic, but their reliance on mobility emphasizes the need for connectivity among complementary habitats. Ameliorating the effects of low summer discharge has been a target of management (USFWS 2014), but this problem may become more severe and difficult to overcome if projected climate-related changes in discharge (chapter 4) are realized. Many of the extant populations are in high-elevation lakes that are presumed to be less vulnerable to the effects of warming or reduced streamflow (USFWS 2014).

Responses to warmer stream temperatures may be complex. With warming summer water temperatures, initiation of the spawning season advanced by more than three weeks over the course of four decades in a population of adfluvial European grayling (*T. thymallus*) in Switzerland (Wedekind and Küng 2010). Paradoxically, earlier spawning meant a longer exposure of incubating eggs and fry to colder spring water temperatures, patterns that coincide with substantial declines in the number of female spawners. This pattern may reflect declining survival of juvenile fish (Wedekind and Küng 2010) or sex-specific vulnerability to changes in thermal regimes (Pompini et al. 2013). Whether this is symptomatic of a broader trend or case study is unknown, but warming stream temperatures, population declines, and sex ratio shifts in salmonids have been observed elsewhere in Europe (Hari et al. 2006). Regardless, the few Arctic grayling populations extant in their historical range are likely to remain the focus of management efforts (USFWS 2014), and the continuation of these efforts may play a significant role in the near-term persistence of grayling in the upper Missouri River basin. At longer time scales, the "climate velocity" associated with warming of low-gradient stream habitats (Isaak and Rieman 2013) may challenge our ability to maintain recent improvements in the conservation status of this species.

Box 5.2—Effects of Climate Change on Fish Species in the Grassland Subregion

Several native fish species are found in the Grassland subregion of NRAP. Located in the eastern portions of the Custer-Gallatin National Forest and the Dakota Prairies National Grassland, these species have received little scientific study and monitoring compared to cold-water salmonids and warm-water sportfish. Many prairie streams have never been sampled or are sampled sporadically at best (S. Barndt, personal observation; G. Gallinat, South Dakota Fish and Game, personal communication; Montana Fish, Wildlife and Parks database). As a result, fish distribution and aquatic habitat are poorly understood at all spatial scales. However, as in most dendritic stream networks, small streams constitute the majority of fish habitat, and species favoring those habitats are likely to be the most common. Small streams may also provide seasonal habitats for spawning and rearing of species favoring larger streams, rivers, and lakes (Thornbrugh and Gido 2009).

Prairie streams are dynamic, tending to vary between periods of floods and flow intermittency, among and sometimes within years (Dodds et al. 2004). Extirpation and recolonization of local habitats by fish species is typical (Falke et al. 2012), and patterns of occupancy by fish species can be considered in the context of metapopulation theory, in which the presence of subpopulations of each species depends on habitat connectivity and duration (Falke and Fausch 2010). Although it is typical for prairie streams to be reduced to sets of disconnected pools in some years, this pattern is more prevalent in agricultural landscapes where surface and groundwater withdrawals are common (Gido et al. 2010; Falke et al. 2011). Climate change is expected to exacerbate these patterns (Jaeger et al. 2014) and lead to greater extremes, including severe droughts and more intense storms and wet intervals in plains and dryland systems (Michels et al. 2007; Starks et al. 2014).

Projecting the responses of prairie fishes to climate change is complicated by difficulty in identifying habitat preferences, partly because many fish species are habitat generalists (Wuellner et al. 2013) and because the dynamics of prairie streams lead to difficulties in predicting interannual habitat occupancy (Falke et al. 2012). Prairie fish assemblages in the analysis area are represented by four species guilds—northern headwaters, darter, madtom, and turbid river guilds (Clingerman et al. 2012)—that are likely to differ in their vulnerability to climate change. Annual air temperature and various indicators of streamflow are strong predictors of presence for the northern headwaters, madtom, and darter guilds.

Observed and modeled patterns allow some inferences to be made about climate vulnerability and adaptation for prairie fishes. First, the northern headwaters guild may be most vulnerable to increasing temperature, as well as to climate-related decreases in ground water recharge (Clingerman et al. 2012). This guild includes the northern redbelly dace (*Chrosomus eos*), a sensitive species in the U.S. Forest Service Northern Region, which occupies small, stable, and relatively cool headwater streams (Stasiak 2006). Accurate mapping of habitat types, species assemblages present in them, and monitoring of habitat conditions will help refine possible climate change effects on both habitat and species, as well as define appropriate management responses. Buffering variations in flow extremes (e.g., securing instream flows) and encouraging the presence of riparian vegetation are practical responses to climate change where the northern headwaters guild is present. Although the other prairie fish guilds seem less vulnerable to changes to temperature, all are influenced by amount and timing of flow. Therefore, climate change adaptation strategies for the northern headwater guild should also be appropriate for the other guilds. Finally, all guilds are currently at risk, and may become more so if flow regimes become more variable, especially if migration barriers prevent fish from moving along stream courses. Many of these species may be ill-adapted to surmounting either height or velocity barriers (Rosenthal 2007; Perkin and Gido 2012). Therefore, removing barriers to fish passage between habitats is a prudent adaptation strategy. This strategy carries the risk of allowing nonnative species to invade, so it should be implemented within the larger conservation context of a site (Fausch et al. 2009).

Box 6.1—Using historical range and variability to assess and adapt to climate change

To effectively implement ecosystem-based management, land managers often find it necessary to obtain a reference or benchmark to represent the conditions that describe fully functional ecosystems (Cissel et al. 1994, Laughlin et al. 2004). Contemporary conditions can be evaluated against this reference to determine status, trend, and magnitude of change, and to design treatments that provide society with valuable ecosystem services while returning declining ecosystems to a more sustainable condition (Hessburg et al. 1999, Swetnam et al. 1999). Reference conditions are assumed to represent the dynamic character of ecosystems and landscapes, varying across time and space (Swanson et al. 1994, Watt 1947).

The concept of *historical range and variability* (HRV) was introduced in the 1990s to describe past spatial and temporal variability of ecosystems (Landres et al. 1999), providing a spatial and temporal foundation for planning and management. HRV has sometimes been equated with “target” conditions (Harrod et al. 1999), although targets can be subjective and somewhat arbitrary, representing only one possible situation from a range of potential conditions (Keane et al. 2009). HRV encompasses a full range of conditions that have occurred across multiple spatiotemporal scales.

HRV represents a broad historical envelope of possible ecosystem conditions—burned area, vegetation cover type area, patch size distribution—that can provide a time series of reference conditions. This assumes that (1) ecosystems are dynamic, not static, and their responses to changing processes are represented by past variability; (2) ecosystems are complex and have a range of conditions within which they are self-sustaining, and beyond this range they transition to disequilibrium (Egan and Howell 2001); (3) historical conditions can serve as a proxy for ecosystem health; (4) the time and space domains that define HRV are sufficient to quantify observed variation; and (5) the ecological characteristics being assessed for the ecosystem or landscapes match the management objective (Keane et al. 2009).

The use of HRV has been challenged because a warmer climate may permanently alter the environment of ecosystems beyond what was observed under historical conditions (Millar et al. 2007a), particularly altered disturbance processes, shifts in plant species distribution, and hydrologic dynamics (Notaro et al. 2007). However, a critical evaluation of possible alternatives suggests that HRV might still be the most viable approach in the near term because it has relatively low uncertainty.

An alternative to HRV is forecasting future variations of landscapes under changing climates using complex empirical and mechanistic models. However, the range of projections for future climate from the commonly used global climate models may be greater than the variability of climate over the past three centuries (Stainforth et al. 2005). This uncertainty increases when we factor in projected responses to climate change through technological advances, behavioral adaptations, and population growth (Schneider et al. 2007). Moreover, the variability of climate extremes, not the gradual change of average climate, will drive most ecosystem response to climate-mediated disturbance and plant dynamics (Smith 2011) that are difficult to project. Uncertainty will also increase as climate projections are extrapolated to the finer scales and longer time periods needed to quantify *future range and variability* (FRV) for landscapes (Araujo et al. 2005, Keane et al. 2009).

Given these cumulative uncertainties, time series of HRV may have lower uncertainty than simulated projections of future conditions, especially because large variations in past climates are already captured in the time series. It may be prudent to wait until simulation technology has improved enough to create credible FRV landscape pattern and composition, a process that may require decades. In the meantime, attaining HRV would be a significant improvement in the functionality of most ecosystems in the Northern Rockies, and would be unlikely to result in negative outcomes from a management perspective. As with any approach to reference conditions, HRV is useful as a guide, not a target, for restoration and other management activities.

Box 7.1—Rangeland definitions used by different federal agencies

U.S. Forest Service

Land primarily composed of grasses, forbs, or shrubs. This includes lands vegetated naturally or artificially to provide a plant cover managed like native vegetation and does not meet the definition of pasture. The area must be at least 1.0 acre in size and 120.0 ft wide.
(USDA FS 2010)

Bureau of Land Management

Land on which the indigenous vegetation (climax or natural potential) is predominantly grasses, grass-like plants, forbs, or shrubs and is managed as a natural ecosystem. If plants are introduced, they are managed similarly. Rangelands include natural grasslands, savannas, shrublands, many deserts, tundra, alpine communities, marshes, and wet meadows.
(Society for Range Management 1998)

Natural Resources Conservation Service

A land cover/use category that includes land on which the climax or potential plant cover is composed principally of native grasses, grass-like plants, forbs or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland. This would include areas where introduced hardy and persistent grasses, such as crested wheatgrass, are planted and practices such as deferred grazing, burning, chaining, and rotational grazing, are used with little or no chemicals/fertilizer being applied. Grasslands, savannas, many wetlands, some deserts, and tundra are considered to be rangeland. Certain low forb and shrub communities, such as mesquite, chaparral, mountain shrub, and pinyon-juniper, are also included as rangeland”
(USDA 2007).

Box 10.1—Subregional assessment of climate change effects on recreation

The broad links between climate, ecological changes, and recreation behavior that form the basis of the activity category assessments are designed to be generally applicable to all locations in the Northern Rockies region. However, in a region that encompasses parts of five states and stretches hundreds of miles from east to west, significant subregional heterogeneity in climate effects may exist. The five subregions (Western Rockies, Central Rockies, Eastern Rockies, Grassland, Greater Yellowstone Area [GYA]) represent a wide variety of geographic and ecological features, and each has distinctive recreation opportunities that may be sensitive to climate changes. Assessing differences between the subregions can yield more geographically specific information about the effects of climate on recreation.

Table 10.B1 summarizes national forest visits by primary activity category for each subregion. Warm-weather activities are the most common category for all subregions, but there are significant differences in the relative importance of each activity category. Snow-based recreation is relatively more important in the Central Rockies, Eastern Rockies, and GYA subregions where there are multiple sites with consistently viable snow seasons and developed ski areas. In contrast, much less snow-based recreation (as a share of total visits) occurs in the West Rockies and Grassland subregions. Wildlife recreation activities (hunting, fishing, wildlife viewing) are most important in the Western Rockies and Grassland, although the Central Rockies, Eastern Rockies, and GYA see a significant minority of visitors engaging in these activities. Forest product gathering and water-based (not fishing) activities represent a small share of visits in all subregions, but the Grassland subregion sees almost no visitation for these activities.

The differences in activity participation also suggest that climate will have different effects on recreation in each subregion. The largest differences in activity participation are for snow-based activities; these activities are also the most likely to see negative impacts due to warming temperatures and decreased precipitation as snow. The Grassland subregion and to a lesser extent the Western Rockies have relatively low exposure to this effect because snow-based recreation is less prominent. The Central Rockies, Eastern Rockies, and GYA have higher participation in snow-based activities that could be exposed to climate change, although it is unclear to what extent snow-based sites will experience changes that degrade conditions for snow-based activities.

Other differences between subregions likely depend on differences in climate effects between subregions. For example, one subregion could experience warming that increases the incidence of extreme heat days, which has a negative impact on warm-weather recreation, whereas another sub-region experiences warming that extends the warm-weather season without a significant increase in the incidence of extreme heat days.

Box 10.2—Climate change in the Greater Yellowstone Area and Glacier National Park

The Greater Yellowstone Area (GYA) provides a wide range of recreation opportunities. The GYA is comprised of two national parks (Yellowstone, Grand Teton), parts of six national forests (Beaverhead-Deerlodge, Bridger-Teton, Caribou-Targhee, Custer, Gallatin, Shoshone), and other federally administered protected areas (John D. Rockefeller Memorial Parkway, National Elk Refuge, Red Rock Lakes National Wildlife Reserve [NWR]). These areas offer the full spectrum of recreation opportunities, from developed and urban settings to wilderness and primitive sites. Glacier National Park (GNP), which straddles the Western and Eastern Rockies subregions of NRAP in northwestern Montana, also provides a broad range of recreation opportunities comparable to those in the GYA.

Recreation visitation to federal units within the GYA and Glacier National Park is summarized in table 10.B2. Yellowstone National Park (YNP) and Grand Teton National Park (GTNP) respectively receive an average of 3.4 million and 2.6 million visitors annually. For both parks, the most common activities included viewing wildlife and viewing scenery and natural features. A majority of YNP visitors also indicated that they engaged in developed camping, walking or hiking, and visiting museums and visitor centers, while GTNP visitors indicated pleasure driving and walking or hiking as common activities (NPS 2006). Wildlife viewing is also an important activity for visitors to the Red Rock Lakes NWR and the National Elk Refuge, although these sites receive only a fraction of the visitors compared with the national parks (NPS 2006). Sightseeing is the dominant activity for the 2.1 million annual visitors in GNP.

National forests in the GYA receive a combined 7.6 million visitors annually. The most popular activity for visitors varies across forests. In the Gallatin and Caribou-Targhee National Forests, hiking and walking are the most popular activities, whereas downhill skiing is the most popular activity in Bridger-Teton and Custer National Forests. In Beaverhead-Deerlodge National Forest, hunting is the most popular activity (32 percent of visitors) and in Shoshone National Forest, viewing natural features is the most popular activity (25 percent of visitors).

Most of the general assessment of climate change effects on recreation in the Northern Rockies applies to the GYA and GNP, although the different activity profile means that exposure to the effects of climate change differs in this subregion. Visitation is dominated by warm-weather visits; 80 percent of visits to YNP and GTNP are during the June-September period. An additional 11 percent of visits occur during the “shoulder” season months of May and October. Warmer temperatures are expected to increase warm-weather recreation; earlier and later season periods of snow- and ice-free sites in the parks may encourage additional off-peak visitation. Some visitors may also substitute early- or late-season visits to avoid extreme summer heat. However, seasonal shifts in visitation may be constrained by summer vacation months determined by academic calendars.

Changes in the distribution and abundance of wildlife may affect recreation visitation and enjoyment due to the large number of YNP and GTNP visitors that engage in wildlife viewing. However, many climate-related changes in target wildlife species are ambiguous because of complex interactions between species, vegetation and forage opportunities, and disturbances (see chapter 9).

Other popular activities, such as driving for pleasure on roads and viewing scenery and special features (e.g., geysers and thermal features in YNP, driving the Going-to-the-Sun road in GNP), may be more or less sensitive to climate changes. In some cases the qualities, characteristics, and features that draw visitors to these activities have a limited connection to climate changes. However, features such as glaciers (in GNP) and snow-capped mountains are a particular draw for some visitors, and visitation tied to such features will likely be affected. Longer warm-weather seasons will likely increase access to roads and sites inaccessible when snow and ice is present, which would have a positive effect on visitation. In addition, wildfire and other disturbances can affect site access and the desirability of visitation to fire-affected sites. For example, wildfires in YNP are associated with decreased visitation in the subsequent month, but there does not appear to be a lasting negative effect on visitation or wildfire occurrence (Duffield et al. 2013).

Box 12.1. National Park Service lands in the Northern Rockies emphasize preservation and management of cultural resources

The National Park Service was created by Congress through the National Park Service Organic Act of 1916, whereby the Agency would allow “access to parks for the public enjoyment of cultural resources while ensuring their protection” (NPS 2011b). Specifically, a cultural resource is considered to be “an aspect of cultural system that is valued by or significantly representative of a culture, or that contains significant information about a culture” (NPS 2015b). Cultural heritage and its preservation are emphasized in the agency’s Cultural Resources, Partnerships and Science directorate, with goals to:

- Preserve cultural resources in cooperation with Indian tribes, Alaska Native villages and corporations, Native Hawaiian organizations, states, territories, local governments, nonprofit organizations, property owners, individuals, and other partners.
- Provide leadership in research and use of advanced technologies to improve the preservation of the nation’s cultural heritage.
- Establish standards and guidance for managing cultural resources within the National Park System and communities nationwide.
- Enhance public understanding and appreciation for the nation’s cultural heritage.

Cultural Resources of National Parks in the Northern Rockies

Glacier National Park

Glacier National Park has six National Historic Landmarks and 350 structures listed in the National Register of Historic Places. Archaeological resources found in the park include prehistoric campsites, mining claims and homesteads. Cultural landscapes in the park include the Going-to-the-Sun-Road, Chief Mountain and Headquarters Historic District.

Grand Teton National Park

Historical sites in Grand Teton National Park pre-date creation of the park, and many structures are found in the National Register of Historic Places. Some structures include homestead remnants from the people who settled in the Jackson Hole area and ranches. Several of these structures have been incorporated in the park and restored to their natural condition. Mining Ditch is an early structure, still in the park today, that carried water in the area of Schwabacher’s Landing. Cunningham Cabin, an early piece of settlement, can be found in the northern area of Jackson Hole. Menor’s Ferry, created by D. Menor, was operational until 1927, taking passengers across the Snake River.

Yellowstone National Park

Yellowstone National Park has been preserved not only for biodiversity but also for information about past human activities and significant archaeological and cultural resources contained within the park. Some historical structures and sites include: (1) Obsidian Cliff where obsidian was first used for tool making over 11,000 B.P., (2) Yellowstone Lake which still has intact cultural deposits from over 9,000 B.P., (3) Mammoth Hot Springs which includes the Mammoth Post Office and Roosevelt Arch from the late 1800s, and (4) the town site of Cinnabar, Montana which was established in 1883 as the last stop on the Northern Pacific Railroad line to Yellowstone Park. The potential effects of climate change on cultural resources have been described for Big Hole National Battlefield, Montana (NPS 2011a). A warmer climate will complicate the goal of management to restore and maintain the battlefield in a biological condition representative of 1877. Scientific understanding of climate change effects provides a foundation for reconciling biological effects with management goals based on historical conditions.

Appendix 1A

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Acronyms:

- *USFS: US Forest Service*
- *USFWS: US Fish and Wildlife Service*
- *NPS: National Park Service*

NRAP Workshop Participants

Bozeman, MT October 9 – 10, 2014

Vegetation

- Andrew Hasen – Montana State University, Ecology Department
- Ann Rodman – Yellowstone National Park, Branch Chief, Physical Sciences
- Bob Keane – USFS Rocky Mountain Research Station, Research Ecologist
- Ben Poulter – Montana State University, Climate Change Modeler
- Cavan Fitzsimmons – Custer/Gallatin National Forest, Hebgen District Ranger
- Jill McMurray – USFS R1/R4, Air Quality
- Julie Shea – Custer/Gallatin National Forest, Fire Ecologist
- Keith Konen – Gallatin National Forest, Silviculturist
- Kelly McCloskey – Grand Teton National Park, Ecologist
- Mary Mahalovich – USFS Rocky Mountain Research Station, Regional Geneticist
- Traute Parrie – Custer/Gallatin National Forest, Beartooth District Ranger

Non-Forest Vegetation

- Denice Swanke
- Diane Abendroth – Grand Teton National Park, Fire Ecologist
- Jeff Dibenedetto – Custer National Forest, Ecologist
- Jessi Salix – Beaverhead-Deerlodge National Forest, Botany
- Kevin Suzuki – Beaverhead-Deerlodge National Forest, Weeds/Botany
- Mary Manning – USFS Region 1 Regional Office, Regional Ecologist
- Matt Reeves – USFS Rocky Mountain Research Station, Research Ecologist
- Rose Lehman – Caribou-Targhee National Forest, Forest Botanist
- Susan Lamont – Gallatin National Forest, Weeds
- Travis Ziehl – Teton County, Assistant Supervisor Weed & Pest District
- Walt Allen – Custer/Gallatin National Forest, Gardiner District Ranger

Wildlife

- Amie Shovlain – Beaverhead Deerlodge National Forest, Wildlife
- Jeff Burrell – Wildlife Conservation Society, Northern Rockies and Yellowstone Program
- Jodie Canfield – Gallatin National Forest, Wildlife
- Kevin McKelvey – USFS Rocky Mountain Research Station, Wildlife Ecologist
- Kristin Legg – Greater Yellowstone Network, Inventory Monitoring Coordinator
- Mary Erickson – Custer/Gallatin National Forest, Forest Supervisor
- Polly Buotte – University of Idaho, Research Associate, Geography
- Rachel Feigley – Custer/Gallatin National Forest, Wildlife Biologist
- Rob Mickelson – Caribou-Targhee National Forest, Resource Staff Officer
- Sue Consolo Murphy – Grand Teton National Park, Chief of Resources

Hydrology

- Alex Sienkiewicz – Custer/Gallatin National Forest, Yellowstone District Ranger
- Andy Ray – NPS Inventory and Monitoring, Hydrologist
- Dave Thoma – NPS Inventory and Monitoring, Hydrologist
- Ed Snook – USFS Region 1 Regional Office, Regional Hydrologist
- Eric Winthers – Bridger-Teton National Forest, Soil and Water Program Manager
- Gretchen Hurley – BLM, Geologist
- Karri Cary – Shoshone National Forest, Hydrologist
- Mike Tercek – Yellowstone National Park Contractor, Ecologist

- Pam Fletcher – Beaverhead-Deerlodge National Forest, Forest Inventory & Monitoring Coordinator
- Richard Raione – Bridger-Teton National Forest, Greys River District Ranger

Fisheries

- Brad Shepard – Wildlife Conservation Society
- Dan Isaak – USFS Rocky Mountain Research Station, Fisheries Scientist
- Dave Hallac – Yellowstone National Park
- Gary Tabor – Center for Large Landscape Conservation , Director
- Jessi Kershner – EcoAdapt, Lead Scientist
- Lisa Stoeffler – Custer/Gallatin National Forest, Bozeman District Ranger
- Michael Young – USFS Rocky Mountain Research Station, Fisheries Biologist
- Molly Cross – Wildlife Conservation Society
- Robert Al-Chokhachy – USGS Northern Rocky Mountain Science Center, Research Fish Biologist
- Scott Barndt – Custer-Gallatin National Forest, Ecosystem Staff Officer
- Shawn Anderson – Shoshone National Forest, Forest Fish Biologist
- Yvette Converse – Great Northern Landscape Conservation Cooperative/NPS, Co-Coordinator

Recreation

- Jamie Schoen – Bridger-Teton National Forest, Archeologist
- Jane Ruchman – Custer/Gallatin National Forest, Landscape Architect Developed Recreation
- Krista Gebert – USFS Region 1 Regional Office, Regional Economist
- Megan Lawson – Headwaters Economics
- Natalie Little – USFS Region 4, Climate Change Coordinator
- Travis Warziniack – USFS Rocky Mountain Research Station, Research Economist
- Trey Schillie – USFS Region 2, Regional Inventory and Monitoring and Climate Change Coordinator
- Virginia Kelly – Greater Yellowstone Coordinating Committee, Executive Coordinator

Bismarck, ND October 15 – 16, 2014

Non-Forest Vegetation

- Adnan Akyuz – North Dakota State University, Climatologist
- Bernadette Braun – Dakota Prairie Grassland, Range
- Chad Prosser – Dakota Prairie Grassland, Weeds
- Karen Dunlap – Dakota Prairie Grassland, NEPA, Appeals, Litigation
- Kurt Hansen – Custer National Forest – Sioux Ranger District, District Ranger
- Libby Knotts – Dakota Prairie Grassland, Botany
- Mary Manning – USFS Region 1 Regional Office, Regional Ecologist
- Meghan Dinkins – Dakota Prairie Grassland, Wildlife Biologist

Hydrology

- Alison Schlag – Dakota Prairie Grassland, Hydrology
- Andy Efta – Custer National Forest, Hydrology, Soils
- Karen Ryberg – USGS North Dakota Water Science Center, Statistician
- Mike Philbin – BLM, Montana, Physical Scientist
- Pam Fletcher – Beaverhead-Deerlodge National Forest, Forest Inventory & Monitoring Coordinator
- Rick Nelson – Plains & Prairie Pothole Landscape Conservation Cooperative, Coordinator
- Scott Barndt – Custer-Gallatin National Forest, Ecosystem Staff Officer

- Steven Krentz – US Fish and Wildlife Service, Mountain Prairie Region, Fisheries Biologist
- Robert Swithers – Dakota Prairie Grassland, Staff Officer
- Kevin Shelley – US Fish and Wildlife Service, Ecological Services
- Babete Anderson – Dakota Prairie Grassland, Public Affairs Officer
- Meredith Webster – USFS Region 1 Regional Office, Regional Soils Scientist

Missoula, MT October 20 – 21, 2014

Vegetation

- Barry Bollenbacher – USFS Region 1 Regional Office, Regional Silviculturist
- Bob Keane – USFS Rocky Mountain Research Station, Research Ecologist
- Bruce Erikson – Lolo National Forest, Silviculturist
- C. Alina Cansler – University of Washington, Fire and Mountain Ecology Lab
- Cheri Hartless – Bitterroot National Forest, Silviculturist
- Elaine Sutherland – USFS Rocky Mountain Research Station, Biologist
- Greg Denitto – USFS Region 1 Regional Office, Forest Pathologist
- Heidi Trechsel – Flathead National Forest, Silviculturist
- Jeremy Amberson – Bitterroot Restoration Committee
- Jerry Kruger – Bitterroot National Forest, Planning Staff Officer
- LaWen Hollingsworth – Fire Modelling Institute, Spatial Fire Analyst
- Linda Donner – Flathead National Forest, IDT Leader
- Melissa Hayes – Montana Forest Restoration Committee, Coordinator
- Melissa Jenkins – Flathead National Forest, Forest Silviculturist
- Rob Carlin – Flathead National Forest, Forest Staff Officer
- Shelagh Fox – USFS Region 1 Regional Office, Reforestation Specialist
- Sheryl Gunn – Lolo National Forest, Silviculturist

Non-Forest Vegetation

- Chantelle Delay – Flathead National Forest, Botany
- Gil Gale – Bitterroot National Forest, Weeds
- Holger Jensen – USFS Region 1 Regional Office, Regional Range Program Leader
- Karen Stockmann – Lolo National Forest, Weeds/Botany
- Mary Manning – USFS Region 1 Regional Office, Regional Ecologist
- Matt Reeves – USFS Rocky Mountain Research Station, Research Ecologist
- Susan Rinehart – USFS Region 1 Regional Office, Native Plant Program Manager
- Tara Carolin – Glacier National Park, Botanist

Wildlife

- Alan Dohmen – USFS Region 1 Regional Office, Wildlife Ecologist
- Greg Gustina – Lolo National Forest, Planning and Preparation Staff Officer
- Kari Eneas – Confederate Salish and Kootenai Tribes, Wildlife Biologist
- Kuennen Reed – Flathead National Forest, Wildlife
- Len Broberg – University of Montana, Environmental Studies
- Melly Reuling – Center for Large Landscape Conservation, Senior Conservation Officer
- Peter Nelson – Defenders of Wildlife, Senior Policy Advisor
- Polly Buotte – University of Idaho, Research Associate, Geography
- Renate Bush – USFS Region 1 Regional Office, Inventory and Analysis
- Tom Reed – Lee Metcalf National Wildlife Refuge, Manager
- Whisper Means – Confederate Salish & Kootenai Tribes, Wildlife Biologist

Hydrology

- Amber Richardson – Bitterroot National Forest, Forest Engineer
- Caryn Miske – Flathead Basin Commission, Executive Director
- Charlie Luce – USFS Rocky Mountain Research Station, Research Hydrologist
- Chris Brick – Clark Fork Coalition, Science Director
- Craig Kendall – Flathead National Forest, Forest Hydrologist
- Ed Snook – USFS Region 1 Regional Office, Regional Hydrologist
- Nate Dieterich – Flathead National Forest, Forest Hydrologist
- Regan Nelson – Crown of the Continent Conservation Initiative

Fisheries

- Anne Carlson – Wilderness Society
- Aubree Benson – Lolo National Forest, Fisheries Biologist
- Bruce Farling – Trout Unlimited
- Cameron Thomas – USFS Region 1 Regional Office, Regional Aquatic Ecologist
- Clint Muhlfeld – USGS Northern Rocky Mountain Science Center, Research Fish Biologist
- Dan Brewer – US Fish and Wildlife Service, Fisheries Biologist
- Dan Isaak – USFS Rocky Mountain Research Station, Research Fisheries Scientist
- David Schmetterling – Montana Fish, Wildlife and Parks, Fisheries Biologist
- Erin Sexton – University of Montana, Research Scientist
- Michael Young – USFS Rocky Mountain Research Station, Research Fisheries Biologist
- Pat Van Eimeren – Flathead National Forest, Fisheries
- Robert Davies – Flathead National Forest, Glacier View Ranger District Ranger
- Ryan Kovach – USGS NOROCK, Fisheries Biologist
- Sims Wade – Idaho Panhandle National Forest, Aquatic Ecologist
- Wade Fredenberg – Montana Ecological Services SubOffice, Fisheries Biologist
- Scott Spaulding – USFS Region 1 Regional Office, Fisheries Biologist

Recreation

- Byron Stringham – Lolo National Forest, Zone Landscape Architect
- Carl Davis – USFS Region 1 Regional Office, Regional Archeologist
- Cynthia Manning – USFS Region 1 Regional Office, Social Scientist
- Jeff Ward – USFS Region 1 Regional Office, Recreation Business Program Manager
- Krista Gebert – USFS Region 1 Regional Office, Regional Economist
- Marsha Moore – Flathead National Forest, Recreation/Wilderness Planner
- Michael Hand – USFS Rocky Mountain Research Station, Research Forester
- Rosa Nygaard – USFS Region 1 Regional Office, Natural Resource Information Coordinator
- Rusty Wilder – Lolo National Forest, Infrastructure and Operations
- Keith Stockmann – USFS Region 1 Regional Office, Economist

Coeur d’Alene, ID October 23 – 24, 2014

Vegetation

- Art Zack – Idaho Panhandle National Forest, Silviculturist, Ecologist
- Barry Bollenbacher – USFS Region 1 Regional Office, Regional Silviculturist
- Bob Boeh – Idaho Forest Group
- Carol McKenzie – Idaho Panhandle National Forest, Deputy Forest Supervisor
- Christopher Schnepf – University of Idaho Extension, Educator - Forestry
- Jason Jerman – Idaho Panhandle National Forest, Silviculturist
- Jessie Grossman – Yaak Valley Forest Council, Forest Watch Coordinator
- Kevin Greenleaf – Kootenai Tribe of Idaho, Environmental Director
- Lee Pederson – USFS Region 1 Regional Office, Forest Entomologist

- Malcolm Edwards – Kootenai National Forest, Libby District, District Ranger
- Megan Strom – Kootenai National Forest, Silviculturist
- Mike Giesey – Kootenai National Forest, Silviculturist
- Pat Behrens – Idaho Panhandle National Forest, Silviculturist
- Paul Zambino – USFS Region 1 Regional Office, Plant Pathologist

Non-Forest Vegetation

- Derek Antonelli – Idaho Native Plant Society
- Jennifer Costich – Thompson – Idaho Panhandle National Forest, Botanist
- LeAnn Abell – BLM, Botanist
- Many Manning – USFS Region 1 Regional Office, Regional Ecologist
- Megan Lucas – Clearwater/Nez Perce National Forest, Hydrologist/Soils Specialist
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Wildlife

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- JJ Teare – Idaho Department Fish and Game, Regional Supervisor
- Kevin McKelvey – USFS Rocky Mountain Research Station, Wildlife Ecologist
- Leona Svancara – Idaho Department of Fish and Game
- Lynn M Johnson – Kootenai National Forest, Wildlife Biologist
- Polly Buotte – University of Idaho, Research Associate – Geography
- Rema Sadak – Clearwater/Nez Perce National Forest, Wildlife

Hydrology

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- Ed Snook – USFS Region 1 Regional Office, Regional Hydrologist
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- Shandra Dekome – Idaho Panhandle National Forest, Ecosystem Staff Officer

Fisheries

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- Greg Hoffman – US Army Corps of Engineers Libby Dam Kootenai River, Fisheries Biologist
- Jessie Kershner – EcoAdapt, Lead Scientist
- Jim Fredericks – Idaho Fish and Game
- Kathrine Thompson – Clearwater/Nez Perce National Forest, Fisheries
- Michael Young – USFS Rocky Mountain Research Station, Research Fisheries Biologist
- William Young – Idaho Panhandle National Forest, Fisheries

Recreation

- Diane Jones – Clearwater/Nez Perce National Forest, Landscape Architect
- Krista Gebert – USFS Region 1 Regional Office, Regional Economist
- Loretta Stevens – Kootenai National Forest/Confederated Salish and Kootenai Tribes, Tribal Liaison
- Morai Helfen – Idaho Panhandle National Forest, Forest Landscape Architect
- Timory Peel – Kootenai National Forest, Forest Planner
- Pam Fletcher – Beaverhead–Deerlodge National Forest, Planner

Helena, MT November 4 – 5, 2014

Vegetation

- Alicia Torregrosa – USGS, Physical Scientist
- Amanda Milburn – Helena National Forest, Forest Silviculturist
- Andrea Woodward – USGS, Biologist
- Rob Gump – Beaverhead-Deerlodge National Forest, Forest Silviculturist
- Stamm Elisa – Beaverhead-Deerlodge National Forest, Silviculturist
- Tanya Murphy – Helena National Forest, Silviculturist

Non-Forested Vegetation

- Amanda Hendrix – Helena/Lewis & Clark National Forest, Wildlife/Botany Technician
- Beth Anderson – Lewis & Clark National Forest, Soil Scientist
- Casey Johnson – Lewis & Clark National Forest, Weeds
- Mary Manning – USFS Region 1 Regional Office, Regional Ecologist
- Matt Reeves – USFS Rocky Mountain Research Station, Research Ecologist
- Rowdy Wood – Helena/Lewis & Clark National Forest, Range Program Leader
- Steve Black – Bighole Battlefield, Superintendent
- Steve Shelly – USFS Region 1 Regional Office, Regional Botanist
- Tammy Cherullo – Beaverhead – Deerlodge National Forest, North Zone Archaeologist

Wildlife

- Anne Roberts – Beaverhead – Deerlodge National Forest, Wildlife Biologist
- Denise Pengeroth – Helena National Forest, Wildlife
- Justin Gude – Montana Fish, Wildlife and Parks, Biologist
- Kevin McKelvey – USFS Rocky Mountain Research Station, Wildlife Ecologist
- Polly Buotte – University of Idaho, Research Associate – Geography
- Bray Beltron – Heart of the Rockies Initiative, Spatial Ecologist
- Gregg DeNitto – USFS Region 1 Regional Office, Forest Health Protection
- Ryan Quire – Helena National Forest, Biological Technician

Hydrology

- Deb Entuistle – Helena National Forest
- Brian Sugden – Plum Creek, Forest Hydrologist
- David Callery – Helena/Lewis & Clark National Forest, Watershed Program Manager
- Ed Snook – USFS Region 1 Regional Office, Regional Hydrologist
- Larry Dolan – Montana Department of Natural Resources and Conservation, Hydrologist
- Pam Fletcher – Beaverhead-Deerlodge National Forest, Forest Inventory & Monitoring Coordinator
- Robert Ray – Montana Department of Environmental Quality
- Sara Rouse – Beaverhead-Deerlodge National Forest, Soil Scientist
- Sue Higgins – Roundtable on the Crown of the Continent, Support Team
- Wayne Green – Lewis & Clark National Forest, Forest Hydrologist

Fisheries

- Anne Carlson – Wilderness Society
- David Moser – Montana Fish, Wildlife and Parks, Fish/Wildlife Biologist
- Jessie Kershner – EcoAdapt, Lead Scientist
- Jim Brammer – Beaverhead-Deerlodge National Forest, Forest Aquatics Program Manager
- Kendall Cikanek – Lewis & Clark National Forest, Fisheries
- Less Nelson – Montana Fish, Wildlife and Parks
- Peru Suernam – Beaverhead-Deerlodge National Forest, Planning Staff Officer

- Scott Spaulding — USFS Region 1 Regional Office, Fisheries Biologist

Recreation

- Charlene Bucha – Beaverhead-Deerlodge National Forest, District Ranger
- David Fothergill – Helena National Forest, Landscape Architect/Recreation
- Elizabeth Casselli – Helena/Lewis and Clark National Forest, Recreation Program Manager
- Jocelyn Dodge – Beaverhead-Deerlodge National Forest, Recreation Forester
- Lis Novack – USFS Region 1 Regional Office, Recreation
- Michael Hand – USFS Rocky Mountain Research Station, Research Forester
- Mike Munoz – Lewis & Clark National Forest, District Ranger
- Patty Bates – Beaverhead-Deerlodge National Forest, Public Services Staff Officer

Organizations Represented in NRAP

- Bitterroot Restoration Committee
- Bureau of Land Management
- Center for Large Landscape Conservation
- Clark Fork Coalition
- Confederate Salish and Kootenai Tribes
- Crown of the Continent Conservation Initiative
- Defenders of Wildlife
- Department of Interior North Central Climate Science Center
- EcoAdapt
- Fire Modeling Insistute
- Flathead Basin Commission
- Great Northern Landscape Conservation Cooperative
- Greater Yellowstone Coordinating Committee
- Headwaters Economics
- Heart of the Rockies Initiative
- Idaho Fish and Game
- Idaho Forest Group
- Idaho Native Plant Society
- Kootenai Tribe of Idaho
- Lee Metcalf National Wildlife Refuge
- Montana Department of Environmental Quality
- Montana Department of Natural Resources and Conservation
- Montana Fish, Wildlife and Parks
- Montana State University
- National Park Service
- North Dakota State University
- Oregon State University
- Plains and Prairie Pothole Landscape Conservation Cooperative
- Plum Creek
- Roundtable on the Crown of the Continent
- The Climate Impacts Research Consortium
- Trout Unlimited
- University of Idaho
- University of Montana
- University of Washington
- US Army Corps of Engineers
- US Fish and Wildlife Service
- US Forest Service
- US Geological Survey
- Walking Shadow Ecology
- Wilderness Society
- Wildlife Conservation Society
- Yaak Valley Forest Council

APPENDIX 1B—AUTHOR AFFILIATIONS

CHAPTER 1

S. Karen Dante-Wood is a Natural Resource Specialist, U.S. Department of Agriculture, Forest Service, Office of Sustainability and Climate Change in Washington, DC.

CHAPTER 2

S. Karen Dante-Wood is a Natural Resource Specialist, U.S. Department of Agriculture, Forest Service, Office of Sustainability and Climate Change in Washington, DC.

CHAPTER 3

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Marian Talbert is a Biostatistician with the U.S. Department of the Interior, North Central Climate Science Center in Fort Collins, Colorado.

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John Stevenson is a Regional Climate Extension Specialist with the Climate Impacts Research Consortium, Oregon State University in Corvallis, Oregon.

CHAPTER 4

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Michael K. Young is a Research Fisheries Biologist with the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station in Missoula, Montana.

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Scott Spaulding is the Fisheries Program Leader with the U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

Cameron A. Thomas is an Aquatic Ecologist with the U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

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Matthew C. Groce is an ORISE Technology Transfer Specialist with the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station in Boise, Idaho.

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Robert E. Keane is a Research Ecologist with the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory in Missoula, Montana.

Mary Frances Mahalovich is the Regional Geneticist with the U.S. Department of Agriculture, Forest Service, Northern, Rocky Mountain, Southwestern, and Intermountain Regions, Forestry Sciences Laboratory in Moscow, Idaho.

Barry L. Bollenbacher is the Regional Silviculturist with the U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

Mary E. Manning is the Regional Vegetation Ecologist with the U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

Rachel A. Loehman is a Research Landscape Ecologist, U.S. Geological Survey, Alaska Science Center in Anchorage, Alaska.

Terrie B. Jain is a Research Forester with the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station in Moscow, Idaho.

Lisa M. Holsinger is an Ecologist with the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory in Missoula, Montana.

Andrew J. Larson is an Associate Professor of Forest Ecology with the University of Montana, College of Forestry and Conservation, Department of Forest Management in Missoula, Montana.

Meredith M. Webster is the Regional Soil Scientist with the U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

CHAPTER 7

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William K. Lauenroth is a Professor with the University of Wyoming, Department of Botany in Laramie, Wyoming.

John B. Bradford is a Research Ecologist with the U.S. Geological Survey, Southwest Biological Science Center in Flagstaff, Arizona.

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CHAPTER 8

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Barbara J. Bentz is a Research Entomologist, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station in Logan, Utah.

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Mary E. Manning is the Regional Vegetation Ecologist with the U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

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CHAPTER 9

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CHAPTER 11

Travis Warziniak is an Economist with the U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station Human Dimensions Program in Fort Collins, Colorado.

Megan Lawson is an Economist with Headwaters Economics in Bozeman, Montana.

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CHAPTER 12

Carl M. Davis is the Regional Archaeologist with the U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

CHAPTER 13

S. Karen Dante-Wood is a Natural Resource Specialist, U.S. Department of Agriculture, Forest Service, Office of Sustainability and Climate Change in Washington, DC.

Linh Hoang is the Regional Inventory, Monitoring, Assessment and Climate Change Coordinator, U.S. Department of Agriculture, Forest Service, Northern Region in Missoula, Montana.

Table 4A.1—Adaptation options that address climate change effects on water resources in the Central Subregion.

Sensitivity to climatic variability and change: Increased flooding will increase damage to roads and infrastructure.			
Adaption Strategy / Approach: Identify and proactively decrease vulnerability of infrastructure to flooding.			
Strategy Objective: Increase resilience.			
Tactic	Specific Tactic – A Identify and restore degraded riparian areas in order to reduce flooding and increase natural storage. Reduce the amount of infrastructure in the floodplain.	Specific Tactic – B Conduct a basin-wide risk assessment of hydrologic interactions with roads and other infrastructure where vulnerability of infrastructure is highest.	Specific Tactic – C Educate private landowners, county managers, and recreational users to increase knowledge on benefits of riparian vegetation, water storage, and effects of floodplain development.
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term and ongoing	Near term	Near term and ongoing
Where can tactics be applied? (geographic)	All lands	Federal and private lands	Partnerships with state agencies, county and municipal governments, and private property owners
Opportunities for implementation	Partnerships with other federal and state agencies, and county and municipal governments	Partnerships with other federal and state agencies, and county and municipal governments	Partnerships with other federal and state agencies, and county and municipal governments
Cost	Moderate	Inexpensive, mostly employee time required	Low
Barriers to implementation	Property rights issues	Social resistance to change (e.g., property rights)	Social resistance to change (e.g., property rights)

Table 4A.2—Adaptation options that address climate change effects on water resources in the Central Subregion.

Sensitivity to climatic variability and change: Reduced base flows will shrinking riparian habitats and alter morphology, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaption Strategy / Approach: Increase natural storage and built storage.			
Strategy Objective: Increase resilience.			
Tactic	Specific Tactic – A Increase natural water storage (mirroring natural processes) with constructed wetlands, beavers, and road obliteration.	Specific Tactic – B Promote distributed small-scale water storage, using small dams, retention ponds, and swales in stream channels and uplands.	Specific Tactic – C Use groundwater injection wells and sills to retain water upstream in alluvial deposits (and retain higher water table).
Tactic effectiveness (risks)	Highly effective at small scales	Dams – high Swales – low to unknown	Variable
Implementation urgency	Near term	Mid term to long term	Near term to long term
Where can tactics be applied? (geographic)	Multiple land ownerships	Agricultural lands, headwaters without native fish species	Injection wells, large aquifers, sills
Opportunities for implementation	Collaboration with other land management activities (timber sales, road decommissioning)	Collaboration with Bureau of reclamation and NGOs, combined with hydropower projects	Areas near high-value water supplies
Cost	Moderate to high	High	High
Barriers to implementation	Lack of available sites, plans for future land use, social acceptance	For dams – significant environmental effects, safety risks, cost, access	Lack of available sites

Table 4A.3—Adaptation options that address climate change effects on water resources in the Central Subregion.

Sensitivity to climatic variability and change: Reduced base flows will shrink riparian habitats and alter morphology, affecting groundwater, storage, and shallow alluvial aquifers.			
Adaption Strategy / Approach: Increase knowledge about the groundwater resource.			
Strategy Objective: Increase knowledge.			
Tactic	Specific Tactic – A Map aquifers and alluvial deposits.	Specific Tactic – B Determine legal availability and better understanding of physical availability of water for aquifer recharge.	Specific Tactic – C Improve monitoring of streamflow and groundwater to improve understanding of surface water-groundwater interactions; obtain real-time data.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Near term – information needed for both water and fisheries	Near term – information needed for both water and fisheries	Near term – information needed for both water and fisheries
Where can tactics be applied? (geographic)	All lands and locations	All lands and locations	All lands and locations
Opportunities for implementation	Collaboration with USFS Rocky Mountain Research Station	Collaboration with state of Montana Water Court and Dept. of Natural Resources and Conservation	Collaboration with USGS; state and research partnerships
Cost	Low to moderate	Moderate	High
Barriers to implementation	Availability of staff and funding	Availability of staff and funding	Availability of staff and funding

Table 4A.4—Adaptation options that address climate change effects on water resources in the Central Subregion.

Sensitivity to climatic variability and change: Reduced base flows will shrinking riparian habitats and alter morphology, affecting groundwater, storage, and shallow alluvial aquifers.		
Adaption Strategy / Approach: Reduce evaporation and transpiration losses.		
Strategy Objective: Increase resilience.		
Tactic	Specific Tactic – A Evaluate how increasing western larch cover would decrease evapotranspiration.	Specific Tactic – B Selectively use forest harvest (patch clearcuts) to increase water yield.
Tactic effectiveness (risks)	Unknown	Low
Implementation urgency	Near term	Long term
Where can tactics be applied? (geographic)	Areas where western larch is currently present	Areas with moderate to high precipitation
Opportunities for implementation	Projects where western larch is planted	Minimal opportunities
Cost	Moderate for study	Moderate for treatment, high for maintenance
Barriers to implementation	Cost	Environmental consequences (loss of forested habitat, more edge, less interior species, more roads); political and social acceptance

Table 4A.5—Adaptation options that address climate change effects on water resources in the Central Subregion.

Sensitivity to climatic variability and change: Reduced snowpack will reduce the quantity and quality of municipal water supplies.		
Adaption Strategy / Approach: Reduce erosion potential to protect municipal water supplies; prioritize municipal systems for protection.		
Strategy Objective: Increase resilience.		
Tactic	Specific Tactic – A Evaluate how increasing western larch cover would decrease evapotranspiration.	Specific Tactic – B Selectively use forest harvest (patch clearcuts) to increase water yield.
Tactic effectiveness (risks)	Unknown	Low
Implementation urgency	Near term	Long term
Where can tactics be applied? (geographic)	Areas where western larch is currently present	Areas with moderate to high precipitation
Opportunities for implementation	Projects where western larch is planted	Minimal opportunities
Cost	Moderate for study	Moderate for treatment, high for maintenance
Barriers to implementation	Cost	Environmental consequences (loss of forested habitat, more edge, less interior species, more roads); political and social acceptance

Table 4A.6—Adaptation options that address climate change effects on water resources in the Central Subregion.

Sensitivity to climatic variability and change: Increased occurrence of disturbances such as drought and flooding will reduce water quality.			
Adaption Strategy / Approach: Build an information base for a timely response to disturbance, thus ensuring that data are available to inform decision making.			
Strategy Objective: Increase knowledge.			
Tactic	Specific Tactic – A Prioritize data collection based on projections of future drought.	Specific Tactic – B Collect pre-disturbance data on stream and riparian conditions, including high-quality values and habitat in need of protection.	Specific Tactic – C Develop a clearinghouse for available funding and programs related to fire and other disturbances.
Tactic effectiveness (risks)	Moderate	High	Moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Mostly federal lands	Mostly federal lands	Mostly federal lands
Opportunities for implementation	NEPA, USFWS	NEPA, ESA, USFWS	Emergency Relief for Federally Owned Roads; BAER implementation; NRCS, Federal Highway Administration
Cost	Low	Low	Low
Barriers to implementation	Agency culture, staffing, budget	Agency culture, staffing, budget	Agency requirements and time to manage clearinghouse

Table 4A.7—Adaptation options that address climate change effects on water resources in the Eastern Subregion.

Sensitivity to climatic variability and change: Large riverine systems are susceptible to a change in timing and quantity of peak flows as well as lower low flows associated with warming temperatures. Lower low flows and flashier flow regimes could lead to bank instability due to loss of vegetation. Changes in precipitation and/or temperature may reduce base flows.			
Adaption Strategy / Approach: Determine how climate change will alter lakes and reservoirs.			
Strategy Objective: Increase resilience; reduce stressors.			
Tactic	Specific Tactic – A Optimize grazing management practices to enhance riparian health and stream channel stability, soil water holding capacity, and shallow groundwater storage.	Specific Tactic – B Promote beaver recolonization and maintenance of beavers where appropriate.	Specific Tactic – C Promote cottonwood, willow, and aspen to improve riparian health and support beaver recolonization.
Tactic effectiveness (risks)	High for riparian health and baseflows	High	Moderate
Implementation urgency	Near term – information needed for water, fisheries, and amphibians	Near term – information needed for water, fisheries, and amphibians	Near term – information needed for water, fisheries, and amphibians
Where can tactics be applied? (geographic)	Forest wide, especially priority watersheds and allotments	Where appropriate, based on local knowledge and inventory and monitoring data	Where appropriate, based on local knowledge and inventory and monitoring data
Opportunities for implementation	Collaboration with private partners, local ranchers, permittees, non-governmental organizations (NGOs), and Montana Fish, Wildlife, and Parks; Clean Water Act, ESA, grass banking	Collaboration with private partners, local ranchers, permittees, NGOs, and Montana Fish, Wildlife, and Parks; Clean Water Act, Endangered Species Act, grass banking	Collaboration with USFS wildlife program, NGOS, and Montana Fish, Wildlife, and Parks
Cost	Inexpensive	Inexpensive	Moderate
Barriers to implementation	Political and social opposition, concern about offsite water use; education and perhaps incentives needed	Social opposition; need education and identification of appropriate locations	Funding, staff availability, competing priorities

Table 4A.8—Adaptation options that address climate change effects on water resources in the Grassland Subregion.

Sensitivity to climatic variability and change: Decreased snowpack will lead to increased frequency of high peak flows.			
Adaption Strategy / Approach: Maintain hydrological and ecological function of watersheds.			
Strategy Objective: Promote resilience, reduce stressors, engage coordination			
Tactic	Specific Tactic – A Implement 17 Indicators of rangeland health, and maintain or restore forest vegetation resilience.	Specific Tactic – B Promote/maintain proper functioning condition of riparian areas and wetlands, including: ensure adequate grazing regimes, adequate riparian buffers, beaver colonization, and restoration of riparian vegetation.	Specific Tactic – C Maintain/improve streamflow continuity by optimizing hydrologic connectivity, including: reduce sediment loading, properly design in-channel infrastructure, ensure adequate culvert size, promote beaver colonization, and procure in-stream flow water rights.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All federal lands	All federal lands	Where watersheds have been heavily fragmented, prioritizing intact habitat where native guilds exist
Opportunities for implementation	State wildlife action plans, grassland/forest plan direction, interdisciplinary approach to management	Coordination with tribes. Watershed Condition Framework documents where this is an issue at the 6 th code scale	Opportunities exist, but need work to be identified; coordination with federal and state agencies, tribes, counties, and watershed restoration plans
Cost	Inexpensive to moderately expensive	Inexpensive to expensive, depending on treatments	Inexpensive to expensive, depending on treatments
Barriers to implementation	Personnel availability, litigation barriers with vegetation management projects, common understanding of purpose	Social barriers – lack of understanding, not valued by some.	Funding, coordination, data gaps

Table 4A.8 (cont.)—Adaptation options that address climate change effects on water resources in the Grassland Subregion

Sensitivity to climatic variability and change: Decreased snowpack will lead to increased frequency of high peak flows.			
Adaption Strategy / Approach: Maintain hydrological and ecological function of watersheds.			
Strategy Objective: Promote resilience, reduce stressors, engage coordination			
Tactic	Specific Tactic – D Minimize expansion of drainage network by disconnecting road system from stream system, including improved road drainage and road decommissioning.	Specific Tactic – E Develop off-channel watering strategies; minimize in-stream dewatering (e.g., horizontal wells), for both livestock and other water uses.	Specific Tactic – F Move infrastructure out of floodplains, and encourage use of best management practices throughout watershed to protect and restore water quality.
Tactic effectiveness (risks)	High	Low	High
Implementation urgency	Near term	Near term	Near to mid term
Where can tactics be applied? (geographic)	Prioritize by value of downstream water and associated biota	Priority watersheds	Where assets exist on floodplains
Opportunities for implementation	Prioritize by value of downstream water and associated biota	Coordination with tribes, federal and state agencies, and counties	Prioritize by values at risk associated with assets; public education opportunity
Cost	Inexpensive to expensive	Inexpensive to moderate	Moderate to expensive
Barriers to implementation	Funding, legal authority (including NEPA), social opposition (road access, changing traditional land use practices)	Water rights, social opposition	Social opposition (effects on recreation sites, public perception), cultural resource concerns

Table 4A.9—Adaptation options that address climate change effects on water resources in the Grassland Subregion.

Sensitivity to climatic variability and change: Higher temperatures will lead to lower low stream flows in the summer.			
Adaption Strategy / Approach: Maintain hydrological and ecological function of watersheds.			
Strategy Objective: Promote resilience, reduce stressors, engage coordination			
Tactic	Specific Tactic – A Implement 17 Indicators of rangeland health, and maintain or restore forest vegetation resilience.	Specific Tactic – B Promote/maintain proper functioning condition of riparian areas and wetlands, including: ensure adequate grazing regimes, adequate riparian buffers, beaver colonization, and restoration of riparian vegetation.	Specific Tactic – C Maintain/improve streamflow continuity by optimizing hydrologic connectivity, including: reduce sediment loading, properly design in-channel infrastructure, ensure adequate culvert size, promote beaver colonization, and procure in-stream flow water rights.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All federal lands	All federal lands	Where watersheds have been heavily fragmented, prioritizing intact habitat where native guilds exist
Opportunities for implementation	State wildlife action plans, grassland/forest plan direction, interdisciplinary approach to management	Coordination with tribes. Watershed Condition Framework documents where this is an issue at the 6 th code scale	Opportunities exist, but need work to be identified; coordination with federal and state agencies, tribes, counties, and watershed restoration plans
Cost	Inexpensive to moderate	Inexpensive to expensive, depending on treatments	Inexpensive to expensive, depending on treatments
Barriers to implementation	Personnel availability, litigation barriers with vegetation management projects, common understanding of purpose	Social barriers – lack of understanding, not valued by some.	Funding, coordination, data gaps

Table 4A.10—Adaptation options that address climate change effects on water resources in the Grassland Subregion.

Sensitivity to climatic variability and change: Increasing air temperature will lead to increased stream temperature, changes in the hydrograph, and changes in land use, affecting water quality.			
Adaption Strategy / Approach: Ensure riparian function and resilience, including groundwater-surface water interactions			
Strategy Objective: Promote resilience, reduce stressors, engage coordination			
Tactic	Specific Tactic – A Promote/maintain proper functioning condition of riparian areas and wetlands: ensure adequate grazing regimes and adequate riparian buffers, promote beaver colonization, and restore riparian vegetation.	Specific Tactic – B Develop adequate inventory and promote protection of spring sources and shallow aquifers.	Specific Tactic – C Promote and educate regarding best management practices for agricultural runoff; form/participate in task forces and working groups.
Tactic effectiveness (risks)	Moderate to high, depending on degree of implementation	Moderate to high	Low to moderate, depending on social factors
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All lands	Priority watersheds	Mostly non-federal lands
Opportunities for implementation	Coordination with tribes; Watershed Condition Framework documents where this is an issue at the 6 th HUC scale	Work with botanists, soil scientists, hydrologists to compile existing information	Partnerships with NRCS, Praire Potholes Landscape Conservation Cooperative
Cost	Inexpensive to expensive, depending on treatments	Inexpensive to moderate, depending on scale	Inexpensive to moderate
Barriers to implementation	Social opposition – lack of understanding and not valued by some	Lack of funding and staff time	Social opposition, lack of staff time, crop values

Table 4A.11—Adaptation options that address climate change effects on water resources in the GYA Subregion.

Sensitivity to climatic variability and change: Higher temperatures and decreased snowpack will reduce water availability.			
Adaption Strategy / Approach: Reduce water use and increase efficiency, demonstrate leadership in water efficiency, and create outreach opportunities.			
Strategy Objective: Reduce stressors, facilitate transition, increase knowledge.			
Tactic	Specific Tactic – A Research successful water saving tactics and apply tactics where appropriate.	Specific Tactic – B Install low -low appliances at administrative sites; replace landscaping with drought tolerant plants.	Specific Tactic – C Communicate water saving tactics and benefits.
Tactic effectiveness (risks)	High	High	Variable—difficult to measure effects
Implementation urgency	Near term	Mid term	Near term
Where can tactics be applied? (geographic)	All lands, where appropriate	All lands, including administrative locations (campgrounds, visitor centers, etc.)	All lands, including administrative locations (campgrounds, visitor centers, etc.); use Internet, press releases, interpretive signing, etc.
Opportunities for implementation	Collaboration with GYCC	Collaboration with GYCC	Collaboration with GYCC
Cost	Inexpensive	Inexpensive	Inexpensive
Barriers to implementation	None	Resistance to xeriscaping, low-flow toilets	None

Table 4A.12—Adaptation options that address climate change effects on water resources in the GYA Subregion.

Sensitivity to climatic variability and change: Discharge from natural springs and seeps may be reduced, affecting water quantity and quality, wetland plant species, wildlife habitat, and water for livestock.			
Adaption Strategy / Approach: Protect natural springs and seeps from potential degradation and development.			
Strategy Objective: Reduce stressors.			
Tactic	Specific Tactic – A Develop map/inventory of springs and seeps locations (6 th code level).	Specific Tactic – B Instrument (piezometer) prioritized representative springs to get detailed flow information.	Specific Tactic – C Develop local protection strategies such as fencing, stock fencing; develop alternative water sources; moratoriums on wells where appropriate.
Tactic effectiveness (risks)	High	High	Variable depending on strategy and stakeholder support
Implementation urgency	Near term	Near to mid term	Near to mid term
Where can tactics be applied? (geographic)	All lands	Priority areas with springs and seeps	Priority areas with springs and seeps
Opportunities for implementation	Collaborations with USGS, state agencies that manage water, NOAA, USFS remote sensing center	Collaborations with USGS, state agencies that manage water, NOAA	Collaborations with federal and state agencies, private landowners, range permittees
Cost	Moderate	Inexpensive to moderate	Inexpensive to moderate
Barriers to implementation	Information may be sensitive	None	Social and legal opposition, especially based on water rights

Table 4A.13—Adaptation options that address climate change effects on water resources in the GYA Subregion.

Sensitivity to climatic variability and change: Higher flows may lead to flooding of valuable infrastructure (roads, buildings, campgrounds, etc.).			
Adaption Strategy / Approach: Reduce risk of damage to infrastructure.			
Strategy Objective: Promote resilience.			
Tactic	Specific Tactic – A Map and prioritize areas with higher peak flows to determine high-risk locations.	Specific Tactic – B Implement tactic A—replace, remove, adjust, and resize as necessary; implement early warning systems.	Specific Tactic – C Communicate risk with all stakeholders, including affected public and private entities.
Tactic effectiveness (risks)	High	Variable, depending on tactic/location. Low—replacing culverts, due to variable nature of stream types and unknown changes in climate affecting flows High—removal of campgrounds from floodplains, installation of bridges, removal of culverts	Variable, depending on reception of information, severity of risk, and ability to implement changes
Implementation urgency	Near term – need this information to take further steps toward adaptation	Near to long term, depending on model predictions and expected flows	Near term, especially where human safety is a concern
Where can tactics be applied? (geographic)	All lands	Priority areas	All locations where stakeholders are at risk
Opportunities for implementation	Collaboration with USGS, FEMA, county emergency management, NOAA	Collaboration with state and local, USGS, FEMA, county emergency management, NOAA	Collaboration with state and local, USGS, FEMA, county emergency management, NOAA
Cost	Inexpensive	Inexpensive to moderate	Inexpensive
Barriers to implementation	None	Legal—NEPA, Social—removal of favorite recreation spots	None

Table 4A.14—Adaptation options that address climate change effects on water resources in the GYA Subregion.

Sensitivity to climatic variability and change: Higher temperatures, higher evapotranspiration rates, and earlier runoff may reduce recharge to shallow aquifers reducing downstream domestic water yields.			
Adaption Strategy / Approach: Identify and protect shallow aquifer recharge zones by communicating and partnering with stakeholders.			
Strategy Objective: Reduce stressors, facilitate transition, engage coordination.			
Tactic	Specific Tactic – A Map/inventory recharge zones, especially in areas where water is heavily utilized (municipal watersheds).	Specific Tactic – B Form watershed user groups—coordinated resource management groups (CRM – federal, state, stakeholders) to identify concerns and solutions.	Specific Tactic – C Improve diversion efficiencies (install headgates, convert from ditch to pipeline, install weirs as needed, etc).
Tactic effectiveness (risks)	High	High to moderate	High
Implementation urgency	Near term	Near to mid term	Near to mid term
Where can tactics be applied? (geographic)	Recharge zones and identified CRMs	Identified CRMs, identified watersheds with stakeholders	Site specific within affected watersheds
Opportunities for implementation	GYA partners. USGS, university, GYCC	Conservation districts, NRCS, state agencies that regulate water, advisory groups, landscape conservation cooperatives, Trout Unlimited	Conservation districts, NRCS, state agencies that regulate water, advisory groups, landscape conservation cooperatives, Trout Unlimited
Cost	Moderate	Inexpensive	Inexpensive to moderate
Barriers to implementation	None	Social opposition; need communication to work through barrier	Variable legal and social opposition; concerns about listed fish species and downstream users.

Table 4A.15—Adaptation options that address climate change effects on water resources in the GYA Subregion.

Sensitivity to climatic variability and change: Higher temperatures and evapotranspiration rates may lead to increased loss of lower elevation, isolated wetlands,			
Adaption Strategy / Approach: Increase understanding of location and risk for all wetland types and apply appropriate management actions to reduce loss.			
Strategy Objective: Reduce stressors, promote resilience.			
Tactic	Specific Tactic – A Update National Wetland Inventory maps for all wetlands, including hydrologic regime and type.	Specific Tactic – B Assess vulnerability of all wetlands.	Specific Tactic – C Increase connectivity of wetlands (e.g., prevent road bisections); avoid degradation of wetlands by new structures; protect beaver dams; consider artificial wetland construction/augmentation of natural wetlands in vulnerable watersheds.
Tactic effectiveness (risks)	High	High	Variable, depending on action
Implementation urgency	Near term	Near term	Mid to long term
Where can tactics be applied? (geographic)	All lands	All lands	Mostly federal lands
Opportunities for implementation	Collaborations with GYCC, Ducks Unlimited, National Academy of Sciences, National Science Foundation, USFWS, National Wildlife Federation	Collaborations with GYCC, Ducks Unlimited, National Academy of Sciences, National Science Foundation, USFWS, National Wildlife Federation	Collaborations with state and federal agencies, private land owners
Cost	Inexpensive	Inexpensive	Moderate
Barriers to implementation	None	None	Social and legal opposition (road removal, augmenting wetlands)

Table 4A.16—Adaptation options that address climate change effects on water resources in the Western Subregion.

Sensitivity to climatic variability and change: Decreased snowpack will increase flooding and damage to roads and infrastructure.			
Adaption Strategy / Approach: Identify and proactively decrease vulnerability of roads and infrastructure to flooding.			
Strategy Objective: Increase resilience.			
Tactic	Specific Tactic – A Identify and restore degraded riparian areas in order to reduce flooding and increase natural storage; reduce the amount of infrastructure in the floodplain.	Specific Tactic – B Increase resilience of infrastructure: culvert sizing, hardened fords, road drainage; remove and relocate infrastructure (e.g., roads, campgrounds).	Specific Tactic – C Increase resilience of stream resources by identifying and restoring degraded riparian areas to reduce flooding and increase natural storage; add large woody debris, improve floodplain connectivity, increase riparian roughness, restore beavers.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Near term and ongoing	Near term and ongoing	Near term and ongoing
Where can tactics be applied? (geographic)	Across the west subregion	Across the west subregion	Across the west subregion
Opportunities for implementation	Partnerships with federal and state agencies, county and municipal governments, NGOs, private landowners	Partnerships with federal and state agencies, NGOs, Avista, US Army Corps of Engineers, Idaho Power	Partnerships with federal and state agencies, NGOs, Avista, US Army Corps of Engineers, Idaho Power
Cost	Moderate to expensive	Expensive	Inexpensive to expensive
Barriers to implementation	Property rights advocates	Public acceptance; depends on location, scale of project, and partnerships.	Public acceptance; depends on location, scale of project, and partnerships.

Table 4A.17—Adaptation options that address climate change effects on water resources in the Western Subregion.

Sensitivity to climatic variability and change: Decreased snowpack will reduce base flows and shrink riparian habitats, altering groundwater, storage, and shallow alluvial aquifers.			
Adaption Strategy / Approach: Increase knowledge of the groundwater resource.			
Strategy Objective: Increase knowledge.			
Tactic	Specific Tactic – A Map aquifers and alluvial deposits; identify groundwater influenced streams.	Specific Tactic – B Determine legal availability and better understanding of physical availability of water for aquifer recharge.	Specific Tactic – C Improve streamflow and groundwater monitoring information to improve understanding of surface water-groundwater interactions; obtain real-time data.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Near term – Information is needed for both water and fisheries	Near term – Information is needed for both water and fisheries	Near term – Information is needed for both water and fisheries
Where can tactics be applied? (geographic)	All lands	All lands	All lands
Opportunities for implementation	USFS Rocky Mountain Research Station, universities, Montana Bureau of Mines	State agencies	USGS, state and research partnerships
Cost	Moderate	Moderate	High
Barriers to implementation	Availability of staff and funding	Availability of staff and funding	Availability of staff and funding

Table 4A.18—Adaptation options that address climate change effects on water resources in the Western Subregion.

Sensitivity to climatic variability and change: Decreased snowpack and increased disturbance will reduce municipal water supply and quality.			
Adaption Strategy / Approach: Reduce erosion potential to protect municipal water supplies; prioritize municipal systems for protection.			
Strategy Objective: Increase resilience.			
Tactic	Specific Tactic – A Reduce hazardous fuels.	Specific Tactic – B Reduce disturbance (e.g., off-road vehicles, grazing, riparian roads).	Specific Tactic – C Manage roads to reduce erosion.
Tactic effectiveness (risks)	Moderate	High	High, although detecting improvements can be difficult and site dependent
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	High-value locations	High-value locations on public and private lands	High value locations on public lands
Opportunities for implementation	Partnerships with municipalities, counties, NGOs, tribes, private landowners.	Partnerships with municipalities, counties, NGOs, tribes, private landowners.	Partnerships with municipalities, counties, NGOs, tribes, private landowners.
Cost	Expensive	Inexpensive to moderate	Moderate to high
Barriers to implementation	Public acceptance, cost	Public acceptance, cost	Public acceptance, cost, some user groups

Table 4A.19—Adaptation options that address climate change effects on water resources in the Western Subregion.

Sensitivity to climatic variability and change: Increased droughts and flooding will reduce water quality.			
Adaption Strategy / Approach: Build an information base for a timely response to disturbance, thus ensuring data are available to inform decision making.			
Strategy Objective: Increase knowledge.			
Tactic	Specific Tactic – A Prioritize data collection based on forecasted drought.	Specific Tactic – B Collect pre-disturbance data on stream and riparian conditions (high-quality values, habitat most in need of protection).	Specific Tactic – C Develop a directory/checklist for sites where disturbance has a direct effect on water quality (metals).
Tactic effectiveness (risks)	Moderate	High	Moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Mostly federal lands	Mostly federal lands	All lands
Opportunities for implementation	Collaboration with other agencies, universities	Collaboration with other agencies, universities	Collaborate with USEPA (TMDL, CERCLA, Natural Resource Damage Assessment)
Cost	Moderate	Moderate	Expensive
Barriers to implementation	Staffing, budget	Staffing, budget	Agency requirements, time to staff and manage the clearinghouse

Table 4A.20—Adaptation options that address climate change effects on water resources in the Western Subregion.

Sensitivity to climatic variability and change: Decreased snowpack and increased disturbance will alter water quantity and quality of lakes and reservoirs (including dam operations).			
Adaption Strategy / Approach: Determine how climate change will alter lakes and reservoirs.			
Strategy Objective: Increase knowledge.			
Tactic	Specific Tactic – A Develop a clearinghouse of information on the effects of climate change from all available sources.	Specific Tactic – B Increase coordination between all partners (federal, state, tribal, private).	Specific Tactic – C Improve understanding about connectivity and interaction of streams and lakes (temperature, nutrient sinks, sources, etc.).
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term – Information needed for water, fisheries, and amphibians	Near term – Information needed for water, fisheries, and amphibians	Near term – Information needed for water and fisheries
Where can tactics be applied? (geographic)	All lands	All lands	All lands
Opportunities for implementation	Forest or regional level for identified sources of data	Forest or regional level for identified sources of data	Collaborations with USGS, state, and research institutions
Cost	Moderate	Moderate	Expensive
Barriers to implementation	Availability of staff and funding	Availability of staff and funding	Availability of staff and funding

Appendix 5A

For the Central Subregion, geographically specific adaptation options were compiled as lists to complement Table 5A.1. Adaptation tactics and other issues are summarized for each location.

Flathead National Forest

- Need aggressive suppression and eradication of non-native fish
- Brook trout more in the Middle Fork Flathead and less in the North Fork; bull trout tanked on west side of the park (Bowman, Logging, Kintla) because of brook trout; Quartz Lake has very active suppression of non-natives
- Some effects from logging (lack of wood in streams, some roads) in Coal Creek, Big Creek, Whale, Red Meadow); active logging in Canada in same drainage has effects (non-natives going upstream, logging effects coming downstream)
- In order to protect westslope cutthroat trout, Montana Fish, Wildlife, and Parks (FWP) are focused on eradicating rainbow trout through rotenone and other techniques
- Efforts to slow spread of hybrids; targeting rainbow trout sources in lower Flathead
- Barriers being installed or removed in North Fork Flathead; removing barriers in Rose Creek; removing culverts in Langford tributary to Big Creek
- Ongoing habitat work by Montana FWP in South Fork of Cold Creek
- Suppression of brook trout in Flathead Lake is a high priority
- Translocated bull trout this year; can use stocks to move them above barriers;
- Genetic rescue of westslope cutthroat trout (tributary to Swan Lake)
- Land acquisition presents huge opportunities for protection of habitat

South Fork Flathead River

- Try to maintain the status quo in Hungry Horse Reservoir, a genetic refuge for bull trout
- Try to manage more natural burns in South Fork of the Flathead; could apply this tactic to land around Hungry Horse Reservoir
- Need a check station at the dam and ranger station to prevent introduction of non-native fish, in combination with public outreach on this issue
- Montana FWP restored connectivity around Hungry Horse reservoir (also around Emery Creek) that was severed when road was constructed, but additional opportunities exist

Swan River

- Non-native issues are similar to Flathead River
- Westslope cutthroat trout are more hybridized with more brook trout characteristics
- Need small barriers to protect bull trout headwater populations
- Need to explore passage barrier issues
- Consider pulling road segments back from streams in critical locations
- Major road management issues exist on former Plum Creek lands, which have a large amount of spawning and rearing habitat relative to size
- Need thermographs throughout floodplains because of the importance of groundwater upwelling for bull trout; this will help improve models of these cold water systems

Clearwater River, Blackfoot River

- Long-term effects of timber harvest and roads, including the effects of roads on connectivity of the hydrologic system
- Unmanaged roads deliver low amounts of sediment;

- Continuing work with The Blackfoot Challenge to expand voluntary drought response plans; irrigation efficiency programs are addressing de-watering issues (particularly in drought years)
- Livestock grazing issues in Monture Creek
- Need to address contaminants issues near Mike Horse Mine
- Conservation easements need to be added more strategically (rather than opportunistically only)
- Restorative work is needed to narrow and deepen creeks to significantly reduce stream temperatures (Nevada Creek); could be applied strategically in other areas (Shanley Creek), as suggested by bull trout recovery plan
- Restoration of the main stem of the Blackfoot River is needed to reduce channel simplification and restore functionality and complexity
- One option is to identify reaches on private land and work to connect landscape and habitat up to higher elevation habitat on public lands
- Ongoing efforts to connect cold-water tributaries in the Upper Blackfoot; also need to do bank restoration in locations with land conversion
- This area has high use for recreation and fishing; this level of use may not be sustainable if habitat quality declines in the future

Upper Clark Fork River, Bitterroot River

- Heavy fishing pressure (catch and release) in this location
- East side of Bitterroot is a stronghold for native fish, but west side has no apparent occupancy (need to confirm)
- Dewatering events in tributaries are important, including issues for mitigation of water quality and quantity
- West Fork of Bitterroot above Painted Rocks Dam has been affected by forest management; road mitigation and removal are helping
- Sleeping Child/Darby timber land restoration is removing roads
- Habitat in Daily Creek (strong producer of bull trout out of Skalkaho) is being improved by placing woody debris in streams
- South Fork Lolo Creek is likely native fish stronghold, although Highway 12 and private land management limit potential restoration options

Middle and Lower Clark Fork River

- Fish passage at the reservoir dams has a huge effect on downstream rearing of westslope cutthroat trout and bull trout
- Legacy effects of management (e.g., placer mining) on cold water patches (Cedar Creek, Trout Creek) have degraded habitat, requiring structural channel remediation and road relocation and mitigation
- Thompson River native fish strong holds (Fish Trap, West Fork Thompson) provide options for improving channel complexity and habitat
- Little Joe River is a very cold water patch but with seasonal disconnection; unclear if this hinders access by bull trout
- Moore Lake is a source of brook trout to the South Fork Little Joe River

Rock Creek

- Bull trout populations are decreasing faster here than anywhere else; brown trout numbers are correspondingly increasing; East Fork above the reservoir has agricultural issues including effects of dewatering events caused by irrigation withdrawals
- Easy restore options have already been implemented to improve connectivity
- Options on east side for road relocation (Burnt Fork)

- Lower Rock Creek has heavy angling pressure
- Water and land restoration options on Ranch Creek

Rattlesnake Creek

- Current bull trout producer, but warming with few options for improving management
- Large wood and channel complexity, especially in the urban interface.

DRAFT

For the Western Subregion, adaptation options were compiled as lists rather than in tabular format. Adaptation options below are summarized by climate change stressor.

Temperature

Adaptation tactics

- Identify and protect groundwater areas and side channels
 - Increase density of sensor network
 - Develop GIS layer and incorporate into stream temperature maps
 - Action application: where groundwater has not yet been captured; everywhere native cold-water fish species occur
 - Remote sensing at microscale (longitudinal profile of larger rivers), which provides more fine-scale temperature mapping to help identify areas of groundwater inputs
 - Action application: Clearwater, St. Joe; anywhere there is private land or proposed development (feeds into floodplain or road development issues); rivers large enough to support this kind of sampling
- Restrict floodplain development and channelization
 - Action application: 3rd order streams
- Remove/relocate roads from creeks/streams
 - Action application: prioritize areas based on proximity to and presence of fish doing well. For example, the Clearwater has one HUC 6 with no human effects that is prioritized for restoration. Alternatively, the Selway is connected to lots of good habitat so less important to prioritize for road removal/relocation.
 - At a site-specific scale, prioritize similarly to watershed but on smaller scale; look at the potential of that habitat to support native fish both now and in the future
- Limit exploitation of groundwater/water withdrawals
 - Action application: anywhere tied to groundwater upwelling
- Hypolimnetic withdrawal
 - Action application: where possible (e.g., Priest Lake, Libby Dam, Albany Falls, Dworshak and Clark Fork dams)
 - In some cases (e.g., Kootenai) the water has been too cold for fish species, but this may change in the future
- Use beaver and/or large woody debris to increase groundwater storage
 - Action application: headwaters/headwater storage in high elevation areas
- Maintain current shade and microclimate characteristics
 - Action application: everywhere
- Identify, prioritize, and protect high-quality watersheds (HUC 6/7) and generate specific standards and guidelines for the area
 - Implement in national forest land management plans. Use this as an overarching strategy to identify high, moderate, and low priority watersheds with specific actions in each
- Reduce grazing effects
 - Identify thresholds that, once exceeded, trigger movement of the cattle to another pasture
 - Generate and implement adaptive management scenarios (similar to described above)
 - Re-evaluate timing of grazing and the amount of time between grazing activities
 - Riparian fencing (not as feasible in forested environments)
 - Retire allotments
 - Action application: target areas most susceptible to grazing (low-elevation meadows) (especially on Nez Perce-Clearwater NF)
- Remove barriers to fish passage

- Action application: remove if barrier prevents bull trout migration (not necessarily westslope cutthroat trout)
 - Other: westslope cutthroat trout database can be compared with stream temperature maps
- Water temperature management through dams. For example, Dworshak dam has contributed to the resilience of downstream fish b/c of temperature mitigations (i.e., they can create thermal refugia downstream of these facilities).
 - Need to match fish migration with thermal window (i.e., when fish migrate and temperatures necessary to sustain that migration) and consider longer, warmer stream temperatures in the future and how that may affect fish migration ability
 - Re-examine water temperature release in light of climate change (e.g., Kootenai)
 - Develop temperature models to better inform this action
- Install snowpack sensors to better anticipate changes in stream temperature and flow regimes

Runoff regime

- Address site-specific activities that make narrower and deeper channels and affect runoff characteristics and peak flow (e.g., clear cutting) by reducing surface area to depth
 - Action application: anywhere with narrow and deep channels, clearcut areas
- Limit actions (e.g., vegetation removal) that contribute to peak yield
 - Action application: primarily in rain-on-snow areas; north end of Clearwater has private/state/federal lands interspersed; need an analysis to determine effects from management activities (e.g., vegetation removal) on all lands to understand potential impacts on runoff characteristics and sedimentation
- Reconnect floodplains to improve the ability of system to deal with large flow events
 - Consider using beavers and large woody debris to help facilitate this process
 - Action application: prioritize areas of past dredge mining, where possible/feasible given social/financial constraints
- Restore water holding capacity using beaver or mechanical storage methods
 - Action application: degraded headwater streams
- Re-examine flow release (variable Q) from dams with projected climate changes (currently use from 1999 and back)
 - Action application: dams
- Increase connectivity, where possible, to allow fish to move to cope with changing conditions
 - Action application: remove mainstem dam passages/impoundments (although these may be non-native selectors too so this needs to be considered at site-level)
- Increase capacity of infrastructure to handle flows (e.g., upsizing culverts/structures to 100-yr flood)
 - Action application: take advantage of Burned Area Emergency Rehabilitation to replace culverts; take advantage of vegetation projects to replace culverts; road and trail relocation outside of 100-year floodplain
- Conduct roads analysis within proposed timber harvest areas, considering riparian/aquatic habitat and fish impacts (e.g., road density is a concern for fish)
- Hydrologically disconnect roads from streams (e.g., adding cross-drains or culverts or outsloping roads)
- Examine current and proposed future campgrounds/dispersed campgrounds on creeks and potential future changes in flow regimes (permanent disturbance regimes for fish habitat)

Invasive species

- Remove brook trout in higher elevations that are likely to be cold-water refugia for bull trout

- Action application: headwater lakes in wilderness (rotenone can be used for brook trout suppression in wilderness); when removing fish, we need to provide an alternative for recreational fisheries
- Create an integrated strategy across the sub-region that supports multiple species. For example, leave some lakes fishless for amphibians, incorporate brook trout strategy (below) at basin scale (HUC5) to balance public need (i.e., recreational fishery) with ecological need (i.e., bull trout)
- Identify brook trout locations and prioritize where to eradicate
 - Need: strong partnership with state and wildlife agencies to do a cross-agency effort (see action above as well); also support from leadership and funding
 - Eradication and preventing re-invasion by:
 - Install barriers
 - Avoid rotenone by using combo of electrofishing and tiger musky (although may be difficult to eliminate source entirely)
 - Expand options for brook trout management (e.g., gill netting)
 - Manipulate gametes and “swamp” current population so species essentially eradicates itself
 - Action application: meadow creeks in upper North Fork Clearwater
- Public education and outreach
- Brown trout and pike are newer invasive species, although management options are limited
 - Take limit off the fisheries (already done)
 - Where feasible and biology of species lends itself to it (e.g., Pend Oreille), can do some suppression
- Manage reservoirs and lakes (e.g., suppression efforts) to protect adult bull trout breeders from smallmouth bass and lake trout
- Utilize changing flow regimes and temperatures to keep invasives out
 - This has been used in Pend Oreille to keep pike out
 - Action application: dams/reservoirs
- Reservoir manipulation
 - Fertilization of species (kokanee); application: putting kokanee in headwater areas
- Establish barriers to invasive species movement
 - Have to make conscious decision to write off fluvial form of bull trout
 - Many factors have to coincide to make this work
 - Small-scale application for cutthroat (e.g., above barriers and more opportunistic)

In areas projected to be cold-water refugia until 2040:

- Suppress non-native fish
- Conduct a status assessment of current species and management actions
- Manage fire and fire effects
- Note: many of these areas in Nez Perce-Clearwater NF are in wilderness, so fewer management options
- Aggressive fish management (e.g., hatcheries)
 - Action application: Lake Coeur d’Alene drainage is historical bull trout drainage and critical habitat, but none there now
 - Questions: where to get fish and how many
 - This is a viable future habitat but may be social barriers (cattlemen’s association, political will, social will) to implementation
 - Use this as template for future
 - Action application: in areas with non-native species, use hatcheries to bring fish in, rotenone habitat, and aggressively re-stock

In areas with fish currently, but projected to be gone by 2040:

- Suppress non-native fish
- Improve connectivity
- Address higher river mainstem temperatures that act as barrier
- Monitor areas (fish there now, historical records, eDNA, presence/absence of juveniles, physical characteristics)

During warm phases of the Pacific Decadal Oscillation

- Warmer, drier conditions may affect year-class strength , potential barometer of how populations may respond in the future.

High-severity wildfire areas

- With connectivity, fire effects and debris torrents may not be an issue
- Nez Perce-Clearwater NF probably would not move fish unless they were spawning populations with limited connectivity
 - Strategy: monitor over time to understand distributions of spawning populations and how they respond to disturbances
 - Action application: translocate brood stocks only in certain situations (no connectivity)

Valued species other than cold-water fish

- Sturgeon and burbot
 - Opportunities: management of dam (temperature and flow), specifically temperature for these species (dependent on season and species)
 - Potential conflict: want to reduce flow in winter for water to cool off, but Bonneville Power Administration wants to release more flow during this time to generate power
- Western pearlshell mussel: increased peak flows may wipe out colonies

Table 5A.1—Adaptation options that address climate change effects on fisheries in the Central Subregion.

Sensitivity to climatic variability and change: Reduced snowpack will alter the thermal regime of streams in space and time.			
Adaption Strategy / Approach: Improve riparian function and increase functional riparian area.			
Strategy Objective: Promote resilience, reduce stressors.			
Tactic	Specific Tactic – A Re-vegetate denuded sections of riparian areas (leading to additional refined tactics for grazing effects, fire effects, etc.).	Specific Tactic – B Strategically relocate, eliminate, and minimize the effects of riparian and upland road segments.	Specific Tactic – C Restore groundwater and hyporheic exchange through beaver reintroduction/protection, channel restoration, and re-establishment of fire regimes.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied?	All locations where riparian areas have been damaged, especially if native fish populations are present or nearby	All locations where streams have been or could be damaged, especially if native fish populations are present or nearby	All locations where each specific tactic is appropriate and likely to be effective
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 5A.2—Adaptation options that address climate change effects on fisheries in the Eastern Subregion.

Sensitivity to climatic variability and change: Reduced snowpack will increase stream temperatures and alter flow regimes.			
Adaption Strategy / Approach: Increase habitat resilience for cold-water aquatic organisms by restoring structure and function of streams.			
Strategy Objective: Promote resilience			
Tactic	Specific Tactic – A Restore natural channel and floodplain form and function (e.g., restore areas with human-caused bank and bed instability).	Specific Tactic – B Restore aquatic organism passage structures through design and placement of appropriate structures.	Specific Tactic – C Maintain functional stream channel morphology with adequate width:depth ratios, pool frequency, and healthy riparian vegetation.
Tactic effectiveness (risks)	Moderate-high	High	High
Implementation urgency	Near term (gradual process, but need to get started)	Near term	Near term
Where can tactics be applied? (geographic)	Areas with ongoing restoration activities and where habitat is a primary limiting factor (especially where roads are present)	Drainages with frequent high peak flows, areas with sensitive geology, areas with important rearing streams	Areas with ongoing restoration activities and where habitat is a primary limiting factor (especially where roads are present)
Opportunities for implementation	Mining restoration projects	Talk to insurance companies to see if they will fund replacements (e.g., in locations where flows can affect downstream communities)	
Cost			
Barriers to implementation			

Table 5A.3—Adaptation options that address climate change effects on fisheries in the Eastern Subregion.

Sensitivity to climatic variability and change: Reduced snowpack will increase stream temperatures and alter flow regimes.			
Adaption Strategy / Approach: Increase habitat resilience for cold-water aquatic organisms by restoring structure and function of streams.			
Strategy Objective: Promote resilience			
Tactic	Specific Tactic – A Restore riparian areas to increase hydrologic function and retain cold water.	Specific Tactic – B Reintroduce beaver where beaver and management of westslope cutthroat trout are compatible.	Specific Tactic – C Remove or relocate roads adjacent to riparian areas, channels, and floodplains where they inhibit complexity; minimize cumulative effect of road network on surface and subsurface flow.
Tactic effectiveness (risks)	High	Moderate	High, but spatially limited
Implementation urgency	Near term	Long term	Near-medium term
Where can tactics be applied? (geographic)	Where riparian areas limit the availability of cold-water habitat	Where beaver will not affect barriers; in stream reaches > 1 mile; in larger population conservation networks; where brook trout are absent	Where roads currently cause problems or may in the future, especially where roads have substantial linear effects
Opportunities for implementation	Mining restoration projects	Talk to insurance companies to see if they will fund replacements (e.g., in locations where flows can affect downstream communities)	
Cost			Very high cost
Barriers to implementation		Beaver habitat can enhance brook trout populations	

Table 5A.4—Adaptation options that address climate change effects on fisheries in the Eastern Subregion.

Sensitivity to climatic variability and change: Reduced snowpack will increase stream temperatures and alter flow regimes.		
Adaption Strategy / Approach: Increase habitat resilience for cold-water aquatic organisms by restoring structure and function of streams.		
Strategy Objective: Promote resilience.		
Tactic	Specific Tactic – A Acquire Montana water compact/rights in a strategic way.	Specific Tactic – B Increase efficiency of irrigation techniques.
Tactic effectiveness (risks)	Low-moderate (for instream flows)	Low-moderate
Implementation urgency	Long term	Long term
Where can tactics be applied? (geographic)	Where future plans for water development may overlap with areas where native fish populations may be declining	Where future plans for water development may overlap with areas where native fish populations may be declining
Opportunities for implementation		
Cost		
Barriers to implementation		

Table 5A.5—Adaptation options that address climate change effects on fisheries in the Eastern Subregion.

Sensitivity to climatic variability and change: Continued livestock grazing will compound stress caused by increased stream temperatures.			
Adaption Strategy / Approach: Manage livestock grazing to restore ecological function of riparian vegetation and channels.			
Strategy Objective: Promote resilience, reduce stressors			
Tactic	Specific Tactic – A Comply with all existing standards and guidelines for maintaining water quality in streams and riparian areas; facilitate compliance through monitoring.	Specific Tactic – B Use innovative techniques to fund and maintain and implement improvements (e.g., riparian fencing, rest-rotation systems, off-channel water, exclosures).	Specific Tactic – C Identify and prioritize vacant allotments for retirement.
Tactic effectiveness (risks)	Moderate	Moderate-high (high for techniques that physically prevent access)	High, but spatially limited and opportunistic
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All locations, with emphasis on areas that are important in terms of ecological value and large financial investment	All locations, with emphasis on areas that are important in terms of ecological value and prior financial investment; prioritize areas with pure native fish populations that are under imminent threat	All locations where vacant allotments exist and opportunities allow
Opportunities for implementation			
Cost			
Barriers to implementation	Lack of public support	Beetle-killed trees damage fences	

Table 5A.6—Adaptation options that address climate change effects on fisheries in the Eastern Subregion.

Sensitivity to climatic variability and change: Continued livestock grazing will compound stress caused by increased stream temperatures.			
Adaption Strategy / Approach: Manage livestock grazing to restore ecological function of riparian vegetation and channels.			
Strategy Objective: Promote resilience, reduce stressors.			
Tactic	Specific Tactic – A Incorporate aquatic resource values in prioritization and implementation of land management plans.	Specific Tactic – B Convene regional meeting to identify and prioritize key fisheries areas; develop implementation plan that describes line officer actions.	Specific Tactic – C Continue and formalize agency coordination for fish habitat conservation (where projects are planned).
Tactic effectiveness (risks)	Moderate-high, depending on how well values are incorporated	High, but depends on spatial extent and number of stakeholders involved	High, but spatially dependent
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All locations, as management plan revisions occur	All areas of Montana	Where projects are planned and where existing conservation issues related to grazing exist
Opportunities for implementation		East-side range meetings; efforts to avoid listing of westside cutthroat trout populations; monitoring plans	
Cost			
Barriers to implementation			

Table 5A.7—Adaptation options that address climate change effects on fisheries in the Eastern Subregion.

Sensitivity to climatic variability and change: Warmer temperatures will increase stream temperature and risk of invasion by non-native fish species.			
Adaption Strategy / Approach: Manage non-native fish populations to eliminate or reduce their impact on native fish.			
Strategy Objective: Promote resilience, reduce stressors.			
Tactic	Specific Tactic – A Construct barriers to restrict non-native fish.	Specific Tactic – B Remove non-native fish and re-establish or restore western cutthroat trout populations.	Specific Tactic – C Secure, maintain, and improve riparian stream function and flows, including temperature.
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term (Big Hole and other locations with urgent issues); Long term (everywhere else)	Near term (Big Hole and other locations with urgent issues); Long term (everywhere else)	Near term
Where can tactics be applied? (geographic)	Where feasible and necessary (Big Hole, Selway Meadows-Red Rock, all drainages on Rocky Mountains front)	Where feasible and necessary (Big Hole, Selway Meadows-Red Rock, all drainages on Rocky Mountains front)	Where native fish populations and impaired riparian function exist, as identified in annual coordination meetings
Opportunities for implementation		East-side range meetings; efforts to avoid listing of westside cutthroat trout populations; monitoring plans	
Cost		Potentially high	
Barriers to implementation	Not socially feasible	Not socially feasible (e.g., high value recreational fishery) or may be unacceptable to kill all non-natives	

Table 5A.8—Adaptation options that address climate change effects on fisheries in the GYA Subregion.

Sensitivity to climatic variability and change: Reduced snowpack will reduce summer streamflows.			
Adaption Strategy / Approach: Increase streamflows and moderate changes in instream flows.			
Strategy Objective: Promote resilience.			
Tactic	Specific Tactic – A Pulse flows during critical times (high temperatures) from regulated streams.	Specific Tactic – B Reduce water withdrawals and improve efficiency for agriculture (especially irrigation), municipal, and industrial uses.	Specific Tactic – C Secure water rights for instream flows.
Tactic effectiveness (risks)	Moderate-high	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	All regulated streams	Where water demands overlap with current and future suitable habitat	Where fish and suitable habitat overlap
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 5A.9—Adaptation options that address climate change effects on fisheries in the GYA Subregion.

Sensitivity to climatic variability and change: Reduced snowpack will reduce summer streamflows.			
Adaption Strategy / Approach: Provide opportunities for native fish to move and find suitable stream temperatures.			
Strategy Objective: Promote resilience.			
Tactic	Specific Tactic – A Increase the patch size of favorable habitat to enhance viable populations and allow adfluvial life histories.	Specific Tactic – B Modify or remove barriers to increase connectivity between areas of cold-water habitat.	Specific Tactic – C Identify and map where groundwater inputs provide cold water.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Mid term
Where can tactics be applied? (geographic)	Where native fish currently exist; where suitable habitat is nearby; where non-natives are not present or can be effectively managed; where populations are fragmented and need greater connectivity	Where barriers prevent movement to suitable habitat, and where removal will not increase invasion of non-natives	All locations
Opportunities for implementation		Locations that are economically advantageous	
Cost			
Barriers to implementation			

Table 5A.10—Adaptation options that address climate change effects on fisheries in the GYA Subregion.

Sensitivity to climatic variability and change: Water temperature will increase, and the hydrograph will change in terms of magnitude and seasonality.			
Adaption Strategy / Approach: Protect and enhance fish habitat.			
Strategy Objective: Promote resilience.			
Tactic	Specific Tactic – A Restore degraded riparian vegetation, reconnect floodplains to rivers.	Specific Tactic – B Reintroduce beaver, encourage beaver recolonization.	Specific Tactic – C Disconnect roads from stream networks to reduce sedimentation.
Tactic effectiveness (risks)	Moderate-high	Moderate	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Smaller streams will be most effective, especially in lower-elevation valleys; prioritize areas with native fish or potentially suitable habitat	Where brook trout do not occur (beaver dams tend to facilitate brook trout) and where suitable beaver habitat exists	Where roads adjacent to streams have the potential to erode and deliver sediment
Opportunities for implementation	Smaller streams	Locations that are economically advantageous	
Cost			
Barriers to implementation			

Table 5A.11—Adaptation options that address climate change effects on fisheries in the GYA Subregion.

Sensitivity to climatic variability and change: Water temperature will increase, and cold-water fish habitat will decline.			
Adaption Strategy / Approach: Reduce stress on native fish species to enhance their ability to tolerate climate-induced stress.			
Strategy Objective: Reduce stressors			
Tactic	Specific Tactic – A Limit angling pressures on native fish.	Specific Tactic – B Reduce effects of recreation and grazing disturbance in streams.	Specific Tactic – C Reduce non-native (non-fish) aquatic species and diseases.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Mid term	Mid term	Near term
Where can tactics be applied? (geographic)	Locations that are at or near temperature thresholds for native fish	Where recreation and grazing activities are high, coincident with occupied or projected suitable fish habitat	Where non-native aquatic species and diseases occur, coincident with occupied or projected suitable fish habitat
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 5A.12—Adaptation options that address climate change effects on fisheries in the GYA Subregion.

Sensitivity to climatic variability and change: Warmer temperatures will increase stream temperature and risk of invasion by non-native fish species.			
Adaption Strategy / Approach: Manage non-native fish populations to eliminate or reduce their impact on native fish.			
Strategy Objective: Promote resilience, reduce stressors.			
Tactic	Specific Tactic – A Encourage increased take/harvest of non-natives, especially near long-term strongholds for natives.	Specific Tactic – B Remove non-natives with manual or chemical techniques.	Specific Tactic – C Implement physical or electrical barriers to exclude non-natives.
Tactic effectiveness (risks)	Low-Moderate (need heavy harvest at the invasion front)	Moderate-High	Moderate-High
Implementation urgency	Mid term	Near term	Near term
Where can tactics be applied? (geographic)	Areas with heavy recreation and sport fishing; most effective at the front of invasions	Where long-term suitable habitat for natives is available and non-natives are present	Where long-term suitable habitat for natives is available and non-natives are present
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 5A.13—Adaptation options that address climate change effects on fisheries in the GYA Subregion.

Sensitivity to climatic variability and change: Higher temperatures will increase wildfire occurrence that can lead to erosion and mass wasting.			
Adaption Strategy / Approach: Increase resilience to fire-related disturbance.			
Strategy Objective: Promote resilience, reduce stressors.			
Tactic	Specific Tactic – A Implement fuel treatments (thinning, prescribed burning) to reduce wildfire severity and size.	Specific Tactic – B Disconnect roads from stream networks to reduce erosion and sediment delivery to streams.	Specific Tactic – C Install erosion control structures following wildfires.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Mid term	Mid term	Near term
Where can tactics be applied? (geographic)	Areas where canopy and surface fuels are high, adjacent to known native fish populations and habitat	Areas adjacent to known native fish populations and habitat	Where wildfire has occurred and erosion would affect known native fish populations and habitat
Opportunities for implementation	Areas that are already being targeted for fuel treatment, especially in the wildland-urban interface		
Cost			
Barriers to implementation			

Table 6B.1—Vulnerability assessment for the three scales of analysis (species, vegetation type, resource concern) for vegetation of the Northern Rockies (NR).

Habitat, ecosystem function, or species	Broad-scale climate change effect	Current condition, existing stressors	Sensitivity to climatic variability and change	Expected effects of climate change
<i>Species</i>				
Limber pine	Warming temperatures, eastern portion of Northern Rockies anticipated increase in precipitation, less snow pack, variable precipitation during growing season	Reduced abundance due to exotic white-pine blister rust infections, native mountain pine beetle outbreaks, continued fire exclusion, and on wetter sites, limber pine dwarf mistletoe can be more of a problem resulting in mortality as compared to blister rust	Shade intolerant, early seral to pioneer species following fire or tree removal; difficulty in competing with other encroaching species on more productive sites; Little to no reproduction at low tree densities (lack of effective pollination cloud) and those seeds that are produced have increased likelihood of inbreeding; minimum of 25 cone-bearing trees per hectare is needed for dispersal by birds (i.e., corvids)	Increased growth; larger seed crops; increased seed dispersal into burned areas due to bird dispersal; lower seed germination due to warmer, drier conditions; loss of ectomycorrhizal associations, increased competition from wind-dispersed conifers; less blister rust infection due to higher temperatures and lower relative humidity disrupting the blister rust cycle; except in wave years; higher blister rust and dwarf mistletoe infections on eastside where precipitation is projected to increase; large and intense wildfires could threaten seed sources
Ponderosa Pine – var. scopulorum	Increasing temperatures; deeper and longer droughts; increasing fire severity and occurrence; shorter growing seasons and longer dormant seasons	Higher than historical tree densities	Generalist adaptive strategy; high phenotypic plasticity; early- to mid-seral species; moderate shade-tolerance; well-adapted to drought	Decreases in dwarf mistletoe and western gull rust damage; competitive capacity will increase; fire effects uncertain; more highly vulnerable to loss of disjunct and isolated populations, as compared to var. ponderosa; declining precipitation and variable spatial and temporal pattern may cause declines in regeneration, except in eastern portion of northern region where precipitation is expected to increase; increases in mountain pine beetle outbreaks; advancing competition, increasing western pine shoot

				borer occurrence; large and intense wildfires could threaten seed sources
Ponderosa pine-var. <i>ponderosa</i>	Minor cold hardiness issues at lower elevations	Precipitation pattern may favor regeneration; increases in pine beetle (western and mountain) <i>Lophodermium</i> sp. <i>Elytroderma</i>, <i>Armillaria</i> root rot, <i>Mycosphaerella pini</i>; extreme fire behavior; competition from grand fir and Douglas-fir	Intermediate adaptive strategy at low to mid elevations; specialist adaptive strategy at higher elevations; moderate phenotypic plasticity; early- to mid-seral species; little shade-tolerance; less adapted to drought	Competitive capacity will increase; increasing fires may have both beneficial and detrimental effects (high uncertainty); dwarf mistletoe and western gull rust may decrease; loss of disjunct and isolated populations on edges of range; limited ectomycorrhizae availability at higher elevations; suitable substrates for may not exist upslope, impedes both natural and artificial regeneration; large and intense wildfires could threaten seed sources
Douglas-fir	Increase in temperature causing increase in soil moisture deficits and less available water especially at lower elevation dry sites	Increase in tree density has increased risk of mortality from a large fire standpoint with will also limit regeneration and species distribution locally; root disease a major cause of mortality in northern Idaho and western Montana	Sensitive to increasing temperatures and increasing soil moisture deficits, this will predispose Douglas-fir to other related mortality agents such as insect and disease	At lower elevation southerly aspects expect ponderosa pine to be better able to cope with moisture deficits and disturbance such as fire, spruce bud worm, less seed source due fire size and due to cone production problems with spruce bud worm, mesic sites expect increase in mortality due to root disease, higher elevation southerly slopes may provide increased climate suitability for Douglas-fir; large and intense wildfires could threaten seed sources
Western larch	Increase in temperature causing increase in evaporative demand and soil moisture deficits	Increase in forest density has increased mortality risk from a fire standpoint, especially existing large size larch trees; past selective harvest and lack of fire has reduced species	Very sensitive to changes in temperature; Spring frosts often reduce pollen, cone and seed production that leads to sporadic seed years; very sensitive to warm temperatures to establish regeneration on high energy,	Range expansion and/or shift to more northerly aspects; reduction of size/age diversity of trees; larger fires may facilitate larch regeneration because the larger larch trees may provide seed on burned areas; increased drought on drier sites may

		distribution and density especially very large individuals.	southerly slopes; rising temperatures and increasing soil moisture deficits will affect potential distribution; increasing amount of fire will likely benefit larch as long as it is not in overly dense forest conditions with poor vigor leading to loss of seed source after fire.	exacerbate competition stress caused by invading shade tolerant species.
Western white pine	Warming temperatures; longer growing seasons; increased fire; increases in drought	Local rates of blister rust infection may hold steady but remains highly susceptible to wave years of infection; increases in Armillaria root rot, mountain pine beetle (endemic- depends on white pine population size and tree size), <i>Lophodermium nitens</i> , <i>Lecanosticta aciocola</i> severe needle blight on-going issue with cool-wet protracted springs; potential seed sources vulnerable to fire damage; critical thresholds for regeneration establishment may be possible resulting in ineffective pollen cloud, no seed production and higher probability of inbreeding	Early spring frost – cold hardiness – may not be physiologically in tune as individuals migrate upslope Moisture: lower elevation ecotones (<25" per year precipitation threshold); moderate shade-tolerance; early- to mid-seral Good competitive ability; up to three (3) years seed viability in soil bank; generalist adaptive strategy; high phenotypic plasticity	Increased growth; increased abundance with less grand fir provided there is a seed source or planting; less blister rust infection due to high temperatures and lower relative humidity except for wave years; if seed source exists fire will increase growing space providing for regeneration potential; the species is dependent on ash cap on many sites which may prevent migration to wetter/warmer sites; limited ectomycorrhizae availability at higher elevations; suitable substrate may not exist upslope so migration may not be expedited; both natural and artificial regeneration may occur with drought; pole blight may occur

Aspen	Warming temperatures, decreasing snowpack, increase in severity and frequency of wildfires	While there are stable climax aspen communities, most aspen is a fire-maintained, early seral component of a forested community; stands are declining in number and size; stressors include competition with and shading by conifers, typically due to fire exclusion, domestic and native ungulate herbivory, and increasing temperature coupled with declining precipitation; reduction of soil moisture may cause severe water stress which reduces aspen's ability to survive (e.g., sudden aspen decline) and to reproduce both vegetatively and by seed, thereby reducing genetic variability.	Sensitivity varies based on site characteristics, primarily soil moisture and solar radiation; it is mostly shade-intolerant; ubiquitous across most of North America; aspen is most persistent on sites with high solar radiation coupled with moist to wet soils; it does not tolerate extended drought; highly fire-adapted and regenerates abundantly after stand-replacing fire, although it can regenerate in conifer dominated stands in some settings ; it will persist or possibly increase with warmer temperatures as long as there is sufficient soil moisture; fringe communities may succumb to sudden aspen decline with long-term and severe water deficit, which will kill the roots.	Communities on warmer, drier sites could decrease due to water deficit; some stands may have significant mortality with little or no regeneration due to herbivory; sudden aspen decline has been associated with severe, prolonged drought, particularly in aspen stands that are on the fringe of the species' distribution (warmer and drier sites than those typically considered optimal for aspen persistence); fewer and smaller stands and of those that persist, there will be increased plant stress due to increased severity of summer droughts; increased fire frequency may likely favor aspen regeneration by removing shading conifers; younger stands (<40 years old) may be more resilient to drought and frequent fires could favor aspen on moister sites; severe fire may kill shallow root systems and eliminate aspen in some hotter and drier sites; growth may increase because photosynthetic rates appear to increase more in aspen than other tree species as atmospheric carbon increases, but this may be offset by increased drought stress and increased atmospheric ozone, which reduces photosynthesis and may increase susceptibility to insects and disease; higher herbivory (browsing) on regenerating stands is possible as adjacent upland vegetation senesces and desiccates earlier in the growing season; areas with mountain pine beetle-caused conifer mortality (especially in lodgepole pine) may release aspen and regenerate once the conifer canopy is removed; conifers use more water than aspen so aspen stands mean more streamflows; aspen forms natural fuel breaks that can be used effectively in fire

				management; pathological rotation is short-lived.
Grand fir	Increasing drought; longer growing seasons; increased fire and disease; highly variable weather	Fire exclusion has increased grand fir in dry and mesic sites but increased tree densities have also stressed fir trees contributing to increased fuel loadings, higher root rot, and greater insect damage and mortality	Late seral, shade tolerant species highly susceptible to fire; usually exists in areas where competition and tree density is high so most trees are stressed; highly stress trees are more susceptible to climatic fluctuations and trends	On xeric sites, increased drought and longer growing seasons will exacerbate stress from competition resulting in high mortality mainly from insects and disease; longer fire seasons and high fuel loadings from exclusion will also reduce this species; on the mesic sites, longer growing seasons coupled with higher temperatures may increase growth rates and regeneration success thereby increasing tree density and competition; fire will reduce grand fir dominance at landscape- and stand-scales
Western redcedar	Longer growing seasons; warmer temperatures; highly variable weather; Enhanced warm and cold cycles; early frosts	Root and butt disease: <i>Phellinus</i> , <i>fomis</i> , and Armillaria root rot; low susceptibility to pathogens	Generalist adaptive strategy; high phenotypic plasticity; high shade-tolerance; long-lived; seed production good; vegetative potential	Increased growth rate; fire adds uncertainty; warm/cold cycle may facilitate red-belt and adversely affect western redcedar (early warming followed by early frost); cedar flagging from dry seasons (entire branch is shed, interferes with seed production); ash cap dependent which may prevent it to migrate to wetter/warmer sites
Western hemlock	Longer growing seasons; warmer temperatures; highly variable weather; early frosts during the growing stage.	Confined to the moister portions of northern Rockies; susceptible to annosus root rot, <i>Echinodontium tinctorium</i> ; High tolerance to Armillaria root rot	Provisionally tends to be a generalist adaptive strategy; high shade-tolerance; needs ample moisture; susceptible to spring frost; very good competitor; high seed producer; seed viability only lasts one year in soil bank; susceptible to acid rain; ash cap dependent	May stay the same and potentially not change its current distribution; vulnerable to water deficits so declines are possible on the drier sites; since the species is ash cap dependent, migration may be retarded to wetter/warmer sites without ash cap soils.
Lodgepole pine	Increasing temperatures; longer droughty periods; increasing	Advancing succession due to fire exclusion is contributing to declines in lodgepole pine in	Shade intolerant conifer that has a wide climatic amplitude in subalpine areas; exists on a wide variety of soil types	Longer drought periods and warmer temperatures may decrease growth and regeneration on the driest sites (lower elevation lodgepole stands); lodgepole is well

	fire occurrence, frequency, and severity; increased productivity;	many areas; current increases in burn areas are creating many new lodgepole stands and some may become dense thickets; increased drought may exacerbate stress from other factors including competition, endemic insects and diseases, and wind; warming temperatures may heighten bark beetle activity resulting in more frequent and severe epidemics	and may be the only species to inhabit infertile and well drained sites; Moderately drought tolerant; reproductive success depends on level of serotiny; well adapted to colonize post-burn environments; highly susceptible to bark beetles, especially when in stress from endogenous and exogenous factors such as competition, fire-damage, and drought	adapted to increases in fire occurrence and size depending on level of serotiny, but it may be eliminated from sites where fires reburn stands before established seedlings and saplings become reproductively mature; In mesic subalpine sites, continued fire exclusion coupled with higher productivities will heighten competitive interactions and put more lodgepole pine into stress thereby increasing mortality, insect and disease vulnerability, canopy and surface fuels, and accelerating succession toward subalpine fir; conversely, increasing fire could expand lodgepole pine occurrence, even when fires are large and severe; increasing insect (i.e., bark beetles) outbreaks may further acceleration towards non-host, shade tolerant species
Subalpine fir	Increased disturbance frequency and severity; highly variable weather and climate; decreasing snowpacks; lengthening growing seasons;	Fire exclusion has increased abundance of this species on many subalpine and upper subalpine landscapes; many current stands have high densities and trees may be stressed from competitive interactions resulting in increasing susceptibility to disturbances; increasing drought could further exacerbate competitive stress and increase mortality	Highly vulnerable to subtle changes in climate; shade tolerant species that is an aggressive competitor in subalpine areas; uniquely adapted to quickly occupy gaps in subalpine forest canopies; relatively intolerant of drought; unable to mature when seasonal drought is common; not adapted to disturbance, especially fire, with high mortality even after low severity fires; frequent cone crops	Longer growing seasons and reduced snowpacks will increase regenerative success, especially in those high elevation areas where snow historically controlled regenerative success; higher productivity in subalpine forests may increase regeneration and species densities, eventually resulting in high competitive stress making these fir stands vulnerable to high mortality and therefore less resilient; declines of the species on drier sites may result from new drought regimes reducing regeneration success; increases of the species on moister sites will result from increased regeneration and competitive advantages; fir may gain in upper subalpine and timberline environments that are controlled by snow dynamics; subalpine fir could also increase as it replaces rust- and beetle-killed whitebark pine, yet whitebark pine can also act as a

				nurse crop to facilitate subalpine fir establishment; increased fire would decrease fir throughout the NR; the future of subalpine fir would depend on both fire suppression levels coupled with climatic responses.
Engelmann spruce	Increased disturbance frequency and severity; highly variable weather and climate; decreasing snowpacks; lengthening growing seasons	Spruce is usually associated with fir in the NR; it occurs as a minor to major component of many subalpine stands and only dominates in wetland or special land types; Fire exclusion has increased abundance of this species on many subalpine and upper subalpine landscapes; many current stands have high densities and trees may be stressed from competitive interactions resulting in increasing susceptibility to disturbances; increasing drought could further exacerbate competitive stress and increase mortality	Like fir, spruce is highly susceptible to changes in climates; it is not as an aggressive competitor and often is only a minor portion of a stand; it is highly vulnerable to drought; it can quickly regenerate in severely burned microsites providing there are seed sources; highly susceptible to windthrow and wind damage	Losses of spruce in the drier portions of its range, especially in those seasonal moist sites that will now be dry; not well adapted to fire so major declines are expected in burned areas, but these declines may be offset by increased regeneration on burned areas with mineral soil substrates; continued suppression activities may maintain spruce on the landscape but it may be at lower levels due to increased drought; it may increase in the upper subalpine when snowpacks become consistently lower and soil becomes drier thereby allowing spruce to encroach into glades, meadows, and balds.
Whitebark pine	Warming temperatures, lower snowpacks, highly variable weather, increasing fires in both intensity and severity, increasing insect and disease	Reduced abundance due to exotic white-pine blister rust infections, native mountain pine beetle outbreaks, and continued fire exclusion; survival due to cold hardiness in seedlings	Inability to compete with encroaching conifers due to low growth rates, moderate shade intolerance, and seed dispersal characteristics. Little to no reproduction may occur once tree densities are	On many upper subalpine sites there may be increased growth, larger seed crops, increased seed dispersal into increasing areas being burned due to bird-mediated dispersal providing there are adequate seed sources; lower seed germination due to warmer, drier conditions; possible loss of ectomycorrhizal associations; lack of suitable

	outbreak frequencies and severities; increase in populations of mountain pine through possible univoltinism shifts	and saplings in frost pockets and swales	low; long-lived species that lasts through climate epochs	substrates (suitable soils) as species moves upslope; increased competition from wind-dispersed, shade tolerant conifers with fire exclusion; less infection due to higher temperatures and lower relative humidity disrupting the highly variable blister rust cycle except in wave years; increased fire may provide caching habitat for nutcrackers that allow decades of unfettered development in the absence of competition from fir and spruce; losses in whitebark pine due to increased beetles, rust, and fire may be offset by increases in growth, cone crops, and abundant regeneration in burned areas, but management actions are needed to augment natural regeneration by planting and direct seedling rust-resistant pine
Alpine larch	Warming temperatures; longer growing seasons; smaller snowpacks that last shorter; less summertime water; possible summertime droughts; increased fire	Found in moist upper subalpine cove sites with abundant above and belowground moisture; exists in mixed stands of whitebark pine and sometimes subalpine fir; can form extensive stands in sub-irrigated upper subalpine areas	Very shade intolerant; intergrades with western larch; while this species is quite sensitive to shifts in climate, it may initially increase because it may colonize upper subalpine non-forest sites quicker than other species, but the newly established individuals may be unable to survive to maturity as drought and temperatures increase, climates become more variable, and fires increase in the upper subalpine; susceptible to damage from fire	Increased growth rates; greater ability to populate upper subalpine and treeline ecotones because of wind-aided seed dispersal and evergreen regenerative properties; increased fire may reduce many stands that historically were too wet to burn; on mesic sites – enhanced growing environment may increase competition from other more competitive, shade tolerant conifers; lack of whitebark pine seed caching because of depressed cone crops may favor alpine larch dominance in areas that currently lack trees (e.g., treeline, subalpine balds, meadows, glades); on xeric sites – lack of summertime ground water may contribute to higher water stress and lower growth rates; years with deep droughts may kill established regeneration; alpine larch may decline in those areas with lower water availability and declining groundwater flow

Green ash	Warming temperatures, decreasing snowpack, increase in severity and frequency of wildfires.	Domestic and native ungulate herbivory has affected both structure and composition of these communities.	Green ash has broad ecological amplitude and can survive droughty conditions, but persists optimally in moist sites; as soil moisture declines, marginal sites may become less favorable for regeneration and survival of young trees; there will probably be increased vegetative regeneration and decreased production of seedlings following fire- fire often kills green ash seed on or near the soil surface, restricting seedling recruitment to surviving seed producing trees.	Green ash may benefit from increased temperatures; seedling growth may increase with increasing soil temperatures; after increased fires, green ash has both root crown and epicormic sprouts, and both are typical following disturbances such as fire; fire may be very important in woody draws and riparian areas of the Great Plains; Since woody draws are typically long and narrow, even though they are more moist than surrounding uplands, they likely were also burned during frequent fires in the surrounding grasslands. Thus ash is well-adapted to fire; low-severity fires might promote regeneration by thinning stands and stimulating sprouting (the primary response to fire); browsing pressure will likely increase with increased drought, as upland grasses and forbs desiccate and senesce earlier, or are replaced by invasive, less palatable species.
Cottonwood	Warming temperatures; decreasing snowpack; increase in severity and frequency of wildfires	There has been a reduction in area due to conversion and development of floodplains; composition and structure of cottonwood forests have been altered due to changes in flow regimes; structural alteration (typically simplification) of the channel (e.g., levees, bank armoring structures) has likely contributed to channel widening, or channel	All species of cottonwood require saturated, but aerobic substrates and full sunlight to germinate and persist; any alteration of hydrologic flow regime (e.g., timing, magnitude and duration) will affect floodplain interaction and plant available water that may reduce recruitment and establishment of seedlings (cottonwoods regenerate primarily by seed); decreased streamflows and floodplain interaction may result in a shift in streamside vegetation to upland species, along with	Timing of flooding is critical to germination success and establishment of young (sapling, pole) cottonwoods both diminished; this will vary based on winter snowpack, and amount and timing of snowmelt (and associated peakflows); seedlings establish on moist to wet bare mineral soil, typically on stream bars, in full sunlight; as the snowpack declines and melts earlier, there will be reduced, more stabilized flows (loss of extreme high and/or low flows) and/or a shift in timing of peakflows to earlier in the season, before cottonwood seed is viable for germination); with earlier peakflows and less discharge, germination success is diminished; increased demand for water (additional diversions, reservoir expansions)

incision and loss of floodplain interaction; nonnative trees which are more drought tolerant are already present along rivers and streams in eastern Montana; increased drought stress will likely favor these species over cottonwood; additional stressors include roads, along with domestic and native ungulate browsing (particularly on young cottonwoods).

reduced growth and regeneration, and increased mortality of cottonwood; since cottonwoods are shade intolerant (require full sunlight) any conifers that establish on the drier fluvial surfaces will grow tall enough to eventually shade out the cottonwoods; as snowpacks decline and melt earlier, peakflows will be reduced and variation in discharge will decline, leading to a loss of various fluvial (depositional) surfaces along the stream, on which cottonwood germinate; the system becomes less complex; there may be fewer recruitment events; in addition, there may be a shift in timing of peakflows to earlier in the season, before cottonwood seed is viable for germination, resulting in both decreased germination and establishment of young cottonwoods; increased demand for water (additional diversions, reservoir expansions) and increased browsing pressure (adjacent upland vegetation senescences and desiccates earlier in the growing season) may also lead to a decline in cottonwood; sizes of cottonwood forests may decrease as these fluvial

and increased browsing pressure (as adjacent upland vegetation senescences and desiccates earlier in the growing season) will also likely lead to a decline in cottonwood.

surfaces are less frequently inundated; there may be little to no recruitment of young cottonwoods.

Vegetation types

Dry ponderosa pine and Douglas-fir forests	Increase in temperature causing increase in soil moisture deficits and less available water especially at lower elevation dry sites	Increases in density has put at risk increased mortality from a fire severity standpoint, root disease a major cause of mortality in northern Idaho and western Montana	Sensitive to increasing temperatures and increasing soil moisture deficits; this will predispose Douglas-fir to other related mortality agents such as insect and disease; this may give ponderosa pine an advantage on these settings	At lower elevation southerly aspects expect ponderosa pine to be better able to cope with moisture deficits and disturbance such as fire, spruce bud worm; less seed source due fire size and due to cone production problems with spruce bud worm; mesic sites expect increase in mortality due to root disease; higher elevation southerly slopes may provide increased climate suitability for Douglas-fir while ponderosa pine will be favored at lower elevations; patches size will increase due to severe fire if density reductions are not implemented
Western larch mixed-conifer forests	Increase in temperatures will likely rearrange current species associations on higher energy slope positions	Larch forests have been reduced significantly in extent due to successional effect from fire suppression, and preferential harvest; forest density increases have been substantial, and it now exists in uncharacteristic dense forest conditions in many areas. In northern Idaho, forest density (and productivity) was a bit denser due to warm mesic climate and deep ash capped soils. In areas once dominated	Larch is sensitive to changes in temperature; very sensitive to warm temperatures to establish regeneration on high energy, southerly slopes; rising temperatures and increasing soil moisture deficits will affect potential distribution and pattern of larch forests especially on high energy aspects. Increasing amount of fire will likely benefit larch as long as it is not in overly dense forest conditions with poor vigor with continuous horizontal	Larch is highly vulnerable to increase in temperature and uncharacteristic fires in dense forest settings; the loss of large tree structure and larch regeneration success could be a major effect due to the current lack of heterogeneity and patch densities; this is especially true for high energy topographic locations; increases in soil moisture deficits could retract the range of western large to more northerly slopes with deep soils; cone production could be positively affected with increasing temperatures which could cause cone maturation to be earlier which could mean earlier fire seasons may still be timed with cone production and seed cast after fire. Adaptation ability for cone production and seeding distance and regeneration ability may be reduced if connectivity is reduced due

		in northern Idaho by western larch, western white pine, and ponderosa pine they are now dominated by mixed grand fir and moist site Douglas-fir forests. The spatial pattern of forest structure has been homogenized in many areas leading to a continuous nature of the horizontal fuel profile atypical of historic fire regime landscape structure in many areas once typical of mixed-severity regime.	fuel profile across landscapes.	to very large and more frequent severe fires occurring. High forest density and low landscape pattern diversity compared to HRV may put at risk medium, large, and old-growth larch stands due to increasing moisture deficits and stand replacing fire. Simplification of within and between patch structure due to increased fire severity and size could lead to loss of diversity and loss of important wildlife habitat such as cavity nesting habitat for birds and mammals. In northern Idaho, the change in species composition of the forest to more intolerant to shade species has resulted in a forest much more susceptible to wide spread root disease mortality. These areas involve millions of acres on which less carbon sequestration is and will take place given the relatively novel species composition of today's forests. Given the likely increase in soil moisture deficits in the future, root disease effects are not likely to reduce; Lower tree densities of reproductively mature larch and loss of connectivity between populations will increase inbreeding depression as a result of disruption of an effective pollen cloud
Lodgepole pine and aspen mixed conifer forests	Increasing temperatures; longer droughty periods; increasing fire occurrence, frequency, and severity; increased productivity;	Many stands of this type are succeeding to subalpine fir-spruce due to fire exclusion; aspen has been declining due to lack of fire and increasing drought; healthiest areas are in wilderness	This type is more sensitive to management actions than climate in that continued fire exclusion will ensure their decline; this type thrives with fire and will even survive insect and disease outbreaks if fire is present on the landscape;	This cover type actually could expand in the future with increasing fires and the warming of the subalpine; disturbances may eliminate competing conifers and facilitate serotiny-aided lodgepole pine regeneration; aspen may decline on the drier parts of its range, but could increase and make major advances into the subalpine as fires burn competing conifers and temperatures moderate creating favorable climates; if fires are too frequent, this cover type may be replaced by semi-permanent shrub-herb, but as long as fire return intervals are greater than the

				reproductive age, lodgepole and aspen should prevail; as fires increase, more areas in this type will be early seral creating more heterogeneous landscapes with more patches of pine and fir mixed with aspen.
Mixed mesic white pine, cedar, hemlock grand fir forests	Increasing temperatures; more drought; more fires	This type is limited to the northwestern portions of the NR and much of this site has had management activities (harvest); western white pine occurrence has been severely reduced by blister rust but has shown increases in some portions of this type; unharvested stands are becoming more dense creating conditions that favor rot, insects, and disease damage	This type includes a fire-tolerant, fast-growing, early seral species (western white pine) with a collection of late seral, shade tolerant, highly competitive species so the type may actually not change in coverage as fires facilitate conversion to pine on these sites.	Western white pine may become a more dominant feature of this type; declines in cedar and hemlock are possible but grand fir; moisture changes are probably not limiting on these sites as much as the dependence on ash cap soils; major gains in the type are probably not possible because of the limited distribution of ash cap soils in some areas and the decrease in moisture outside of the current type's range; Similar to other types, the distribution of seral types may be more heterogeneous due to fire but the long period of fire exclusion might foster atypical high severity fires that might burn entire landscapes in some areas and this might result in homogeneous pine stands providing sufficient rust-resistance and seed sources
Whitebark pine-spruce-fir forests	Declining snowpacks; increasing fire; increasing temperatures	This type is probably increasing in the NR from effective fire exclusion; losses in whitebark pine are successional replaced by fir-spruce; the low elevation spruce-fir types are becoming more dense and crowded	This type might not be as sensitive as other more xeric sites to direct climate change impacts because there is abundant water, and predicted increases in both regeneration and growth may actually increase its climate resilience; increasing fires may cause a shift to more early seral communities and if whitebark pine populations were not experiencing rust outbreaks, these early seral	This type may contract into the future due to several interacting factors – whitebark pine will continue to decline due to rust and beetle outbreaks, spruce-fir forest may decline due to increased fire and reduced soil water; this site could be replaced by lodgepole-aspen in the drier parts of the NR; if agencies plant and conduct restoration activities, whitebark pine could make major gains into the increasing burned areas thereby replacing spruce-fir and limiting the contraction of this type; low elevation spruce-fir stands are probably going to move towards the western larch/mixed conifer type because of

			communities would probably be dominated by whitebark pine.	prolonged droughts and increasing temperatures, especially after fires
Resource concerns				
Landscape heterogeneity	Increased productivity causing accelerated succession; increases in disturbance frequency and extent; highly variable drought intensity and extent; migration of species to new habitats; changes in magnitude, season, and variability of water availability	Ninety years of fire exclusion coupled with past management activities (e.g., grazing) has reduced landscape heterogeneity	Landscape heterogeneity is highly susceptible to subtle shifts in climate because it is the reflection of the interaction of vegetation dynamics with disturbance regimes, topography, and land use. Small changes in climate may facilitate large changes in disturbances or vegetation dynamics causing new landscape mosaics	Increased fire across most of the NR may both increase and decrease landscape heterogeneity. Wildfires and wildland fire use fires may create patchworks of fire severity types across burned areas that will increase heterogeneity and therefore landscape resilience, but some fires may burn fire-excluded landscapes with high severities causing atypical large patches of high plant mortality that may decrease heterogeneity. While large, severely burned patches occurred in historical fires, the frequency and size of these patches may be different today. The highly variable species migration rates into areas with new climates may increase heterogeneity, but the rapidly changing climates may only facilitate generalist species thereby decreasing heterogeneity.
Timber production	Increase in temperature causing increase in soil moisture deficits and less available water that larch need, will shift species composition to root disease prone species particularly Douglas-fir and grand fir. Higher temperatures likely	Composition shift causing reduced productivity is likely in the western portion of the region on root disease prone sites and in southerly exposures Region wide. Risk of uncharacteristic fire severity very high due to uncharacteristic high forest density which will reduce timber production opportunities	Sensitivity high in northern Idaho and southerly exposures Region wide due to increasing moisture deficits and increase in uncharacteristic disturbance such as severity and extent of fire and root disease	Expect some theoretical increase in production at mid and higher elevations due to warming temperatures. This could be offset overall by losses due to root disease and increase in fire severity across the areas suitable for timber productions in Forest Plans. Less production (sequestration) anticipated in northern Idaho if current species compositions are not changed.

	to extend fire season and to reduce forest inventory on areas suitable for timber production. Some increase in productivity may occur at mid to higher elevations; however increase in fire may reduce timber production opportunities.	especially in dry forest areas.		
Carbon sequestration	Increased fire; increasing drought; productivity gains and losses;	Past policies of fire exclusion have created late seral landscapes that sequester little carbon; past timber activities may have created younger stands that sequester more carbon; increasing disturbances (fire, insect, disease) has caused short-term losses in carbon sequestration	Carbon sequestration is very sensitive to climate change impacts on vegetation and disturbance; Rates of carbon sequestration are going to largely dependent on the rate of burning in the future and the gains and losses of productivity in NR ecosystems; productivity gains and losses need to be evaluated at large spatial and temporal scales to understand future carbon dynamics	fire exclusion will tend to push most ecosystems into later successional stages where sequestration rates are minimal; burning from controlled and uncontrolled wildfires and prescribed burning will cause short-term losses but the high productivity of the developing early seral stands may increase sequestration for decades; sites that were historically dry will probably experience decreases in production and carbon sequestration in the future, while those mesic sites that experience abundant water (e.g., subalpine, upper subalpine, timberline) may experience increases in productivity

Table 6B.2—Risk assessment and vulnerability ratings for species, vegetation types, and resources of concern.

Habitat, ecosystem function, or species	Adaptive capacity	Exposure	Risk Assessment Magnitude of effects	Risk Assessment Likelihood of effects	Northern Rockies Vulnerability Ranking
<i>Species</i>					
Limber pine	Intermediate adaptive strategy largely driving by timing of pollen cloud dispersal (elevational effect); highly adapted to populating the burned areas predicted for the future due both to wind and corvid-mediated dispersal; poor competitor on more productive sites, if future fires are larger, more severe, there will be less competition from other subalpine conifers; possesses moderate genetic variation (capacity) in blister rust resistance; major gene resistance to blister rust has not been identified in several studies of interior populations, warmer temperatures favor expansion of alternate host species (currant, lousewort and Indian paintbrush); little to no opportunity to hybridize with western white pine due to non-overlapping species distributions, cannot hybridize with whitebark pine; very high risk of loss of disjunct and isolated populations due to genetic drift, ineffective pollen cloud, and substrate availability	High	Moderate	Moderate	15
Ponderosa pine var. <i>scopulorum</i>	Generalist adaptive strategy; high phenotypic plasticity; better adapted to drought	Moderate	Low	Low	17
Ponderosa pine var. <i>ponderosa</i>	Intermediate adaptive strategy at low to mid elevations Specialist adaptive strategy at higher elevations; moderate phenotypic plasticity; less adapted to drought	Moderate	Moderate	Moderate	16
Douglas-fir	Specialist adaptive strategy at low to mid elevations, generalist adaptive strategy at higher elevations; no opportunity of hybridizing with coastal Douglas-fir subspecies since distributions do not overlap; highly adaptive to a large range of moisture and temperature gradients. In moist forest settings Douglas-fir is limited to a relatively short-lived seral species due to the influence of two root diseases; With warming temperatures and a possible decrease in summer moisture drought conditions, Rocky Mountain Douglas-fir may increase along with an increase abundance of associated stressors; vulnerable to	High	High	High	5

	uncharacteristic fire behavior and severity due to increased densities; increase in susceptibility to Douglas-fir bark beetle mortality uncertain but probably an increased activity; moderate change in species distribution expected away from driest margins. High potential for natural regeneration failure due to reduced seed source from large wildfires and difficult micro climate especially on southerly exposures at lower elevations with increasing moisture deficits expected. On moist sites (mixed mesic forest), increases in root disease mortality due to increasing moisture stress on sites where western white pine, ponderosa pine and larch occurred historically. Less carbon sequestration expected in Douglas-fir in those forest setting; there is a high likelihood of change in local distribution due to moisture deficits and fire severity and a high probability of carbon sequestration in northern ID if Douglas-fir remains a dominant species in mixed mesic forests				
Western larch	Intermediate adaptive strategy, Low capacity to regenerate with increasing moisture deficits on higher energy slopes. Larch is adapted to warm moist and cool moist settings. It does best on northerly cool aspects. It is a prolific light seed cone producer but in sporadic years. High adaptive capacity on lower energy slopes; wind disperses seed further than many associates so it can take advantage of newly opened areas due to harvest or fire as an early seral species; larch has few insect and disease stressors unlike associates and is adapted to fairly frequent mixed-severity fire; it can be a dominant, long lived seal tree species in much of the western portion of the NR on lower energy slopes; concerning are potential serious reductions in extent of larch on higher energy slope positions.	High	High	Very High	4
Western white pine	Generalist adaptive strategy, high phenotypic plasticity; cold hardiness may influence distribution; Lack of abundance may influence its role in the moist forest ecosystem; especially adapted to future climates in the mesic regions of the NR; there could be major expansions into historical ranges and the subalpine as rust-resistance increases in western white pine populations	Moderate	High	High	3
Aspen	Aspen has the widest distribution of all trees in this report; it is circumpolar across multiple continents; it is highly	Moderate	Moderate	High	14

	susceptible to many insect and diseases; with a warmer climate gypsy moth may have greater impacts and cause possible mortality; aspen distribution may shift upslope or to northeast (cooler, moister) aspects if drought and repeated fire causes mortality on the warmer, drier sites. Riparian aspen communities will likely persist or increase in extent, particularly if the sites remain moist throughout the growing season and increased fire burns the riparian zone, killing conifers. Fire will favor aspen, but prolonged drought will cause mortality. Younger aged stands (<40 years) may be more resilient to drought; long distance dispersal by light seed may enhance its ability to colonize recently burned areas and establishment of young (sapling, pole) cottonwoods are both diminished; this will vary based on winter snowpack, and amount and time of melt (and associated peakflows) but only if there is sufficient moisture.				
Grand fir	Generalist adaptive strategy, only differences are racial (blue and green race); increases in disease, insects, and fire may reduce populations	Low	Moderate	Moderate	8
Western redcedar	Generalist adaptive strategy; high phenotypic plasticity; cold/warm cycles early in spring or winter may cause red belt.	Moderate	Moderate	Moderate	6
Western hemlock	Inferred or putative generalist adaptive strategy Information limited concerning western hemlock Susceptible to early frost	Moderate	Moderate	Moderate	7
Lodgepole pine	Specialist adaptive strategy; especially adapted to occupy post-burn landscapes that may be more common in the future; highly susceptible to increasing bark beetle outbreaks, especially on landscapes dominated by mature individuals; Varying levels of serotiny allow the species to both occupy new upper subalpine environments while also regenerating after fire; its intolerance of deep droughts may reduce its capacity along the xeric edges of its current range; High heterogeneity at landscape scales may mitigate adverse impacts from fire and mountain pine beetles.	Moderate	Moderate	Moderate	11
Subalpine fir	Generalist adaptive strategy; increasing fire will dramatically reduce subalpine fir populations to historical levels; fire exclusion may foster subalpine fir	Low	Moderate	Moderate	10

	encroachment into larch, lodgepole pine, and whitebark pine late seral stands; increasing subalpine temperatures may increase fir growth and accelerate succession toward fir-dominated stands, however, as competition increases, the warmer climates may facilitate increased mortality from insects and disease as trees become more stressed from high densities				
Engelmann spruce	Intermediate adaptive strategy with strong opportunities to hybridize with white spruce, hybrids may be more suited to future climates and hybridization is another key driver in speciation	Low	Moderate	Moderate	9
Mountain hemlock		Low	Moderate	Moderate	12
Whitebark pine	Highly adapted to populating the greater burned areas predicted for the future due to bird-mediated dispersal; if future fires are larger, more severe, there will be less competition from other subalpine conifers; ability to survive fire better than its competitors; moderately shade tolerant so it can exist in competition with limited cone crops; delayed germination adaptation may mitigate warmer, drier conditions; possesses moderate to high genetic variation (capacity) in adaptive traits (blister rust resistance, late winter cold hardiness and drought tolerance), as well as phenotypic plasticity to respond to climate change. Warmer temperatures favor expansion of alternate host species (currant, lousewort and Indian paintbrush). No opportunity to hybridize with another stone pine and cannot cross with western white or limber pine where species distributions overlap; high risk and loss of disjunct and isolated populations; more drought tolerant than its associates; long distance bird dispersal will increase regeneration potential as more of the landscape burns.	High	High	High	2
Alpine larch	Its specific habitat requirements may make it difficult for alpine larch to remain on the landscape over the long term; short-term gains in alpine larch encroachment in upper subalpine and treeline glades and meadows may be lost in those years with deep drought; effective, long-term establishment of alpine larch may depend on the ability of seed dispersal to find those areas with sufficient moisture to maintain the species.	High	High	High	1

Green ash	Since green ash communities are already fire adapted (most associated species display some fire tolerance and/or post-fire sprouting ability), increased fire will likely not affect most of the moister communities. However, those communities associated with either ephemeral drainages (e.g., woody draws) or moist upland microsites (e.g., northeast facing residual snow-loaded depressions) may experience more drought stress as snowpack declines and melts sooner, and regeneration may decrease, eventually resulting in loss of those communities.	Moderate	Moderate	High	18
Cottonwood	Plains cottonwood may be more persistent due to greater plant available soil water in the unsaturated zone (as a result of finer textured soils). Black and narrowleaf cottonwood typically occur in coarser substrate which will become more droughty as flows are lower and recede earlier than in the past, or are attenuated due to diversions. Seedling and sapling mortality may increase in these species. Plains cottonwood regeneration occurs with episodic flooding, whereas black and narrowleaf cottonwood typically regenerate with 1-3 year bankfull flow return intervals; therefore plains cottonwood will likely be more adapted to irregular flows (in timing, magnitude and duration) that may occur with climate change.	Moderate	Moderate	Moderate to High	13
Vegetation Types					
Dry ponderosa pine and Douglas-fir forests	Douglas-fir highly adaptive to a large range of moisture and temperature gradients. Ponderosa pine adapted to settings that are moisture limited and can grow well where moisture is less limited such in association currently with grand fir; exposure of Douglas-fir to increasing moisture deficits may change composition to more ponderosa pine; Increasing moisture deficits will give ponderosa pine the advantage on dry forest settings due to fire, insect and disease	High	High	High	3
Western larch mixed conifer forests	Larch forest thrive on northerly cool aspects locations in the Region; it is a prolific light seed cone producer but in sporadic years; may seed longer distances than many associates so can take advance of newly opened areas due to harvest or fire as an early seral species; larch has few insect and disease stressors unlike associates, and is adapted to fairly frequent fire; it can out-dominate long	High	High	Very High	2

	lived seal tree species in much of the western portion of the Region, and due to the large diameters it can attain is important to many cavity nesters as habitat when it reaches ages over 200 years in patches large enough, and connected enough to provide functional habitat; exposure on southerly aspects; with warming temperatures, and possible decrease in summer moisture and associated drought may decrease distribution of western larch which could mean that it will retreat to low energy northerly slope settings; distribution of larch in patches on high energy slopes would be reduced significantly; Serious reduction in extent of larch in patches on higher energy slope positions in the long run 50yrs + reduced distribution of wildlife habitat				
Lodgepole pine and aspen mixed conifer forests	This type has the capacity to absorb climate changes and either remain constant or expand into the upper subalpine; losses in aspen due to drought may be offset by gains in lodgepole pine, especially after fire; there may be long-term migrations of this type to higher elevation areas with increasing disturbance	High	Moderate	High	4
Mixed mesic white pine, cedar, hemlock grand fir forests	This type may also have the capacity to remain intact with changing climates; it may not be able to expand due to ash cap; increasing fire will favor western white pine while fire exclusion with favor the shade tolerant species; drier sites may see grand fir becoming more common than cedar or hemlock	Low	Moderate	Low	5
Whitebark pine-spruce-fir forests	This type may have the capacity to respond favorably to changes in climate but the depressed populations of whitebark pine coupled with the increasing fire may result in short-term losses of this type; however, if rust-resistant whitebark pine are planted and restoration activities are implemented, whitebark pine can easily dominate on these sites, especially if fires are large and severe, and whitebark pine may be able to make advances into the timberline; continued fire exclusion will probably aid in keeping this type somewhat static, and it may encroach on lower timberline sites if no fires are allowed	High	High	High	1
Resource Concerns					

Landscape heterogeneity	Since heterogeneity is an expression of disturbance, vegetation, and climate interactions it really is dependent on other factors to determine its adaptive capacity	High	Moderate	High	NA
Timber production	Productivity could increase at higher elevation sites. Productivity in northern Idaho will likely decrease on southerly aspects due to root disease reducing productivity of alternate species unless western larch, ponderosa pine and western white pine are aggressively restored; high exposure due to species composition changes and risk to increased disturbance	High	Moderate to high in north Idaho	High in north Idaho	NA
Carbon sequestration	All ecosystems have an inherent capability to store carbon and the rate and capacity of carbon storage depends on plant productivity and disturbance with the maximum levels of productivity dependent on climate while the instantaneous levels of productivity depend on successional stage or time since disturbance; Many modeling studies have shown that many areas in the NR will actually increase productivity and increase sequestration rate and magnitude; the delicate balance between disturbance and climate coupled with land management will dictate where sequestration will increase and where it will decrease; it is important to know that over the long term (centuries), sequestration is near zero (disturbance and respiration losses are balanced by productivity gains)	High	High	Moderate	NA

Table 6C.1—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Aspen will be lost with increasing drought and lack of disturbance.				
Adaption Strategy / Approach: Increase aspen populations.				
Strategy Objective: Increase aspen populations.				
Tactic	Specific Tactic – A Actively decrease impact of ungulate browsing through an increase in predation of ungulates.	Specific Tactic – B Increase fire disturbance.	Specific Tactic – C Develop techniques to successfully artificially regenerate aspen; improve drought tolerance with genetic selection of drought-tolerant mother trees and identify and target areas most likely to successfully regenerate or provide favorable planting habitat.	Specific Tactic – D Protect existing aspen populations and regeneration treatments from browsing.
Tactic effectiveness (risks)	High where ungulates concentrate			
Implementation urgency				
Where can tactics be applied? (geographic)				
Opportunities for implementation				
Cost				
Barriers to implementation				

Table 6C.2—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Known unknowns and unknown unknowns.			
Adaption Strategy / Approach: Increase knowledge and implement adaptive management.			
Strategy Objective: Increase knowledge.			
Tactic	Specific Tactic – A Monitor blister rust resistance within planted white pine stands, and try to understand the relationship between infection rates and climatic/weather drivers like fog.	Specific Tactic – B Identify other resource management goals (not directly related to stand structure and composition) that may modify management strategies for forest vegetation, such as water yield, snow retention, and wildlife habitat.	Specific Tactic – C Support the adaptive management research framework through a partnership between Region 1 and Rocky Mountain Research Station to evaluate management treatments and how they contribute to resiliency. Develop monitoring framework that will be consistently be implemented so that long-term change can be captured.
Tactic effectiveness (risks)			
Implementation urgency			
Where can tactics be applied? (geographic)			
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 6C.3—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Potential shifts in lodgepole pine ecosystems with changing climate.			
Adaption Strategy / Approach: Promote resilience by maintaining age-size class composition at the stand and landscape level.			
Strategy Objective: Maintain lodgepole pine on the landscape.			
Tactic	Specific Tactic – A Identify areas appropriate for wildfire use and increase flexibility in how we manage fire; emphasize modified suppression and resource benefit fire; allow moderate season fires to burn.	Specific Tactic – B Proactively treat stands with prescribed fire to reduce fire and insect mortality and increase individual tree vigor.	Specific Tactic – C Implement silvicultural mechanical treatments.
Tactic effectiveness (risks)	Other unintended consequences could lower it from high to moderate	Highly variable depending on scale, district expertise, and landscape position	Highly variable depending on scale
Implementation urgency	High/near term		
Where can tactics be applied? (geographic)	Implement Wildland Fire Decision Support System forest wide		
Opportunities for implementation	Highly dependent on other resource concerns and political and social issues		
Cost			
Barriers to implementation	Integration between forest and fire team	Prescribed fire air quality restrictions limit what we can do; other resource constraints (e.g., lynx)	Other resource constraints (e.g., thermal cover, lynx habitat, marten and wolverine)

Table 6C.4—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Homogenization of the ponderosa forest type across the landscape resulting in: increase in density causing associated increase in risk of severe stand replacing fires; increased risk of mortality from drought; loss of ponderosa pine on stressful sites; loss of large ponderosa pine and large ponderosa snag recruitment; and reduced water yield.			
Adaption Strategy / Approach: Decrease the density within ponderosa pine-Douglas-fir stands, and increase structural.			
Strategy Objective: Develop resilience to fire, moisture and stress.			
Tactic	Specific Tactic – A Reduce stand density with thinning, prescribed fire, and wildland fire use, with density and structural goals based on past and predicted future conditions.	Specific Tactic – B Promote age class and structural diversity across the landscape, through regeneration harvest, thinning, prescribed fire, and wildland fire use.	Specific Tactic – C Monitor establishment, survival and development of ponderosa by age class and in different conditions (e.g., aspect, heat load and soil moisture) using Forest Inventory and Analysis data and project-level stocking exams.
Tactic effectiveness (risks)	Thinning = high, prescribed fire = high, wildland fire use = moderate	High where implemented	High
Implementation urgency	Near-term in Wildland Urban Interface areas. Mid-term elsewhere	Near-term in Wildland Urban Interface areas. Mid-term elsewhere	Long-term
Where can tactics be applied? (geographic)	Ponderosa pine – Douglas-fir forests	Harvesting and thinning on non-reserved lands; prescribed fire and wildland fire use where approved.	Ponderosa pine – Douglas-fir forests
Opportunities for implementation	Work with collaborators on private and state land to include the wildland urban interface; work with other organizations to get funding and do work on private lands	Work with collaborators on private and state land to include the wildland urban interface; work with other organizations to get funding and do work on private lands	Forest Inventory and Analysis; restoration and resiliency report; forest regeneration reports; adapting Common Stand Exam protocols
Cost	Varies by treatment	Varies by treatment	Inexpensive
Barriers to implementation		Some: cost, litigation	None

Table 6C.5—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Changing moisture regimes with changing climate.			
Adaption Strategy / Approach: Replace plant association group-habitat typing with an index based on biophysical variables.			
Strategy Objective: Increase knowledge; plant associations are not expected to remain the same under climate change.			
Tactic	Specific Tactic – A Identify a set of biophysical predictors related to habitat types, site productivity, vegetation composition, and structure. Possible predictors include landform, soil depth, texture, type (specifically ash cap soil), actual evapotranspiration, potential evapotranspiration and water balance deficit.	Specific Tactic – B Predict site productivity based on biophysical predictors; make concept operationally implementable so it can be used to aid in planting decisions, and aid understanding of long-term effects of management and long-term goals for a site.	Specific Tactic – C Project into the future based on climate change models.
Tactic effectiveness (risks)	Unknown	Unknown	Unknown
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)			
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 6C.6—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Subalpine forest shifts as a result of climate change.		
Adaption Strategy / Approach: Monitor and detect change through measurement of seedling survival, species composition and mortality of mature trees.		
Strategy Objective: Increase knowledge on climate-induced subalpine forest shifts.		
Tactic	Specific Tactic – A Install and analyze additional plots where trend information is needed over time; more intensified grid plots could also be installed.	Specific Tactic – B Initiate the use of Forest Inventory and Analysis plot information.
Tactic effectiveness (risks)	High	Moderate to low, depending on how fast changes are occurring
Implementation urgency	High - need to know now	Already part of regional strategy
Where can tactics be applied? (geographic)	Target areas of risk where we expect to see changes, focusing on disturbance areas; in especially sensitive forests such as whitebark pine	Large enough geographic area that information can be statistically meaningful
Opportunities for implementation	Very few because of lack of funding, but protocols and analysis tools already established	Already paid for, and existing expertise and knowledge are available
Cost	High based on information needs; a lot of plots needed	Minimal
Barriers to implementation	Need training and oversight of data collection; need to have consistent, replicable protocol in order to be able to detect change; lack of immediate and long term funding	Difficult to get data updates in a timely manner; getting non-Forest Service data is difficult

Table 6C.6 (cont.)—Adaptation options that address climate change effects on forest vegetation in the Central Subregion

Sensitivity to climatic variability and change: Subalpine forest shifts as a result of climate change.		
Adaption Strategy / Approach: Monitor and detect change through measurement of seedling survival, species composition and mortality of mature trees.		
Strategy Objective: Increase knowledge on climate-induced subalpine forest shifts.		
Tactic	Specific Tactic – C Expand reforestation monitoring to include additional monitoring and different electronic formats.	Specific Tactic – D Implement pre- and post- treatment monitoring over time to be able to determine if treatments are meeting objectives.
Tactic effectiveness (risks)	High	High
Implementation urgency	High	Moderate
Where can tactics be applied? (geographic)	Everywhere we are planting sensitive vegetation types	Treated areas
Opportunities for implementation	Often doing it anyway, and methodology is already in place; need to make sure we are collecting right data in the right electronic format	Existing systems
Cost	Low unless data collection becomes arduous	Moderate to high; depends on number of plots variability, length of time to monitor, what data is being collected; less expensive than intensifying grid across landscape.
Barriers to implementation	Need to establish protocols, conduct training, identify a location for data storage and determine who would do the analysis; lack of immediate and long term funding	Lack of immediate and long term funding; lack of training and oversight; lack of treatments to monitor

Table 6C.7—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Subalpine forest shifts as a result of climate change.		
Adaption Strategy / Approach: Promote resilience of subalpine forests to climate-induced shifts.		
Strategy Objective: Create conditions that will be resilient to perturbations.		
Tactic	Specific Tactic – A Identify areas appropriate for wildfire use; increase the flexibility of how we manage fire and de-emphasize suppression.	Specific Tactic – B Artificially regenerate seedlings with higher levels of rust resistance than the natural population.
Tactic effectiveness (risks)	Other unintended consequences could lower it from high to moderate	High at site level; low at landscape level
Implementation urgency	High-near term	High-near term
Where can tactics be applied? (geographic)	Highly dependent on other resource concerns and political and social issues; problematic in areas with mixed ownership	Have process established to develop rust resistant seedlings; coordinate with tree improvement and nursery to continue to improve rust resistant sources
Opportunities for implementation	All lands - federal, state, districts, communities, universities	All lands - federal, state, districts, communities, universities
Cost	Inexpensive	Moderately expensive; cost of seedlings high
Barriers to implementation	Integration between forest and fire team; sociopolitical environment and backlash; lack of public support; decline in air quality	Access; cost; unable to plant in wilderness or research natural areas

Table 6C.7 (cont.)—Adaptation options that address climate change effects on forest vegetation in the Central Subregion

Sensitivity to climatic variability and change: Subalpine forest shifts as a result of climate change.			
Adaption Strategy / Approach: Promote resilience of subalpine forests to climate-induced shifts.			
Strategy Objective: Create conditions that will be resilient to perturbations.			
Tactic	Specific Tactic – C Proactively treat with prescribed burn or mechanical thinning to reduce the risk of fire and insect mortality; increase individual tree vigor to establish the desired species composition and establish appropriate patch sizes.	Specific Tactic – D Implement a broad scale review of most current literature, develop a regional library, and implement a climate change information system.	Specific Tactic – E Educate the public on the need to increase resilience and develop a cohesive broader message.
Tactic effectiveness (risks)	Highly variable depending on scale, district expertise, and landscape position	High if used	Low
Implementation urgency	Moderate-mid term	High near term	Low-long term
Where can tactics be applied? (geographic)		All	National
Opportunities for implementation	All lands - federal, state, districts, communities, universities		National
Cost	Low to high depending on the combination of treatment, objectives and local conditions		
Barriers to implementation	This type is not as far from historic conditions, so there is not as much reason to restore; more complex and difficult to access; window for treatment is narrower		

Table 6C.8—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Homogenization of the larch forest type across the landscape resulting in increased density and associated increase risk of severe stand-replacing fires, increased risk of mortality from drought, loss of western larch on stressful sites, loss of large larch, large larch snag recruitment across the landscape, and reduced water yield.			
Adaption Strategy / Approach: Decrease density within stands, and increase structural diversity across the landscape.			
Strategy Objective: Develop resilience to fire and moisture stress.			
Tactic	Specific Tactic – A Reduce density with thinning, prescribed fire, and wildland fire use.	Specific Tactic – B Promote age class and structural diversity across the landscape, through regeneration harvest, thinning, prescribed fire and wildland fire use.	Specific Tactic – C Monitor establishment and survival of western larch by age class across different aspects/heat load/soil moisture. Use Forest Inventory and Analysis data to capture regeneration success by topographical position.
Tactic effectiveness (risks)	Thinning = high; prescribed fire = moderate; wildland fire use = low when first implemented, moderate over time	High where implemented	High
Implementation urgency			
Where can tactics be applied? (geographic)			
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 6C.8 (cont.)—Adaptation options that address climate change effects on forest vegetation in the Central Subregion

Sensitivity to climatic variability and change: Homogenization of the larch forest type across the landscape resulting in increased density and associated increase risk of severe stand-replacing fires, increased risk of mortality from drought, loss of western larch on stressful sites, loss of large larch, large larch snag recruitment across the landscape, and reduced water yield.

Adaption Strategy / Approach: Decrease density within stands, and increase structural diversity across the landscape.

Strategy Objective: Develop resilience to fire and moisture stress.

Tactic	Specific Tactic – D	Specific Tactic – E
	Prioritize management for larch on landscape facets where monitoring indicates it is going to persist (e.g., on north aspects, but not southern aspects, or by habitat types).	Maintain and promote large diameter western larch across the landscape, so that large diameter snags, larch seed sources, and wildlife habitats are also maintained.
Tactic effectiveness (risks)	High	High if A and B are implemented
Implementation urgency		
Where can tactics be applied? (geographic)		
Opportunities for implementation		
Cost		
Barriers to implementation		

Table 6C.9—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: High density of mixed-mesic white pine, cedar, hemlock, grand fir forests stands, leading to lower carbon sequestration because of lower density of some species (western larch, ponderosa pine and western white pine) and increased shade tolerant species. High densities increased susceptibility to wildfire. Heart rot and root rot in cedar and hemlock decreases carbon sequestration and timber values. Adaption Strategy / Approach: Promote diversity in species composition and structure at multiple spatial scales (within stands and across the landscape). Strategy Objective: Promote resilience and increase carbon sequestration.					
	Specific Tactic – A	Specific Tactic – B	Specific Tactic – C	Specific Tactic – D	Specific Tactic – E
Tactic	Conduct regeneration harvest and planting to promote shade-intolerant tree species (western larch, ponderosa pine, white pine, birch) and rust-resistant white pine.	Promote western white pine.	Conduct density management thinning to retain shade-intolerant trees and develop large trees across the landscape; prune younger western white pine to promote resistance to blister rust.	Increase knowledge on how the different tree densities and species compositions within this group function as habitats and how the mosaic of stands influence connectivity for wildlife.	Develop a site-related prioritization approach for implementing management tactics.
Tactic effectiveness (risks)	High	High	High	Unknown	High
Implementation urgency	Mid-term				
Where can tactics be applied? (geographic)	Within this vegetation type				
Opportunities for implementation					
Cost					
Barriers to implementation					

Table 6C.10—Adaptation options that address climate change effects on forest vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Whitebark pine mortality from increased mountain pine beetle outbreaks, fire and blister rust and shifts/loss of site conditions that support whitebark pine.		
Adaption Strategy / Approach: Restore whitebark pine.		
Strategy Objective: Increase rust resistant regeneration and cone bearing trees.		
Tactic	Specific Tactic – A Assess condition; save seed sources; grow rust resistant seedlings; collect seed; plant seedlings; monitor activities; prioritize treatment; and conduct research (Mirror Keane range-wide restoration strategy).	Specific Tactic – B Identify sites that are likely to not be as heavily affected (refugia), and focus on those sites for restoration.
Tactic effectiveness (risks)		
Implementation urgency		
Where can tactics be applied? (geographic)		
Opportunities for implementation		
Cost	Cost of planting is high	
Barriers to implementation	The majority of whitebark pine is in wilderness or other protected areas, or in roadless areas with limited access. Thus, the ability to treat directly is limited. There is a lack of understanding or commitment by personnel. Need comprehensive long term planning and commitment at multiple levels. Funding for climate change adaption implementation is not coming to the ground level.	

Table 6C.11—Adaptation options that address climate change effects on forest vegetation in the Eastern Subregion.

Sensitivity to climatic variability and change: Increased frequency of disturbance, drought, browsing, and livestock trampling may reduce vigor and extent of aspen, even given the unique upward trend of aspen in pine forests that have extensive beetle-caused mortality.			
Adaption Strategy / Approach: Maintain and restore/promote the health and vigor of clones (specific key stressors include repeat disturbance, conifer competition, browse/trampling).			
Strategy Objective: Maintain the current population trend, promote resilience, reduce stressors/threats, and increase knowledge.			
Tactic	Specific Tactic – A Actively manage ungulates during regeneration phase through slash barriers, increase in hunting pressure, grazing management and salt block placement.	Specific Tactic – B Implement conifer removal on multiple scales and through hand and commercial treatments.	Specific Tactic – C Monitor extent and condition of aspen clones to determine the effect of disturbance frequency on aspen survival, effects of sudden aspen decline, and incidence of new clones; potentially implement strategic protection measures for specific clones.
Tactic effectiveness (risks)	High	Highest	Moderate to high
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Wherever aspen regeneration prescriptions are applied	Wherever aspen occurs outside of protected areas	Wherever aspen occurs
Opportunities for implementation	Rocky Mountain Elk Foundation, permittees	Rocky Mountain Elk Foundation	Rocky Mountain Elk Foundation
Cost	Varies by tool Expensive – fencing Inexpensive – grazing management	Inexpensive	Moderate
Barriers to implementation	Some – litigation, scale and timing to be effective (staffing capacity), priority, permittees	Some – litigation, scale and timing to be effective (staffing capacity), priority	None

Table 6C.12—Adaptation options that address climate change effects on forest vegetation in the Eastern Subregion.

Sensitivity to climatic variability and change: Ability of Douglas-fir to develop stands with large, old-growth structure in face of fire, drought, beetles, budworm and limited cone production.				
Adaption Strategy / Approach: Establish age class and structural diversity to promote landscape heterogeneity, which could provide appropriate amounts and distribution of large tree structure.				
Strategy Objective: Promote resilience, and reduce stressors and threats.				
Tactic	Specific Tactic – A Manage stand level disturbance through thinning, prescribed fire and natural fire management to accelerate the development of large tree structure.	Specific Tactic – B Manage landscape disturbance to achieve heterogeneity in structural diversity.	Specific Tactic – C Identify critical stands with high value and large diameter for direct protection from fire and insects; protect using pesticides, stand manipulation, fire protection, and windthrow monitoring.	Specific Tactic – D Improve cone production in key seed collection areas through fertilizer, pesticides and stand manipulation.
Tactic effectiveness (risks)	High – thinning Moderate – fire	Moderate–high	High	Moderate
Implementation urgency	Near–mid term	Near–mid term	Near term	Near term
Where can tactics be applied? (geographic)	Throughout species range	Throughout species range	Throughout species range	Throughout species range
Opportunities for implementation	Forest plan; restoration committees	Forest plan; restoration committees	Coordinate with wildlife priorities	Inland Empire Cooperatives
Cost	Inexpensive	Inexpensive	Inexpensive	Inexpensive–moderate
Barriers to implementation	Some – litigation, scale and timing to be effective (staffing capacity), priority	Some – litigation, scale and timing to be effective (staffing capacity), priority	None	None

Table 6C.13—Adaptation options that address climate change effects on forest vegetation in the Eastern Subregion.

Sensitivity to climatic variability and change: Limited ability of limber pine to persist and regenerate in the face of frequent fires, blister rust and pine beetle; challenges include uncertainties in genetic variation and geographically disjunct populations found in the eastern subregion.

Adaption Strategy / Approach: Maintain viable populations of limber pine in suitable environments.

Strategy Objective: Promote resilience, reduce impacts of stressors/threat, increase knowledge, engage coordination.

Tactic	Specific Tactic – A Address information gaps on current location, potential habitat and stand condition through coordination with other groups.	Specific Tactic – B Address genetic data gaps by establishing a breeding program that includes rust resistance screening, seed zones and drought tolerance through coordination with other groups.	Specific Tactic – C Conduct stand treatments to promote resilience over a wide geographic area; protect remaining trees with pesticides and stand thinning, and establish a planting program to achieve scattered, mature individuals.
Tactic effectiveness (risks)	High	High	High at local stand level Moderate at population level
Implementation urgency	Near term	Near term	Near term: improve resilience of existing stands Mid term: planting (answer genetic questions first)
Where can tactics be applied? (geographic)	Forest plans, Region 1 broad scale monitoring strategy	Inland Empire Cooperatives	Forest plans, restoration committees
Opportunities for implementation	All lands – federal, state, districts, communities, universities	All lands – federal, state, districts, communities, universities	All lands – federal, state, districts, communities, universities
Cost	Moderate	Moderate	Inexpensive
Barriers to implementation	None	None	Some – litigation, scale and timing to be effective (staffing capacity), priority

Table 6C.14—Adaptation options that address climate change effects on forest vegetation in the Eastern Subregion.

Sensitivity to climatic variability and change: Small, fragmented populations of eastside ponderosa pine are vulnerable to loss of regeneration capability following repeated disturbance, especially in ecotone sites.			
Adaption Strategy / Approach: Maintain genetic diversity, population viability, increase resilience, and promote big-tree structure.			
Strategy Objective: Promote resilience, reduce stressors/threats, and facilitate transition.			
Tactic	Specific Tactic – A Manage stand level disturbance through thinning, prescribed fire and natural fire management to accelerate the development of large tree structure and facilitate the transition to a savanna ecotone.	Specific Tactic – B Develop seed collection and reforestation strategies to address potential loss of genetic variability due to disjunct populations and shortened mean return interval of severe disturbances.	Specific Tactic – C Identify critical stands with high value and large diameter for direct protection from fire and insects; protect with pesticides, stand manipulation and fire protection.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Low elevation ecotones; suitable ponderosa pine sites	Low elevation ecotones; suitable ponderosa pine sites	Low elevation ecotones; suitable ponderosa pine sites
Opportunities for implementation	Forest management; coordination with fire management	Forest management; Inland Empire Cooperatives	Forest management; wildlife habitat priorities
Cost	Inexpensive	Inexpensive-moderate	Inexpensive
Barriers to implementation	Some – litigation, scale and timing to be effective (staffing capacity), priority	None	Some – litigation, scale & timing to be effective (staffing capacity), priority

Table 6C.15—Adaptation options that address climate change effects on forest vegetation in the GYA Subregion.

Sensitivity to climatic variability and change: Climate change forces us to work across boundaries. Stressors cross boundaries. The public expects coordination.			
Adaption Strategy / Approach: Work across jurisdictions at larger scales.			
Strategy Objective: Encourage coordination.			
Tactic	Specific Tactic – A Align budgets/priorities for program of work for neighboring lands (e.g., constrained budget forces cooperation for invasive species strategies).	Specific Tactic – B Communicate about adjacent projects and coordinate on the ground; develop memorandum of understanding for adjacent projects.	Specific Tactic – C Preserve roads, trails, and access in despite increased fire and flood events.
Tactic effectiveness (risks)	High (if we succeed)	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation	All lands - federal, state, districts, communities, universities	All lands - federal, state, districts, communities, universities	All lands - federal, state, districts, communities, universities
Cost	Inexpensive	Inexpensive	Moderately expensive
Barriers to implementation	Major barriers - politics	Some barriers - politics, time, lack of priority, distance, travel budget	Major barriers – shrinking budget, staffing

Table 6C.16—Adaptation options that address climate change effects on forest vegetation in the GYA Subregion.

Sensitivity to climatic variability and change: Increased fire and disease, and interactions with the wildland urban interface.				
Adaption Strategy / Approach: Increase the resilience of forest stands to disturbance, and protect people from potential risks of increased fire.				
Strategy Objective: Manage fires in a way to protect the wildland urban interface.				
Tactic	Specific Tactic – A Create buffer zones between fire and residential development, and implement thinning.	Specific Tactic – B Influence development zoning in high risk areas with local government and insurance companies.	Specific Tactic – C Increase forest diversity through heterogeneity of species composition, age class and structure.	Specific Tactic – D Promote education and communication about responsible land owner tactics.
Tactic effectiveness (risks)	Moderate – intense fires cross boundaries, having unintended impacts on resources and cultural landscapes	High (if we can do it)	Moderate – huge fires, climate change	Moderate
Implementation urgency				
Where can tactics be applied? (geographic)				
Opportunities for implementation				
Cost				
Barriers to implementation	Land designation			

Table 6C.17—Adaptation options that address climate change effects on forest vegetation in the GYA Subregion.

Sensitivity to climatic variability and change: Increased impacts from fire, pests, disease, climate and increased competition.				
Adaption Strategy / Approach: Promote resilient whitebark pine communities.				
Strategy Objective: Maintain whitebark pine on the landscape.				
Tactic	Specific Tactic – A Actively remove other dominant tree species, such as lodgepole pine, spruce and fir.	Specific Tactic – B Prioritize management for populations with high potential survival.	Specific Tactic – C Implement a variety of management strategies/options, such as control sites, fire management, and possibly planting at lower elevations.	Specific Tactic – D Replant screened, grafted, genetically-selected seedlings to promote blister rust resistance.
Tactic effectiveness (risks)	Unknown – Not sure if it will work. See barriers.	Moderate – uncertainty, models not considering all factors	Moderate – see barrier	Moderate – see barriers
Implementation urgency	Near term	Near term to long term – more information needed	Near term	Near term
Where can tactics be applied? (geographic)	Where we have access; road, management designation	Greater Yellowstone Area	Greater Yellowstone Area	Where we have access and permission
Opportunities for implementation	Overall whitebark pine strategies, investment strategy niches, Greater Yellowstone Coordinating Committee (GYCC)	Overall whitebark pine strategies, investment strategy niches, GYCC	Overall whitebark pine strategies, investment strategy niches, GYCC	We already have the trees and selected planting locations
Cost	Moderately expensive	Inexpensive	Expensive	Moderately expensive
Barriers to implementation	Major barriers - Limited by wilderness designations, road access, litigation, compliance	Major barriers - Limited by wilderness designations, road access, litigation, cost	Major barriers - - Limited by wilderness designations, road access, litigation, cost	Some barriers – ideal places, access, cost

Table 6C.18—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increased impacts from moisture stress and fire.			
Adaption Strategy / Approach: Actively reduce density and maintain low densities.			
Strategy Objective: Promote forest resilience through density management.			
Tactic	Specific Tactic – A Implement precommercial and commercial thinning.	Specific Tactic – B Conduct prescribed fires.	Specific Tactic – C Influence stand density with planting.
Tactic effectiveness (risks)	High	Moderate – depends on stand conditions	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Be cautious with root disease sensitive species and sites	Applied to maintain fire tolerant conifer species and maintaining structure	Apply where opportunities for thinning are null due to species or stand condition
Opportunities for implementation			
Cost	Inexpensive	Inexpensive	Inexpensive
Barriers to implementation	Some - barriers greater for federal lands. Funding at the landscape scale is less than needed. There are thinning restrictions due to lynx.	Some - barriers greater for federal lands	Some - barriers greater for federal lands

Table 6C.19—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increased frequency and scale of disturbances such as fire and drought.			
Adaption Strategy / Approach: Promote disturbance-resilient species, such as ponderosa pine, western larch, western white pine, Douglas-fir, and lodgepole pine.			
Strategy Objective: Promote forest vegetation resilience to disturbance.			
Tactic	Specific Tactic – A Promote thinning to favor disturbance-resilient species.	Specific Tactic – B Promote planting of disturbance-resilient species.	Specific Tactic – C Promote resilient species with prescribed fire and/or natural fire use.
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Western larch and western white pine on moist sites, ponderosa pine on dry sites, Douglas-fir on extremely dry sites, and lodgepole pine on harsh, difficult to regenerate sites	Western larch and western white pine on moist sites, ponderosa pine on dry sites, Douglas-fir on extremely dry sites, and lodgepole pine on harsh, difficult to regenerate sites	Western larch and western white pine on moist sites, ponderosa pine on dry sites, Douglas-fir on extremely dry sites, and lodgepole pine on harsh, difficult to regenerate sites
Opportunities for implementation	Any place management is feasible and allowed	Any place management is feasible and allowed	Any place management is feasible and allowed
Cost	Inexpensive	Inexpensive	Inexpensive
Barriers to implementation	Scale will vary because of budgetary limitations	Scale will vary because of budgetary limitations	Scale will vary because of budgetary limitations. Natural fire may not occur where or when manageable.

Table 6C.20—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing disturbance, moisture deficits, stress due to densities, and longer growing seasons.			
Adaption Strategy / Approach: Increase knowledge on current issues, strategies, and future goals.			
Strategy Objective: Increase knowledge for agency land managers and stakeholders.			
Tactic	Specific Tactic – A Address definition of connectivity, including species guilds and scale, and identify existing and historical conditions in order to develop desired conditions.	Specific Tactic – B Share knowledge on tree species migration at fine and broad scales, and track regeneration success, species distribution at the fine scale, species transfer zones, habitat type and soil type.	Specific Tactic – C Share knowledge on fire regimes in spruce-fir forests and increase collaboration with the Rocky Mountain Research Station.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Landscape	Landscape	Landscape
Opportunities for implementation	All lands – federal, state, districts, communities, and universities	All lands – federal, state, districts, communities, and universities	All lands – federal, state, districts, communities, and universities
Cost	Inexpensive	Inexpensive	Moderately expensive
Barriers to implementation	Funding, lack of understanding	Funding, lack of understanding	Funding, lack of understanding

Table 6C.21—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing disturbance, moisture deficits, stress due to densities, and longer growing seasons.			
Adaption Strategy / Approach: Increase knowledge on current issues, strategies, and future goals.			
Strategy Objective: Increase knowledge for agency land managers and stakeholders.			
Tactic	Specific Tactic – A Address how to manage conservation areas, such as research natural areas and roadless wilderness. Promote the important components within these areas and desired conditions.	Specific Tactic – B Communicate the accurate mapping of important species such as whitebark pine.	Specific Tactic – C Address the desired conditions at the landscape level and also for important wildlife habitat by tackling the “how much is enough?” question.
Tactic effectiveness (risks)	Moderate	High	High
Implementation urgency	Mid-term	Near term	Near term
Where can tactics be applied? (geographic)	Program level	Program and forest level	Program and forest level
Opportunities for implementation	Rocky Mountain Research Station, The Nature Conservancy, Wilderness Society, universities, tribes, conservation partners	Universities, conservation partners, state heritage programs	Rocky Mountain Research Station, universities, tribes, conservation partners
Cost	Moderate	Moderate	Moderate
Barriers to implementation	Time	Time	Time

Table 6C.22—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing disturbance, moisture deficits, stress due to densities, and longer growing seasons.		
Adaption Strategy / Approach: Increase knowledge on current issues, strategies, and future goals.		
Strategy Objective: Increase knowledge for agency land managers and stakeholders.		
Tactic	Specific Tactic – A Increase awareness on the role of root disease in carbon sequestration by publishing Hagues root disease data.	Specific Tactic – B Communicate the need for improved integration between wildlife managers and forest ecologists, and between research and management. Conduct an annual meeting with Rocky Mountain Research Station on management needs for research.
Tactic effectiveness (risks)		High
Implementation urgency		Near term
Where can tactics be applied? (geographic)		Program/Region 1 and Rocky Mountain Research Station
Opportunities for implementation		Program/Region 1 and Rocky Mountain Research Station
Cost		Inexpensive
Barriers to implementation		Lack of time and impetus to do it

Table 6C.23—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing disturbance, moisture deficits, stress due to densities, and longer growing seasons.			
Adaption Strategy / Approach: Promote resilience in forest vegetation.			
Strategy Objective: Promote resilience by reducing stressors and facilitating transitions.			
Tactic	Specific Tactic – A Reduce forest densities to increase fire resilience in lodgepole pine and whitebark pine sites with precommercial thinning.	Specific Tactic – B Reduce forest densities to increase fire resilience in lodgepole pine and whitebark pine sites with commercial thinning.	Specific Tactic – C Promote appropriate density conditions and landscape heterogeneity within mapped lynx habitat in spruce-fir forests.
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term	Near term	Mid term
Where can tactics be applied? (geographic)	Higher elevations	Higher elevations	Higher elevations
Opportunities for implementation	Whitebark Pine Ecosystem Foundation, Forest Health Protection, programmatic National Environmental Policy Act work, stewardship contracting	Whitebark Pine Ecosystem Foundation, Forest Health Protection, programmatic National Environmental Policy Act work	Rocky Mountain Research Station, state fish and game, U.S. Fish and Wildlife Service, fire management
Cost	Moderate	Moderate	Moderate
Barriers to implementation	Endangered species (lynx), lack of available funding, access and short operating season, management limitations within roadless wilderness, and potential litigation	Endangered species (lynx), lack of available funding, access and short operating season, management limitations within roadless wilderness, and potential litigation	Knowledge gaps in desired conditions

Table 6C.24—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing disturbance, moisture deficits, stress due to densities, and longer growing seasons.			
Adaption Strategy / Approach: Promote resilience in forest vegetation.			
Strategy Objective: Promote resilience by reducing stressors and facilitating transitions.			
Tactic	Specific Tactic – D Promote legacy trees of western larch, Douglas-fir, western white pine, Engelmann spruce, whitebark pine, and alpine larch.	Specific Tactic – E Establish seed collection and seed bank needs for alpine larch, whitebark pine, and high-elevation western larch. Coordinate with other land managers/owners on post-wildfire reforestation and planting of whitebark pine.	Specific Tactic – F Promote landscape heterogeneity and create connectivity at multiple scales through strategic placement of treatment units. Increase patch size/treatments and cross-ownership boundary coordination.
Tactic effectiveness (risks)	High	High	Moderate
Implementation urgency	Near term	Near term	Mid term
Where can tactics be applied? (geographic)	Within dense spruce-fir-lodgepole pine sites	Where these species occur	Landscape
Opportunities for implementation	Forest plan desired conditions and project	Whitebark Pine Ecosystem Foundation, volunteers (e.g., backcountry horseman and stakeholders), Forest Health Protection	Forest plan desired conditions and project
Cost	Inexpensive – can be done in conjunction with project	Expensive because of remote location/poor access, but volunteers can help reduce costs	Moderately expensive
Barriers to implementation	None other than lack of these trees in some areas and windthrow risk	Budget (to reduce this barrier, solicit partners); wilderness/roadless policy limitations	Some barriers - knowledge gaps in desired conditions.

Table 6C.25—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing disturbance, moisture deficits, stress due to densities, and longer growing seasons.			
Adaption Strategy / Approach: Promote resilience in forest vegetation.			
Strategy Objective: Promote resilience by reducing stressors and facilitating transitions.			
Tactic	Specific Tactic – G Promote rapid response and assessment for post-fire reforestation.	Specific Tactic – H Implement a triage approach to soil moisture conditions (e.g., loess soil mapping) for prioritizing areas for western white pine and whitebark pine.	Specific Tactic – I Protect high value trees (plus other trees, cone producers, and rare species) via management actions, including pheromones and seed orchards.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Throughout zone	Throughout zone	Throughout zone
Opportunities for implementation	Burned area emergency response	Intermountain Forest Tree Nutrition Cooperative, Natural Resources Conservation Service, Rocky Mountain Research Station	Whitebark Pine Ecosystem Foundation, volunteers, Forest Health Protection
Cost	Moderate	Moderate	Moderate
Barriers to implementation	Burned area emergency response does not fund planting; commitment from forests; lack of strategy	Funding; lack of understanding of utility by forests	Funding

Table 6C.26—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Accelerated root disease mortality due to climate stressors.			
Adaption Strategy / Approach: Reduce dominance of root disease sensitive species (e.g., Douglas-fir and grand fir) on root disease-prone sites.			
Strategy Objective: Facilitate transition.			
Tactic	Specific Tactic – A Regenerate and plant with species less susceptible to root disease.	Specific Tactic – B Thin out root disease-susceptible species where less root disease-susceptible species are abundant.	Specific Tactic – C Conduct a hot prescribed burn, followed by a re-burn.
Tactic effectiveness (risks)	High	Moderate	Unknown
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Root disease-prone sites with current root disease losses and where management is allowed	Root disease-prone sites; in areas where management is allowed; where adequate, less susceptible species are present and current losses are low	Root disease prone sites and in areas where management is allowed
Opportunities for implementation			
Cost	Inexpensive	Inexpensive	Inexpensive
Barriers to implementation	Where losses are severe and timber value may not cover cost of site preparation	May not be highest priority	5-year regeneration requirement

Table 6C.28—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing moisture demands and drought stress in moisture demanding species (western hemlock and western redcedar) on upland sites.

Adaption Strategy / Approach: Minimize the effects to the stand from the affected species (western hemlock and western redcedar).

Strategy Objective: Promote resilience and facilitate transition.

Tactic	Specific Tactic – A Implement precommercial thinning to limit dominance of these species on drought-prone sites.	Specific Tactic – B Encourage regeneration harvest and planting with a more diverse species mix.	Specific Tactic – C Preserve road and trail access despite increased fire and flood events.
Tactic effectiveness (risks)	Moderate	High	Moderate
Implementation urgency	Near term	Near term	Mid term
Where can tactics be applied? (geographic)			
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 6C.28—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increasing moisture demands and drought stress in moisture demanding species (western hemlock and western redcedar) on upland sites.

Adaption Strategy / Approach: Minimize the effects to the stand from the affected species (western hemlock and western redcedar).

Strategy Objective: Promote resilience and facilitate transition.

Tactic	Specific Tactic – A Implement precommercial thinning to limit dominance of these species on drought-prone sites.	Specific Tactic – B Encourage regeneration harvest and planting with a more diverse species mix.	Specific Tactic – C Preserve road and trail access despite increased fire and flood events.
Tactic effectiveness (risks)	Moderate	High	Moderate
Implementation urgency	Near term	Near term	Mid term
Where can tactics be applied? (geographic)			
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 6C.29—Adaptation options that address climate change effects on forest vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Western white pine is resilient but underrepresented.			
Adaption Strategy / Approach: Increase presence of western white pine.			
Strategy Objective: Promote resilience and facilitate transition.			
Tactic	Specific Tactic – A Implement planting of blister rust resistant western white pine.	Specific Tactic – B Implement blister rust pruning.	Specific Tactic – C Retain existing natural white pine when thinning, harvesting, and burning.
Tactic effectiveness (risks)	High	High	Thinning/harvest – high Burning – moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Western redcedar, western hemlock and moist grand fir habitat types (and on moister microsites of drier habitat types)	Stands with moderate infection, but low infection above pruning height; may be critical if thinning	Where western white pin is present
Opportunities for implementation			
Cost	Inexpensive	Inexpensive	Inexpensive
Barriers to implementation	Openings are lacking because of limited timber harvest and fire suppression.	Insufficient funds and access	More difficult on steep ground, where fire is needed for site preparation

Table 7A.1—Adaptation options that address climate change effects on non-forested vegetation in the Central Subregion.

Sensitivity to climatic variability and change: Increased susceptibility of vegetation communities (e.g., grasslands) to invasive species. Effects of climate change on grasslands will be amplified by management actions.				
Adaptation Strategy / Approach: Increase proactive management actions in order to prevent invasive species				
Strategy Objective: Reduce stressors/threats, engage coordination, increase knowledge				
Tactic	Specific Tactic – A Conduct integrated weed management (i.e., spraying, chemical, biological, mechanical, manual control, education, targeted grazing).	Specific Tactic – B Develop weed management areas and coordinate with multiple agencies, non-governmental organizations, and public.	Specific Tactic – C Apply early detection rapid response (EDRR) and inventory and mapping.	Specific Tactic – D Update weed risk assessment (WRA) to enhance integrated weed management.
Tactic effectiveness (risks)	High	High (if properly implemented)	High	Moderate
Implementation urgency	Near term	Near term	Near term	Mid term
Where can tactics be applied? (geographic)	Recreation high use areas (roads), administrative areas; Lolo Creek (Missoula District for sheep/goat grazing)	Recreation high use areas (roads); administrative areas	Wilderness protected areas	Multi-scale effort
Opportunities for implementation	Coordinate with multiple agencies, non-governmental organizations, public; opportunity to graze in newly acquired lands (sheep/goats)	Coordinate with multiple agencies, non-governmental organizations, public	Coordinate with multiple agencies, non-governmental organizations, public, employees	Coordinate with federal and state agencies
Cost	Expensive	Inexpensive/moderately expensive (depends on implementation scale)	Inexpensive/moderately expensive	Moderately expensive
Barriers to implementation	Management support; conflict between bighorn sheep and domestic	Community support; social economic barriers (e.g., education, trust, holdouts)	Lack of acceptance that it is a priority	Time, lack of prioritization

Table 7A.2—Adaptation options that address climate change effects on non-forested vegetation in the Eastern Subregion.

Sensitivity to climatic variability and change: Increased temperature and drought will cause more and larger wildfires, leading to mortality of sagebrush and grasslands and increased dominance of fire-adapted herbaceous and non-native species.				
Adaptation Strategy / Approach: Maintain intact ecosystems, and increase resilience and resistance of native sagebrush-grass ecosystems.				
Strategy Objective: Promote resilience, reduce stressors/threats, engage coordination, and increase knowledge.				
Tactic	Specific Tactic – A Inventory intact/high native cover/weed free areas.	Specific Tactic - B Employ preventative measures to reduce the spread and introduction of invasive species into intact/weed free plant communities.	Specific Tactic – C Survey for new invasive species.	Specific Tactic – D Manage priority invasive species on priority acres.
Tactic effectiveness (risks)	High	Moderate to high	High	Moderate
Implementation urgency	Near term	Near term	Near term	Near term
Where can tactics be applied? (geographic)	On all lands (where access can be granted)	Areas that are currently weed free	On all lands (where access can be granted)	On priority acres
Opportunities for implementation	Work with agencies, counties, state, non-profit and private land owners to share and incorporate current and future inventory data	Work with agencies, counties, state, non-profit and private land owners to partner in weed prevention strategies and practices	Work with agencies, counties, state, non-profit and private land owners to share and incorporate current and future survey data, technology	Work with agencies, counties, state, non-profit and private land owners to collaborate on invasive species management activities
Cost	Moderately expensive	Inexpensive to moderately expensive	Moderately expensive	Inexpensive to moderately expensive
Barriers to implementation	Some to major barriers - staff capacity; budgets; priorities	Some to major barriers - public and internal awareness and perception; funding	Some to major barriers - staff capacity; budgets; priorities	Some to major barriers - budget; plant identification and phenology; capacity

Table 7A.2 (cont.)—Adaptation options that address climate change effects on non-forested vegetation in the Eastern Subregion

Sensitivity to climatic variability and change: Increased temperature and drought will cause more and larger wildfires, leading to mortality of sagebrush and grasslands and increased dominance of fire-adapted herbaceous and non-native species.				
Adaptation Strategy / Approach: Maintain intact ecosystems, and increase resilience and resistance of native sagebrush-grass ecosystems.				
Strategy Objective: Promote resilience, reduce stressors/threats, engage coordination, and increase knowledge.				
Tactic	Specific Tactic – E Restore to minimize or reverse adverse effects.	Specific Tactic - F Manage conifer encroachment.	Specific Tactic – G Manage fire for resource benefits.	Specific Tactic – H Promote the occurrence and growth of early-season natives.
Tactic effectiveness (risks)	Moderate to high	Low to high	Moderate to high	Moderate
Implementation urgency	Near term	Near term	Near term	Short term
Where can tactics be applied? (geographic)	Degraded non-forest vegetation communities	Priority areas based on current condition and potential response to treatment	Priority areas based on current condition and potential response to fire	Sagebrush-dominated areas where native species have significant populations and non-natives are not dominant
Opportunities for implementation	Collaborate with partners on the design and implementation of restoration activities	Collaborate with partners on conifer encroachment management activities	Collaborate with agencies, counties, state, non-profit and private land owners on fire management	Coordinate with range permittees
Cost	Inexpensive to expensive	Inexpensive to moderately expensive	Inexpensive to moderately expensive	Moderately expensive, depending on work needed
Barriers to implementation	Some to major barriers – awareness and recognition of need	Some to major barriers – litigation; burn windows; awareness and recognition of need	Some to major barriers - Recognition of need; public and internal perception and risk aversion	Some barriers: Some public opposition

Table 7A.2 (cont.)—Adaptation options that address climate change effects on non-forested vegetation in the Eastern Subregion

Sensitivity to climatic variability and change: Increased temperature and drought will cause more and larger wildfires, leading to mortality of sagebrush and grasslands and increased dominance of fire-adapted herbaceous and non-native species.				
Adaptation Strategy / Approach: Maintain intact ecosystems, and increase resilience and resistance of native sagebrush-grass ecosystems.				
Strategy Objective: Promote resilience, reduce stressors/threats, engage coordination, and increase knowledge.				
Tactic	Specific Tactic – I Reduce grazing in July and August to encourage perennial growth.	Specific Tactic – J Manage livestock grazing through planning efforts that serve as livestock movement guides (within-season triggers) and allow for the maintenance and/or enhancement of plant health (end-point indicators).	Specific Tactic – K Use targeted grazing to address contemporary vegetation management challenges (e.g., control invasive exotic and noxious weeds and undesirable species, reduce fire risk).	Specific Tactic – L Identify and manage (e.g., close, obliterate, re-route) non-system/user created routes (roads and trails).
Tactic effectiveness (risks)	Moderate	Low to moderate	Low to moderate	Low to high
Implementation urgency	Mid term	Near term	Near to mid term	Near term
Where can tactics be applied? (geographic)	Areas with high probability of recovery, primarily moist sites	On all grazed lands	Priority areas based on current condition and potential response to treatment	On priority areas
Opportunities for implementation	Coordinate with range permittees	Livestock managers	Livestock managers	Partner with National Forest Foundation, NGOs
Cost	Inexpensive	Inexpensive to moderately expensive	Inexpensive to moderately expensive	Inexpensive to moderately expensive
Barriers to implementation	Opposition by some permittees	Commitment by managers; compliance by livestock managers; staff capacity	Public perception, National Environmental Policy Act; litigation; logistics and access	Awareness; detection; budget; perception of need (internal and external);

Table 7A.3—Adaptation options that address climate change effects on non-forested vegetation in the Grasslands Subregion.

Sensitivity to climatic variability and change: Phenological mismatch between pollinators and host plants.		
Adaptation Strategy / Approach: Maintain and restore natural habitat to ensure pollination.		
Strategy Objective: Promote resilience, reduce stressors/threat.		
Tactic	Specific Tactic – A Restore and enhance habitat (using tools such as grazing, fire, herbicide application, reseeding).	Specific Tactic – B Implement long term monitoring of pollinators (e.g., research, tech transfer, education, citizen science projects, and monitor existing populations).
Tactic effectiveness (risks)	Depends on the combination of tools	Not applicable
Implementation urgency	Near term	Near term
Where can tactics be applied? (geographic)	Use ecological site descriptions to identify priority areas for restoration or enhancement	Look at native and non-native ecosystems, overlap in these ecosystems and the types of pollinators present
Opportunities for implementation	Take advantage of other restoration activities; public involvement	Search for existing information; engage with Natural Resources Conservation Service, Agricultural Research Service, state extensions, North Dakota Department of Agriculture for education on pollinators and agricultural practices; opportunity for citizen science projects to detect broad trends
Cost	Cost varies by tool; shared cost with other restoration projects	Inexpensive with partnerships (i.e., citizen science projects)
Barriers to implementation	Some of the restoration tools may adversely impact the habitat.	

Table 7A.4—Adaptation options that address climate change effects on non-forested vegetation in the Grasslands Subregion.

Sensitivity to climatic variability and change: Encroachment of native species into grasslands (i.e., willow [<i>Salix</i>], sumac [<i>Rhus</i>], juniper [<i>Juniperus</i>], snowberries [<i>Gaultheria</i>], ponderosa pine [<i>Pinus ponderosa</i>]).			
Adaptation Strategy / Approach: Restore natural disturbance regimes in grasslands.			
Strategy Objective: Promote resilience, reduce stressors/threats			
Tactic	Specific Tactic – A Conduct prescribed fires.	Specific Tactic – B Conduct mechanical treatments (chainsaws, mowing, mastication, logging, lop and scatter, haying, grazing).	Specific Tactic – C Use herbicide (use appropriate delivery method).
Tactic effectiveness (risks)	Moderate	Moderate/high	High
Implementation urgency			
Where can tactics be applied? (geographic)	Use ecological site descriptions to determine where to apply prescribed fire		
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 7A.5—Adaptation options that address climate change effects on non-forested vegetation in the Grasslands Subregion.

Sensitivity to climatic variability and change: Encroachment of non-native species into grasslands (i.e., leafy spurge [<i>Euphorbia esula</i>], knapweed [<i>Centaurea</i>], sulphur cinquefoil [<i>Potentilla recta</i>], Canada thistle [<i>Cirsium arvense</i>], Russian olive [<i>Elaeagnus angustifolia</i>], hounds tongue [<i>Cynoglossum officinale</i>], redtop [<i>Agrostis stolonifera</i>], cattail [<i>Typha</i>], reed canary grass [<i>Phalaris arundinacea</i>], paleyellow iris [<i>Iris pseudacorus</i>], Japanese brome [<i>Bromus japonicus</i>], Kentucky bluegrass [<i>Poa pratensis</i>], smooth brome [<i>Bromus inermis</i>], crested wheatgrass [<i>Agropyron cristatum</i>], cheatgrass [<i>Bromus tectorum</i>], sweet clover [<i>Melilotus</i>], absinth wormwood [<i>Artemisia absinthium</i>], black henbane [<i>Hyoscyamus niger</i>], buckthorn [<i>Rhamnus</i>]).			
Adaptation Strategy / Approach: Maintain and increase resilience of native grassland communities.			
Strategy Objective: Promote resilience.			
Tactic	Specific Tactic – A Use ecological site descriptions to prioritize areas for treatment (<i>wouldn't apply to all the species listed above</i>).	Specific Tactic – B Apply biological control.	Specific Tactic – C Implement prescriptive grazing, fire, herbicide and re-seeding (timing, duration, frequency, kind and class of livestock).
Tactic effectiveness (risks)	Moderate/high	Low-high	Moderate/high
Implementation urgency	Near term	Dependent on research	Near term
Where can tactics be applied? (geographic)	Forest/grassland/sub region level	Where it is likely to be effective and not have unintended consequences	Forest/grassland/sub region level
Opportunities for implementation	Interagency weed working groups	Interagency weed working groups	Interagency weed working groups; US Fish and Wildlife Service; interagency fire program; ranchers
Cost	Varies	Varies by agent	Moderately expensive/ expensive
Barriers to implementation	Lack of knowledge; funding and training	Uncertainty and unintended consequences of using biological control in a changing climate	Social perceptions (e.g., grazing, fire, herbicide use)

Table 7A.5 (cont.)—Adaptation options that address climate change effects on non-forested vegetation in the Grasslands Subregion

Sensitivity to climatic variability and change: Encroachment of non-native species into grasslands.				
Adaptation Strategy / Approach: Maintain and increase resilience of native grassland communities.				
Strategy Objective: Promote resilience.				
	Specific Tactic – D	Specific Tactic – E	Specific Tactic – F	Specific Tactic – G
Tactic	Apply early detection rapid response.	Use best invasive management practices to address vectors; emphasize invasive species education (e.g., teach people how to clean their equipment, boots).	Conduct internal and external education and outreach.	Maintain and increase agency, state and county cooperation on invasive weeds.
Tactic effectiveness (risks)	High	High	High	High
Implementation urgency	Near term	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Wherever new invasions are	Forest/grassland/region level	Forest/grassland/region level	Forest/grassland/region level
Opportunities for implementation	Interagency weed working groups	Interagency weed working groups; field technicians	Interagency weed working groups; field technicians	Interagency weed working groups
Cost	Inexpensive	Inexpensive	Inexpensive	Inexpensive
Barriers to implementation	Plant identification skills	Plant identification skills; turnover of local population	Plant identification skills; turnover of local population	Coordinated action (need mechanism to ensure continued coordination)

Table 7A.6—Adaptation options that address climate change effects on non-forested vegetation in the GYA Subregion.

Sensitivity to climatic variability and change: Increase in fire frequency and intervals, invasive species, herbivory, and species shift (C4)				
Adaptation Strategy / Approach: Increase resilience of C3 grassland communities to the above sensitivities, and maintain C3 grassland communities on the landscape.				
Strategy Objective: Promote resilience, reduce stressors/threats.				
Tactic	Specific Tactic – A Allow natural and prescribed fire.	Specific Tactic – B Conduct ecologically based invasive plant management; use herbivory (goats), biocontrol, wildfire, and seeding (e.g., smooth brome).	Specific Tactic – C Conduct inventory of data, including maps and risk assessments; use Early Detection Rapid Response (EDRR) and weed-free policies regarding stock; conduct inventory and monitoring.	Specific Tactic – D Remove conifers with mechanical treatments, prescribed fire, and harvest.
Tactic effectiveness (risks)	Moderate	Moderate	High	High
Implementation urgency	Mid term	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Expand beyond wildland urban interface; apply in areas with healthy vegetation	Prioritize small/new invasions by most critical species; work back to road corridors and developed areas	EDRR for all new findings	Encroached communities
Opportunities for implementation	Implement projects per forest management plan	Effective at local levels; not at landscape scale	Effective at local levels; not at landscape scale	Small watershed or landscape of 1000-1500 acres
Cost	Cost varies by project size and complexity	Moderately expensive	Inexpensive	Moderately expensive
Barriers to implementation	Some barriers: Community acceptance; litigation; risk aversion; lack of non-WUI funding	Major barriers: Community acceptance; capacity; need to scale up to be effective; perceived lack of urgency	Some barriers: Lack of champions; workforce availability; perceived lack of urgency	Some barriers: Staffing; litigation; availability of burn windows; fiscal year limitations; risk aversion

Table 7A.7—Adaptation options that address climate change effects on non-forested vegetation in the GYA Subregion.

Sensitivity to climatic variability and change: Increase in fire severity and frequency, invasive species, and herbivory.			
Adaptation Strategy / Approach: Increase resilience of mountain sagebrush community to the above sensitivities, and maintain sagebrush communities on the landscape.			
Strategy Objective: Maintain current trend. Promote resilience. Reduce stressors/threats.			
Tactic	Specific Tactic – A Strategically place fuels treatments (thinning, mulching, limited suppression) across the landscape.	Specific Tactic – B Conduct ecologically based invasive plant management (EBIPM); use herbivory (goats), biocontrol, wildfire, and seeding.	Specific Tactic – C Conduct inventory of data, including maps and risk assessments; use Early Detection Rapid Response (EDRR) and weed-free policies regarding stock; conduct inventory and monitoring.
Tactic effectiveness (risks)	Moderate	Moderate	High
Implementation urgency	Near term/mid term	Near term	Near term
Where can tactics be applied? (geographic)	Expand beyond wildland urban interface; apply in areas with existing healthy vegetation	Prioritize small/new invasions by most critical species; work back to road corridors and developed areas	EDRR for all new findings
Opportunities for implementation	Implement projects per forest management plan; be opportunistic when wildfire does strike (crew availability; community acceptance)	Public Lands Day and other volunteer projects; partner with wildlife and other stakeholder groups for habitat improvement	Public Lands Day and other volunteer projects; partner with wildlife and other stakeholder groups for habitat improvement (Trout Unlimited, friends group).
Cost	Moderately expensive; cost varies by project size and complexity	Moderately expensive	Inexpensive
Barriers to implementation	Some barriers: political; community acceptance; litigation; risk aversion; lack of non-wildland urban interface funding	Major barriers: community acceptance; availability of workforce; need to scale up to be effective; perceived lack of urgency	Some barriers: lack of champions; workforce availability; perceived lack of urgency

Table 7A.7 (cont.)—Adaptation options that address climate change effects on non-forested vegetation in the GYA Subregion

Sensitivity to climatic variability and change: Increase in fire severity and frequency, invasive species, and herbivory.		
Adaptation Strategy / Approach: Increase resilience of mountain sagebrush community to the above sensitivities, and maintain sagebrush communities on the landscape.		
Strategy Objective: Maintain current trend. Promote resilience. Reduce stressors/threats.		
Tactic	Specific Tactic – D Determine and implement proper grazing; conduct adaptive management that recognizes climate changes will lead to different availability of range; use rest and rotation practices.	Specific Tactic – E Remove conifers with mechanical treatments, prescribed fire, and harvest.
Tactic effectiveness (risks)	High	High
Implementation urgency	Moderate	Near term
Where can tactics be applied? (geographic)	Everywhere	Encroached communities
Opportunities for implementation	Coordinate with range permittees; cultivate management support.	Coordinate with fuels and habitat objectives for interagency and partnership work (and funding; commercial harvest
Cost	Inexpensive	Moderately expensive
Barriers to implementation	Some barriers: Lack of stakeholder support (real or perceived); lack of trust; noncompliance; perceived lack of urgency	Some barriers: Staffing levels; litigation; uncertain availability of burn windows due to climate change; fiscal year limitations; challenges with interagency and/or non-fed implementation and coordinated planning efforts; risk aversion

Table 7A.8—Adaptation options that address climate change effects on non-forested vegetation in the GYA Subregion.

Sensitivity to climatic variability and change: Increase in fire severity and frequency, invasive species, and herbivory.		
Adaptation Strategy / Approach: Increase resilience of Wyoming sagebrush community to the above sensitivities.		
Strategy Objective: Maintain sagebrush communities on the landscape; create and maintain a healthy and diverse plant community.		
Tactic	Specific Tactic – A Strategically place fuels treatments (thinning, mulch, limited suppression) across the landscape.	Specific Tactic – B Conduct ecologically based invasive plant management (EBIPM); use herbivory (goats), biocontrol, wildfire, and seeding.
Tactic effectiveness (risks)	Moderate	Moderate (unless strict adherence to EBIPM, then high)
Implementation urgency	Near term/Mid term	Near term
Where can tactics be applied? (geographic)	Anywhere we can; expand beyond wildland urban interface; apply tactic in areas with existing healthy intact vegetation; avoid degraded areas	Prioritize small/new invasions by most critical species; work back to road corridors and developed areas in non-wilderness.
Opportunities for implementation	Implement projects per forest management plan; be opportunistic when wildfire does strike (crew availability; community acceptance)	Public Lands Day and other volunteer projects; partner with wildlife and other stakeholder groups for habitat improvement (Trout Unlimited, friends groups)
Cost	Moderately expensive; cost varies by project size and complexity	Moderately expensive
Barriers to implementation	Some barriers: Political; community acceptance; management and community tolerance; litigation; risk aversion; lack of non-wildland urban interface funding	Major barriers: Community acceptance; availability of workforce; methodology; public perception; technology; need to scale up to be effective; perceived lack of urgency

Table 7A.8 (cont.)—Adaptation options that address climate change effects on non-forested vegetation in the GYA Subregion

Sensitivity to climatic variability and change: Increase in fire severity and frequency, invasive species, and herbivory.		
Adaptation Strategy / Approach: Increase resilience of Wyoming sagebrush community to the above sensitivities.		
Strategy Objective: Maintain sagebrush communities on the landscape; create and maintain a healthy and diverse plant community.		
Tactic	Specific Tactic – C Conduct inventory of data, including maps and risk assessments; use Early Detection Rapid Response (EDRR) and weed-free policies regarding stock; conduct inventory and monitoring.	Specific Tactic – D Determine and implement proper grazing; conduct adaptive management that recognizes climate changes will lead to different availability of range; use rest and rotation practices.
Tactic effectiveness (risks)	High	High
Implementation urgency	Near term	Moderate
Where can tactics be applied? (geographic)	EDRR for all new findings	Everywhere
Opportunities for implementation	Public Lands Day and other volunteer projects; partner with wildlife and other stakeholder groups for habitat improvement (Trout Unlimited, friends groups)	Coordinate with range permittees; cultivate management support.
Cost	Inexpensive	Inexpensive
Barriers to implementation	Some barriers: Lack of champions; workforce availability; perceived lack of urgency	Some barriers: Lack of stakeholder support (real or perceived); lack of trust; noncompliance; perceived lack of urgency

Table 7A.9—Adaptation options that address climate change effects on non-forested vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Increase in fires, warmer drier conditions, and invasive species, and decline in pollinators. With warmer wetter conditions, conifers are establishing in balds and snow belts because of changes in precipitation from snow to rain.		
Adaptation Strategy / Approach: Maintain healthy and intact grasslands.		
Strategy Objective: Maintain and increase resilience from perturbation and resistance to invasive species; reduce weed invasion; increased knowledge of the ecology of grasslands.		
Tactic	Specific Tactic – A Maintain or restore adequate native plant cover, vigor, and species richness; ensure ecologically significant remnant populations of endemics are maintained; tools include appropriate grazing management, focused herbicide use, re-vegetation (with locally adapted and site specific species, forbs and graminoids), appropriate fire management, appropriate travel management, maintaining public land management of ecologically significant remnant plant communities (e.g., rough fescue, Palouse prairie), and conservation easements.	Specific Tactic – B Encourage native pollinators; provide other habitats for pollinators (nesting cover, feeding cover, brooding cover); tools include re-vegetation (with native species), appropriate herbicide and insecticide use, and education for public and within agency.
Tactic effectiveness (risks)	Low/moderate/high	Moderate/high
Implementation urgency	Near term/ongoing	Near term/ongoing
Where can tactics be applied? (geographic)	Throughout current range of grasslands; management activities are species specific	Throughout
Opportunities for implementation	Acquiring remnant populations (partners: The Nature Conservancy (TNC), working with tribes, private landowners, land trusts); conservation easements (TNC, local land trusts)	Xerces Society; native plant societies; local garden clubs; local conservation groups; Idaho Master Naturalists; youth organizations (high schools, 4H)
Cost	Inexpensive/moderately expensive	Inexpensive/ moderately expensive
Barriers to implementation	Multiple land ownership and fragmentation; lack of scientific knowledge; reduced budgets for inventory and monitoring	Farm Bill language; introduction of non-native pollinators; use of insecticides; multiple ownerships

Table 7A.9 (cont.)—Adaptation options that address climate change effects on non-forested vegetation in the Western Subregion

Sensitivity to climatic variability and change: Increase in fires, warmer drier conditions, and invasive species, and decline in pollinators. With warmer wetter conditions, conifers are establishing in balds and snow belts because of changes in precipitation from snow to rain.		
Adaptation Strategy / Approach: Maintain healthy and intact grasslands.		
Strategy Objective: Maintain and increase resilience from perturbation and resistance to invasive species; reduce weed invasion; increased knowledge of the ecology of grasslands.		
Tactic	Specific Tactic – C Step 1 - Identify and map soil types (locate molisols); Step 2 - Prioritize restoration based on Step 1; sites that were historically maintained have now shifted to conifer savannas; identify sites that were fire maintained versus snow maintained.	Specific Tactic - D Step 1 - Map risk areas for severe drought, and conduct snow melt risk analysis; Step 2 - Establish targeted areas for monitoring based on step 1 (re-visit and monitor established plots); Step 3 - Work with geneticists to isolate frost and drought hardiness, early emergence; Step 4 - Use seed sources with those traits (step 3) to help vegetate specific sites that were identified in step 1.
Tactic effectiveness (risks)	Step 1/2 moderate	High
Implementation urgency	Near term	Step 1 – near term; step 2 – ongoing dependent on prioritization of areas
Where can tactics be applied? (geographic)	In identified and mapped areas	In identified risk areas
Opportunities for implementation	Partnerships with Natural Resources Conservation Service (NRCS)	Heritage Program (for monitoring); partner with NRCS, National Oceanic and Atmospheric Administration (snow melt data), Rocky Mountain Research Station; local cooperators to help with seed accessions and Forest Service nursery
Cost	Moderately expensive	Moderately expensive
Barriers to implementation	Funding; time and personnel intensive; Requires finer-scale knowledge to be effective; higher priorities (mindset)	Funding; time and personnel intensive; higher priorities? (mindset); sequential process

Table 7A.10—Adaptation options that address climate change effects on non-forested vegetation in the Western Subregion.

Sensitivity to climatic variability and change: Loss of topsoil and invasion of weeds.		
Adaptation Strategy / Approach: Maintain and increase montane shrublands.		
Strategy Objective: Maintain and increase resilience from perturbation and resistance to invasive species; reduce weed invasion; increased knowledge of the ecology of shrublands.		
Tactic	Specific Tactic – A Implement fuel reduction projects (i.e., reduce conifer encroachment, brush cutting, slashing/ mastication without burning, targeted browsing); if burning is used, design prescriptions according to requirements of desired shrub species (soil moisture requirements, desired end result conditions).	Specific Tactic – B Maintain adequate shrub cover, vigor, and species richness, and avoid bare ground; create different age classes and compositions of shrubfields (shifting mosaic); no action is a viable alternative dependent on system; tools include removal of timber products, targeted grazing, prescribed burning, and mastication/slashing.
Tactic effectiveness (risks)	Moderate (unintended consequences, higher priorities)	Moderate/high
Implementation urgency	Near term/ongoing	Near term/ongoing
Where can tactics be applied? (geographic)	Throughout; critical areas for restoration	Throughout and across jurisdictional boundaries
Opportunities for implementation	Partners – Rocky Mountain Elk Foundation, sportsmen associations, Idaho Fish and Game, Bureau of Land Management, Idaho Forest Landowner association; forest harvests open up new shrublands	Partners – Rocky Mountain Elk Foundation, sportsmen associations, Idaho Fish and Game, BLM, Idaho Forest Landowner association, Turkey Federation
Cost	Inexpensive/moderately expensive (depends on scale)	Inexpensive/moderately expensive (depends on scale)
Barriers to implementation	Current forest management policies about allowing shrubfields to be maintained rather than reforestation; mindset of current land managers (tradition)	Mindset of current land managers (tradition); lack of equipment; availability of target livestock; road access; inaccessibility (slope); multi-resource objectives

Table 7A.10 (cont.)—Adaptation options that address climate change effects on non-forested vegetation in the Western Subregion

Sensitivity to climatic variability and change: Loss of topsoil and invasion of weeds.		
Adaptation Strategy / Approach: Maintain and increase montane shrublands.		
Strategy Objective: Maintain and increase resilience from perturbation and resistance to invasive species; reduce weed invasion; increased knowledge of the ecology of shrublands.		
Tactic	Specific Tactic – C Apply early detection rapid response (EDRR), and use ecologically based invasive plant management (EBIPM); tools include biocontrol, herbicides, timing burning prescriptions (to avoid annual brome expansion, and targeted grazing).	Specific tactic - D Educate fuels specialists, forest ecologists, wildlife biologists and silviculturists on ecology and disturbances affecting shrublands; effects of repeated burns; shifting mosaics (creating a balance of types across landscapes); and weeds (identification, awareness, reporting).
Tactic effectiveness (risks)	Low/moderate	Moderate
Implementation urgency	Near term/ongoing	Near term/ongoing
Where can tactics be applied? (geographic)	Throughout and across jurisdictional boundaries	Throughout and across land management jurisdictions
Opportunities for implementation	Coordinate with private landowners; cooperative weed management areas; partner with Bonneville Power, tribes, private groups such as backcountry horsemen, National Forest Foundation; use volunteer cooperators (for surveys and monitoring)	Revise Forest Service manual; brownbag lunch – weed webinar; educational products such as flyers, posters; ross training and/or internal training for line officers
Cost	Inexpensive/moderately expensive (depends on scale)	Moderately expensive
Barriers to implementation	Multiple jurisdictions; National Environmental Policy Act – not being able to adapt to new chemicals; logistically inaccessible (backpack or on horse); public mindset of using chemicals; budgets are prohibitive.	Tie implementation to performance for achieving objectives (misuse of herbicides, treating non-target native plants); need line officer support; mindset of current land managers (tradition); public mindset of using chemicals

Table 9A.1—Adaptation options that address climate change effects on wildlife in the Central Subregion.

Sensitivity to climatic variability and change: Potential conversion to grassland type; many ponderosa pine forests have converted to Douglas-fir types with fire exclusion and are therefore more susceptible to future fires (putting dry forest cavity nester habitat at risk).			
Adaption Strategy / Approach: Restore fire-adapted ponderosa pine stand conditions for dry forest cavity nesters.			
Strategy Objective: Promote resilience.			
Tactic	Specific Tactic – A Reduce competition from Douglas-fir and grand fir (thin, burn) in current mature ponderosa pine stands.	Specific Tactic – B Conduct frequent understory burning.	Specific Tactic – C Retain current mature and older ponderosa pine stands and plant where it has been lost.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Low elevations with emphasis on where compatible with wildland urban interface (WUI) objectives; need redundancy across the landscape to buffer against future fire or drought mortality	Has to follow tactic A in the WUI, not necessarily in non-developed areas; need redundancy across the landscape to buffer against future fire or drought mortality	Wherever they occur; need redundancy across the landscape to buffer against future fire or drought mortality
Opportunities for implementation	Collaboration with other landowners	Collaboration with other landowners	Collaboration with other landowners
Cost	Low in places with market size DF, otherwise moderate.	Moderate, depending on location	Low for retaining, moderate for planting
Barriers to implementation	Some	Major	None

Table 9A.2—Adaptation options that address climate change effects on wildlife in the Central Subregion.

Sensitivity to climatic variability and change: Drying of inland maritime forest types that fishers depend on.			
Adaption Strategy / Approach: Maintain current, restore historical, and promote potential future fisher habitat. Conserving fisher habitat preserves cool wet forest types that provide habitat for multiple other wildlife species.			
Strategy Objective: Promote resilience, facilitate transition			
Tactic	Specific Tactic – A Conserve current old-growth cedar and larch, but reduce density to increase resilience to drought.	Specific Tactic – B Restore white pine with a cedar understory to create future habitat.	Specific Tactic – C Maintain or create necessary structure in modeled future fisher habitat.
Tactic effectiveness (risks)	Moderate	Uncertain	Unknown (will that be habitat) and uncertain (can the conditions be effectively created)
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Northern ID, Kootenai, Bitterroot divide; where risk of loss is greatest (edge of range); eed redundancy across the landscape to buffer against future fire or drought mortality	Northern ID, Kootenai, Bitterroot divide; need redundancy across the landscape to buffer against future fire or drought mortality	Mission side of Swan; need redundancy across the landscape to buffer against future fire or drought mortality
Opportunities for implementation	Fits with Collaborative Forest Landscape Restoration Program (CFLRP) objectives	Fits with CFLRP objectives	Fits with CFLRP objectives
Cost	Inexpensive	Moderate	Varies
Barriers to implementation	Major	None	Some

Table 9A.3—Adaptation options that address climate change effects on wildlife in the Central Subregion.

Sensitivity to climatic variability and change: Snow melt occurring earlier in the spring creates snowshoe hare pelage mismatch. Lynx adapted to deep soft snow and denser snow could give other predators a competitive advantage. Burn intensity is predicted to increase, and repeat burns can reduce tree seed source; in winter, lynx avoid high intensity burns until tree regeneration allows for branches at snow surface.				
Adaption Strategy / Approach: Manage vegetation for long-term lynx and hare habitat and connectivity.				
Strategy Objective: Promote resilience, reduce stressors, and facilitate transition.				
Tactic	Specific Tactic – A Thin some young stands to create a variety of multi-storied hare habitat across the landscape to prevent boom and bust cycles.	Specific Tactic – B Maintain forest cover connections between good habitat patches.	Specific Tactic – C Maintain current multi-storied forest conditions, prevent large monoculture stand conditions (burning, harvest).	Specific Tactic – D Analyze female home ranges to determine necessary mix of habitat patches (distribution and size).
Tactic effectiveness (risks)	Uncertain	Moderate	Moderate	Moderate
Implementation urgency	Near Term	Near Term	Near Term	Near Term
Where can tactics be applied? (geographic)	Anywhere in current range of lynx	Anywhere in current range of lynx	Anywhere in current range of lynx	Anywhere in current range of lynx
Opportunities for implementation	Forest Planning; U.S. Fish and Wildlife Service	U.S. Fish and Wildlife Service	Northern Rockies Lynx Management Direction; critical habitat rule; U.S. Fish and Wildlife Service	U.S. Fish and Wildlife Service; Rocky Mountain Research Station; Collaborative Forest Landscape Restoration Program; Southwest Crown Partnership
Cost	Moderate	Inexpensive	Moderate	Inexpensive
Barriers to implementation	Major	Major	None	None

Table 9A.4—Adaptation options that address climate change effects on wildlife in the Central Subregion.

Sensitivity to climatic variability and change: Townsend's big-eared bat maternal colonies winter hibernacula are sensitive to temperature change, loss of access to habitat, and spread of white-nose syndrome.

Adaption Strategy / Approach: Maintain maternal colony and hibernacula sites, and reduce non-climate stressors.

Strategy Objective: Increase knowledge, promote resilience, reduce stressors, engage coordination

Tactic	Specific Tactic – A Identify, and protect current maternal colony sites.	Specific Tactic – B Monitor environmental conditions at identified sites, compared to unoccupied sites.	Specific Tactic – C Educate the public (caver groups) about spread of white-nose syndrome and stress decontamination procedures.	Specific Tactic – D Maintain, or create, open wetland complexes (for insects) near maternal colony sites.
Tactic effectiveness (risks)	High	Moderate, but not an end point itself	Moderate	Unknown
Implementation urgency	Near term	Near term	Near term	Near to mid term
Where can tactics be applied? (geographic)	Range wide	Public land	Range wide	Public land
Opportunities for implementation	Local caving clubs	Local caving clubs	Local caving clubs	Mostly on private lands
Cost	Moderate	Inexpensive	Inexpensive	Variable
Barriers to implementation	Some	Some	None	Some

Table 9A.5—Adaptation options that address climate change effects on wildlife in the Central Subregion.

Sensitivity to climatic variability and change: Increasing winter temperatures reduce snowpack, and snow melt occurs earlier in the spring. Wolverine are obligate snow denners.			
Adaption Strategy / Approach: Maintain wolverine female reproductive capacity and core habitat connection.			
Strategy Objective: Reduce stressors.			
Tactic	Specific Tactic – A Map areas with high persistent snow potential; identify protection status and development potential to identify areas of concern and connection between mountain ranges.	Specific Tactic – B Identify dispersal habitat requirements.	Specific Tactic – C Conduct multi-carnivore genetic monitoring.
Tactic effectiveness (risks)	High	Variable	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Range wide	Range wide	Range wide
Opportunities for implementation			Coordinate existing monitoring, and develop regional monitoring goals.
Cost	Inexpensive	Expensive	Expensive
Barriers to implementation	None	Some	Some

Table 9A.6—Adaptation options that address climate change effects on wildlife in the Eastern Subregion.

Sensitivity to climatic variability and change: Pygmy rabbits are dependent on big-sage, which may be vulnerable to climate change, but range could expand with climate change.			
Adaption Strategy / Approach: Increase information on distribution and sensitivities of pygmy rabbit.			
Strategy Objective: Increase knowledge.			
Tactic	Specific Tactic – A Produce more accurate sage distribution layer.	Specific Tactic – B Update and expand knowledge of existing pygmy distribution.	Specific Tactic – C Understand climate influences on pygmy rabbits.
Tactic effectiveness (risks)	Moderate	Moderate	Moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Eastern subregion	Eastern subregion	Eastern subregion
Opportunities for implementation		Heritage program.	Wildlife Conservation Society study at the Idaho National Lab; candidate for State Wildlife Grant funding
Cost	Moderate	Moderate	Moderate
Barriers to implementation	Some: funding priority	Some: funding priority	Some: funding priority, not on anyone's radar screen

Table 9A.7—Adaptation options that address climate change effects on wildlife in the Eastern Subregion.

Sensitivity to climatic variability and change: Pygmy rabbits are dependent on big-sage, which may be vulnerable to climate change, but range could expand with climate change.			
Adaption Strategy / Approach: Conserve pygmy rabbit habitat.			
Strategy Objective: Promote resilience.			
Tactic	Specific Tactic – A Obtain conservation easements in current sagebrush areas.	Specific Tactic – B Lease sagebrush.	Specific Tactic – C Understand succession after fire in sagebrush in the region.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Sagebrush habitat on unprotected private land	Sagebrush habitat on private and state land	Sagebrush habitat
Opportunities for implementation	Land Reliance; partners		
Cost	Inexpensive (cost-sharing and is happening now, even though a lot of money is spent)	Inexpensive (happening now, even though a lot of money is spent)	Inexpensive to moderate
Barriers to implementation	Some: land owner willingness; political consequences	Some	Funding priorities; lack of understanding for the need for the information; difference of opinion about what we already know

Table 9A.8—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Bat hibernaculum temperature change linked to white-nose syndrome; alternative energy development impacts (wind power).			
Adaption Strategy / Approach: Maintain healthy bat populations.			
Strategy Objective: Reduce stressors; increase knowledge and coordination.			
Tactic	Specific Tactic – A Consider summer roosting in vegetation management.	Specific Tactic – B Protect hibernaculum from disturbance.	Specific Tactic – C Survey for hibernacula.
Tactic effectiveness (risks)	Uncertain	Moderate	Uncertain
Implementation urgency			
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 9A.9—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Reduced stream flow, loss of riparian vegetation, incised stream channels due to flood events.			
Adaption Strategy / Approach: Maintain healthy beaver populations on the landscape.			
Strategy Objective: Promote resilience; reduce stressors; increase public knowledge (slow down the water).			
Tactic	Specific Tactic – A Inventory current and potential habitat (include multiple factors).	Specific Tactic – B Restore riparian habitat (e.g., plant willows, manage grazers, raise water level).	Specific Tactic – C Translocate beavers, manage trapping.
Tactic effectiveness (risks)	High	High	High
Implementation urgency			
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 9A.10—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Habitat shifts and disease transmission in bighorn sheep from direct and indirect effects of climate change (e.g., increase in overlap with domestics, increased disease transmission, shifts in pressure from recreation).			
Adaption Strategy / Approach: Maintain healthy bighorn sheep populations.			
Strategy Objective: Increase knowledge; reduce stressors; promote resilience.			
Tactic	Specific Tactic – A Monitor sheep disease trends to determine if there are climate drivers.	Specific Tactic – B Identify locations and improve connectivity between seasonal ranges; maintain separation from domestic sheep.	Specific Tactic – C Maintain communication among research groups and promote sharing of information and collaboration of research/management efforts.
Tactic effectiveness (risks)	Unknown	High	Moderate
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation	Focus of current attention (state, federal, non-governmental organizations, universities)	Focus of current attention (state, federal, non-governmental organizations, universities)	Focus of current attention (state, federal, non-governmental organizations, universities)
Cost	Inexpensive	Moderately to expensive depending on scale	Inexpensive
Barriers to implementation	None	Some to major (social, legal, jurisdiction)	None

Table 9A.11—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Loss of mountain sage and grassland habitat for Brewer's sparrow.			
Adaption Strategy / Approach: Maintain adequate mountain sage grassland communities for Brewer's sparrow.			
Strategy Objective: Promote resilience, reduce stressors, and increase knowledge.			
Tactic	Specific Tactic – A Manage fire to maintain desired habitat (see sage-grouse conservation strategy).	Specific Tactic – B Control invasive vegetation.	Specific Tactic – C Restore formerly cultivated land.
Tactic effectiveness (risks)	High	Low to high depending on the invasive species	Low to high depending on site conditions
Implementation urgency			
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 9A.12—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Water supply; habitat loss; habitat shifts; vegetation phenology shifts; human population expansion and redistribution; snowpack dynamics.			
Adaption Strategy / Approach: Maintain connectivity within and through the Greater Yellowstone Area (GYA), including daily, seasonal, dispersal, and range shift connectivity.			
Strategy Objective: Facilitate transition; engage coordination; increase knowledge			
Tactic	Specific Tactic – A Monitor connectivity (genetics, tracking, remote sensing).	Specific Tactic – B Compile table of connectivity (daily through range shift) vulnerability by species.	Specific Tactic – C Identify and remove barriers.
Tactic effectiveness (risks)	Moderate	High	High
Implementation urgency			
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation	New technologies (e.g., eDNA, remote cameras, GPS collars) make this more accessible		
Cost			
Barriers to implementation			

Table 9A.13—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Moose prefer colder temperatures; increased disease potential in warmer climates; increased algal growth in warmer ponds; precipitation patterns affect growth of preferred vegetation.			
Adaption Strategy / Approach: Maintain healthy moose habitats (e.g., riparian, aspen, spruce-fir) and populations.			
Strategy Objective: Reduce stressors; engage coordination.			
Tactic	Specific Tactic – A Reduce mortality; coordinate with state agencies to reduce hunting quotas; coordinate to reduce highway mortality.	Specific Tactic – B Increase knowledge and monitoring of disease and pests.	Specific Tactic – C Improve riparian habitat: see beaver sheet.
Tactic effectiveness (risks)	Moderate	Moderate	High
Implementation urgency			
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 9A.14—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Loss of aspen due to warmer, drier climate and lower water table.			
Adaption Strategy / Approach: Maintain adequate habitat structural diversity to support ruffed grouse populations.			
Strategy Objective: Promote resilience; increase knowledge.			
Tactic	Specific Tactic – A Promote disturbance (fire, cutting) in older aspen stands.	Specific Tactic – B Protect from grazing (fencing, manage grazing).	Specific Tactic – C Reduce conifer competition (fire, cutting) in any age aspen stand.
Tactic effectiveness (risks)	High	High	High
Implementation urgency			
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 9A.15—Adaptation options that address climate change effects on wildlife in the GYA Subregion.

Sensitivity to climatic variability and change: Loss of sage and grassland habitat for greater sage grouse.				
Adaption Strategy / Approach: Maintain adequate sage grassland communities, with inclusion of mesic meadows (brood rearing), for greater sage grouse.				
Strategy Objective: Promote resilience, reduce stressors, increase knowledge				
Tactic	Specific Tactic – A Manage fire to maintain desired habitat (see sage-grouse conservation strategy).	Specific Tactic – B Control invasive vegetation.	Specific Tactic – C Restore formerly cultivated land.	Specific Tactic – D Limit anthropogenic disturbance (e.g., grazing, hunting, infrastructure).
Tactic effectiveness (risks)	High	Low to High depending on the invasive species	Low to high depending on site conditions	High
Implementation urgency				
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation				
Cost				
Barriers to implementation				

Table 9A.16—Adaptation options that address climate change effects on wildlife in the Western Subregion.

Sensitivity to climatic variability and change: Conversion to nonnatives; change in fire frequency; reduction in cover; change of available forage could affect insects, affecting mountain quail habitat.			
Adaption Strategy / Approach: Reduce stressors on mountain quail.			
Strategy Objective: Promote resilience, reduce stressors			
Tactic	Specific Tactic – A Reduce high intensity burns using fuel breaks and late winter burning to reduce fuel buildup.	Specific Tactic – B Maintain conifer components, including north face and higher elevation riparian stringers to retain moisture in microsites; replant; protect from burning; avoid harvesting.	Specific Tactic – C Need more information on insect production and the forb component associated with moist areas; how will insects react with phenology changes?
Tactic effectiveness (risks)			
Implementation urgency			
Where can tactics be applied? (geographic)	Western subregion	Western subregion	Western subregion
Opportunities for implementation			
Cost			
Barriers to implementation			

Table 10A.1—Adaptation options that address climate change effects on recreation in the Central Subregion.

Sensitivity to climatic variability and change: Risk to infrastructure with changes in the frequency and severity of natural hazards and disturbances.			
Adaption Strategy / Approach: Manage recreation sites to mitigate natural hazards.			
Strategy Objective: Increase the resiliency of recreation sites by reducing threats and encouraging coordination with partners.			
Tactic	Specific Tactic – A Maintain safety by assessing risk factors.	Specific Tactic – B Identify flood plains and risks to campgrounds (developed sites) and dispersed recreation sites.	Specific Tactic – C Identify effects after disturbance to recreation sites and prioritize treatments or conversions (e.g., relocate, arming, and/or mitigation measures).
Tactic effectiveness (risks)	Moderate–high	Moderate–high	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)	Forest lands or adjacent lands; high risk disturbance areas	Forest wide	National Forest System lands
Opportunities for implementation	Work with other agencies, such as the Federal Emergency Management Agency; use existing data for tree mortality and add species and overlay of use areas	Model risk of storm events, such as rain-on-snow events and flood events (including post-fire floods)	Rapid assessment teams; learn from other agencies, such as the Park Service
Cost	Moderately expensive	Moderately expensive	Moderately expensive
Barriers to implementation	Some - organizational will; leadership commitment; internal resistance, priority setting; integration and interpretation of data and models	Some - external partner support and coordination	Some - forest capacity (resources and funding); public resistance to relocations and closures

Table 10A.2—Adaptation options that address climate change effects on recreation in the Central Subregion.

Sensitivity to climatic variability and change: Changes in demand for warm weather recreation.			
Adaption Strategy / Approach: Transition to address extended seasons or changing use patterns.			
Strategy Objective: Provide sustainable recreation opportunities in response to changing demand.			
Tactic	Specific Tactic – A Assess use patterns to understand demand shifts and address recreation niches identified for the area.	Specific Tactic – B Identify natural resource impacts and increase coordination with partners and concessionaires.	Specific Tactic – C Adjust capacity issues such as enlarging campgrounds and fee opportunities.
Tactic effectiveness (risks)	Moderate	Moderate-high	High
Implementation urgency	Near term	Mid term	Mid term
Where can tactics be applied? (geographic)	National, regional, forest and local levels	Forest level	Local level
Opportunities for implementation	Coordinate with states, local communities; enhance National Visitor Use and Monitoring processes with sub-surveys	Annual operation meetings, meetings with target user groups, special interest groups meetings	Limited opportunities
Cost	Moderately expensive	Moderately expensive	Moderate – expensive
Barriers to implementation	Ability to acquire or predict patterns of use is difficult because demand is difficult to determine; lack of leadership support to engage in studies; low priority in program of work regionally and nationally; declining budgets and staffing	Shifting demographics	Political and environmental justice fees

Table 10A.3—Adaptation options that address climate change effects on winter recreation in the Central Subregion.

Sensitivity to climatic variability and change: Threats to winter recreation			
Adaption Strategy / Approach: Transition to address shorter average season and changing use patterns.			
Strategy Objective: Provide sustainable recreation in response to changing demand.			
Tactic	Specific Tactic – A Shift winter use, address safety concerns, and engage partners to implement changes needed in use.	Specific Tactic – B Create management areas and direction addressing concentrated winter use areas through forest planning; communicate with partners, cooperators and other agencies and maintain recreation internet sites with access information.	Specific Tactic – C Relocate sites as necessary and add signs to guide the public.
Tactic effectiveness (risks)	Moderate	Moderate-high	Moderate
Implementation urgency	Mid term	Near term	Mid term
Where can tactics be applied? (geographic)	Winter recreation sites	Designated management areas	Winter recreation sites
Opportunities for implementation	Nordic clubs; special interest groups; partnerships; increased public interest; impacts as climate changes	Forest Planning – Revision Efforts Project planning Avalanche Centers State Agreements	Integrate projects to include recreation; large landscape efforts; adjusted stewardship law to include recreation
Cost	Moderately expensive	Moderately expensive	Expensive
Barriers to implementation	Our ability to respond	Timing, unclear direction for those not in revision; lacks leadership support to engage	Environmental resources; cultural and political

Table 10A.4—Adaptation options that address climate change effects on recreation in the Eastern Subregion.

Sensitivity to climatic variability and change: Recreation access needs may change with climate change, including change to location, season of use, type of use, and duration of use.			
Adaption Strategy / Approach: Ensure that access is adequate for projected recreation use and demand and compatible with resource and climate change conditions.			
Strategy Objective: Facilitate transition of recreation access to ensure relevancy and resiliency by season of use and changing use patterns.			
Tactic	Specific Tactic – A Evaluate and prioritize existing access by season (e.g., trailheads and trails) to ensure consistency with changing recreation opportunity spectrum settings with climate change.	Specific Tactic – B Identify new access needs and potential changes to existing access by season.	Specific Tactic – C Strategically invest in new and potential changes to existing access by season.
Tactic effectiveness (risks)	High	High	High/moderate
Implementation urgency	Near term	Mid term	Mid term
Where can tactics be applied? (geographic)	Federal lands	Federal lands	Federal lands
Opportunities for implementation	Partners	Partners	Partners
Cost	Moderate	Moderate	Moderate
Barriers to implementation	Some (funding/capacity)	Some (funding/capacity)	Some (funding)

Table 10A.5—Adaptation options that address climate change effects on recreation in the Eastern Subregion.

Sensitivity to climatic variability and change: Recreation settings (recreation opportunity spectrum and scenery), both motorized and non-motorized, during all seasons will be affected by the expected changes in climate.			
Adaption Strategy / Approach: Align our recreation settings with changing landscape conditions and demand.			
Strategy Objective: Facilitate transition of recreation settings to achieve flexibility, relevancy and resiliency; maintain those recreation settings that complement our niches.			
Tactic	Specific Tactic – A Assess existing recreation opportunity spectrum settings and scenic character to determine which are most vulnerable to climate change effects.	Specific Tactic – B Develop management strategies to shift or maintain existing recreation opportunity spectrum settings and scenic character in response to climatic change.	Specific Tactic – C Develop a sub-regional niche.
Tactic effectiveness (risks)	High	High	Moderate/low
Implementation urgency	Mid term	Mid term	Near term
Where can tactics be applied? (geographic)	Federal lands	Federal lands	Federal lands
Opportunities for implementation	None	None	None
Cost	Moderately expensive	Moderately expensive	Inexpensive
Barriers to implementation	Some barriers	Some barriers	None

Table 10A.6—Adaptation options that address climate change effects on recreation in the Eastern Subregion.

Sensitivity to climatic variability and change: Cultural and heritage resources may be affected by changes in climate, technology, demographics, and culture.		
Adaption Strategy / Approach: Protect cultural and heritage sites and the sacred uses of traditional cultural landscapes.		
Strategy Objective: Acknowledge the importance of cultural and heritage sites and protect valuable sites.		
Tactic	Specific Tactic – A Inventory and identify those areas at most risk to climate change and changes in use patterns, and mitigate the effects.	Specific Tactic – B Develop interpretation and education opportunities to educate the public in areas or resources most at risk.
Tactic effectiveness (risks)	Moderate	Moderate
Implementation urgency	Near term	Near term
Where can tactics be applied? (geographic)	Greater Yellowstone Area	Greater Yellowstone Area
Opportunities for implementation	Tribes; Tribal Historic Preservation Office; universities, State Historic Preservation Officer; Passport in Time volunteers	Tribes; Tribal Historic Preservation Office; universities, State Historic Preservation Officer; Passport in Time volunteers
Cost	Expensive	Moderately expensive
Barriers to implementation	Some - Forest Service capacity and funding	Some - Forest Service capacity and funding

Table 10A.7—Adaptation options that address climate change effects on recreation in the Eastern Subregion.

Sensitivity to climatic variability and change: Recreation user demand and the shift in recreation activity, amount of use, and patterns of use will be driven by climate change, technology, demographics, and culture.			
Adaption Strategy / Approach: Align our recreation opportunities with future demand to commercial (permitted) and non-commercial recreation users.			
Strategy Objective: Facilitate transition of recreation opportunities to achieve flexibility, relevancy and resiliency.			
Tactic	Specific Tactic – A Understand the changes in demand, demographics, and economic trends, both regionally and nationally.	Specific Tactic – B Conduct research to clearly identify localized impacts of climate change.	Specific Tactic – C Conduct research to understand the latest and upcoming technology that impacts recreation.
Tactic effectiveness (risks)	High	High	High
Implementation urgency	Near term	Near term	Near term
Where can tactics be applied? (geographic)			
Opportunities for implementation	Partners, research, university, non-governmental organizations	Partners, research, university, non-governmental organizations	Partners, research, university, non-governmental organizations
Cost	Moderate	Moderate	Moderate
Barriers to implementation	Some - expertise, agency culture	Some - expertise, agency culture	Some - expertise, agency culture

Table 10A.8—Adaptation options that address climate change effects on recreation in the Eastern Subregion.

Sensitivity to climatic variability and change: The future viability of recreation facilities will be affected by changes in climate.			
Adaption Strategy / Approach: Provide recreation facilities that accommodate future demand, and reduce user and natural resource conflicts.			
Strategy Objective: Facilitate transition of recreation opportunities to achieve flexibility, relevancy and resiliency.			
Tactic	Specific Tactic – A Prioritize existing recreation facilities, by season, for viability, investment, and change in services.	Specific Tactic – B Invest strategically in developed recreation facilities.	Specific Tactic – C Design facilities for flexibility in use.
Tactic effectiveness (risks)	Moderate	Moderate-high	Moderate
Implementation urgency	Near term	Mid term	Mid term
Where can tactics be applied? (geographic)			
Opportunities for implementation	Partners, including permittees, public and non-governmental organizations	None	None
Cost	Moderate	Expensive	Moderate
Barriers to implementation	Some - funding, internal agency	Some - funding	Some - funding and capacity

Table 10A.9—Adaptation options that address climate change effects on recreation in the GYA Subregion.

Sensitivity to climatic variability and change: Archeological sites are susceptible to damage and destruction with increase in wildland fires, erosion and floods, vandalism due to increased recreation activities and longer summer season, and rot from loss of protective snow cover hiding archeological sites.				
Adaption Strategy / Approach: Get cultural resources more involved in the climate change discussion.				
Strategy Objective: Increase education and reduce stressors.				
Tactic	Specific Tactic – A Increase pro-active surveys and site recording.	Specific Tactic – B Increase post-fire inventories.	Specific Tactic – C Prioritize site sensitivities and management allocation.	Specific Tactic – D Mitigate adverse effects.
Tactic effectiveness (risks)	High	High	Medium	Medium-high
Implementation urgency	Near term	Near term	Near term	Near term
Where can tactics be applied? (geographic)	High elevation – determine locations by predictive modeling	In burned areas	Unit wide	Site specific
Opportunities for implementation	Section 110 of National Historic Preservation Act; engage with university partners; historical societies; Passport in Time projects	Burned area emergency response; engage with university partners	Forest Service manual	Section 110 of National Historic Preservation Act (when not related to specific undertaking)
Cost	Moderately expensive	Moderately expensive	Inexpensive	Expensive
Barriers to implementation	Forest leadership team may not see benefit, would rather concentrate on support to other functions	Limitation of use of burned area emergency response funds	None	Major costs

Table 10A.10—Adaptation options that address climate change effects on recreation in the GYA Subregion.

Sensitivity to climatic variability and change: Infrastructure location, sizing, safety, and resource protection. Will our infrastructure be able to accommodate the projected future use in a safe manner, considering shorter winters with less snow, increased and earlier runoff, increased erosion, increased hazard trees from insects, disease and windthrow mortality, population shifts to higher elevation, and rapidly growing outdoor recreation locations?		
Adaption Strategy / Approach: Proactively determine sites where projected climate change impacts may cause safety, resource or recreation-quality issues.		
Strategy Objective: Assess infrastructure and set priorities while considering limited funding and capacity.		
Tactic	Specific Tactic – A Install appropriately sized culverts; relocate infrastructure; or eliminate infrastructure.	Specific Tactic – B Develop additional restrictions in the permitting process, seasonal closures or allowable uses.
Tactic effectiveness (risks)	Very high	Medium
Implementation urgency	Near to mid term, unless major infrastructure, then 50 years.	Near term
Where can tactics be applied? (geographic)	After catastrophic events using burned area emergency response funds; first priorities from climate analysis	Where needed – site specific
Opportunities for implementation	Department of Transportation, Emergency Relief for Federally Owned Roads	Existing user groups
Cost	Expensive, except when incorporated in already funded projects.	Moderately expensive – staff time
Barriers to implementation	None to major: funding; political and social barriers to road closures	Some barriers: social and political

Table 10A.10 (cont.)—Adaptation options that address climate change effects on recreation in the GYA Subregion

Sensitivity to climatic variability and change: Infrastructure location, sizing, safety, and resource protection. Will our infrastructure be able to accommodate the projected future use in a safe manner, considering shorter winters with less snow, increased and earlier runoff, increased erosion, increased hazard trees from insects, disease and windthrow mortality, population shifts to higher elevation, and rapidly growing outdoor recreation locations?		
Adaption Strategy / Approach: Proactively determine sites where projected climate change impacts may cause safety, resource or recreation-quality issues.		
Strategy Objective: Assess infrastructure and set priorities while considering limited funding and capacity.		
Tactic	Specific Tactic – C Develop new opportunities or new recreation sites; be proactive in encouraging use in locations where the use will be sustainable and resources can support the use.	Specific Tactic – D Monitor closure and restriction dates and set trigger points to determine changes.
Tactic effectiveness (risks)	Very high	Moderate
Implementation urgency	Near – mid term	Near term
Where can tactics be applied? (geographic)	Urban interface	Site specific
Opportunities for implementation	Any rec site planning process	Unit level; user groups
Cost	Expensive	Moderately expensive – staff time
Barriers to implementation	Some	Some: lack of staff time; lack of priority

Table 10A.11—Adaptation options that address climate change effects on recreation in the GYA Subregion.

Sensitivity to climatic variability and change: Lower snow amounts, earlier snowmelt and a longer summer season.				
Adaption Strategy / Approach: Focus on regulation, education, enforcement, and infrastructural changes.				
Strategy Objective: Increase education and reduce stressors.				
Tactic	Specific Tactic – A Adjust dates of orders, as needed, such as extended dates of food storage, travel management, closures and trail shares.	Specific Tactic – B Implement social media technology to disperse use, direct users, educate, and promote etiquette.	Specific Tactic – C Engage Chambers of Commerce and Development organizations to help deal with the increased pressures on forest and park resources.	Specific Tactic – D Install infrastructure as needed (e.g., fences, signs, gates).
Tactic effectiveness (risks)	Medium-high	Medium-high	Low-medium	Moderate
Implementation urgency	Near term	Near term	Mid to long term	Near term
Where can tactics be applied? (geographic)	Anywhere appropriate, but especially in areas with high occurrence of resource-user conflicts	Everywhere – messages can be general or site specific	Starting with the larger urban centers (i.e. Jackson, Bozeman, Cody, Idaho Falls and Billings)	Anywhere appropriate
Opportunities for implementation	Laws; revised travel management	The “GYA app”; National Geographic Magazine	Chambers of Commerce; state departments of tourism; state development councils; regional-scale employers; influential people who settle in the GYA	User groups; businesses
Cost	Inexpensive	Inexpensive to medium	Medium	Inexpensive (with partners)
Barriers to implementation	Small to large, depending on social/cultural opposition from users and communities	Medium to small - lack of coverage in remote areas and seniors not using social media; cost barrier	Medium to high - internal cultural barriers and political differences and external barriers	Low to implement; high to avoid vandalism

Table 10A.12—Adaptation options that address climate change effects on recreation in the GYA Subregion.

Sensitivity to climatic variability and change: Shorter winters with less snow, and wetter or icier snow.

Adaption Strategy / Approach: Consider diversifying permitted activities, assess infrastructure and recreation sites, and develop prioritization process and criteria.

Strategy Objective: Increase knowledge, assess options, and engage industry and community partners.

Tactic	Specific Tactic – A Develop options for diversifying snow-based recreation.	Specific Tactic – B Use master development plan to determine if we can add uses and extend seasons (or modify the plan).	Specific Tactic – C Examine viability of agency snow-based recreation sites, permitted downhill resorts and all permitted winter operations.	Specific Tactic – D Monitor snow dates, snow event dates, and snowpack depth.
Tactic effectiveness (risks)	High in the short-term; must consider cost–exclusivity and resource impacts	Low-medium	Low	Moderate
Implementation urgency	Mid term	Mid term	Mid-long term	Near term
Where can tactics be applied? (geographic)	For permitted areas, in and around the existing permitted area, within driving distance of population centers	Within and around permitted area	In and around recreation area	Existing snow telemetry (SNOTEL) sites
Opportunities for implementation				Unit
Cost				Inexpensive (especially with partners)
Barriers to implementation				Low to implement; high to avoid vandalism

Table 10A.13—Adaptation options that address climate change effects on recreation in the Western Subregion.

Sensitivity to climatic variability and change: Increased human exposure to contaminated sediment due to dropping lake levels in the Coeur d'Alene basin and/or increased desire for water-based recreation in higher temperatures in the contaminated areas.			
Adaption Strategy / Approach: Avoidance of contaminated areas.			
Strategy Objective: Reduce stressors/threat and increase knowledge.			
Tactic	Specific Tactic – A Cap or harden contaminated areas.	Specific Tactic – B Establish vegetation barriers.	Specific Tactic – C Concentrate use in areas that have been hardened.
Tactic effectiveness (risks)	High in the short-term (requires maintenance)	High	Moderate to low.
Implementation urgency	Near term (but ongoing in long term)	Near term (but ongoing in long term)	Near term (but ongoing in long term)
Where can tactics be applied? (geographic)	Throughout the basin, but focus on priority areas identified in the Coeur d'Alene Basin Restoration Plan Environmental Impact Statement	Throughout the basin, but focus on priority areas identified in the Coeur d'Alene Basin Restoration Plan Environmental Impact Statement	Throughout the basin, but focus on priority areas identified in the Coeur d'Alene Basin Restoration Plan Environmental Impact Statement
Opportunities for implementation	Federal, state, tribal, non-governmental organization partners	Federal, state, tribal, non-governmental organization partners	Federal, state, tribal, non-governmental organization partners
Cost	Moderately expensive	Moderately expensive	Moderately expensive
Barriers to implementation	Issues with sensitive species or other resource concerns	Minimal to none	Social

Table 10A.14—Adaptation options that address climate change effects on recreation in the Western Subregion.

Sensitivity to climatic variability and change: Increased desire for water-based recreation with higher temperatures will lead to increased dispersed recreation sites in riparian areas.		
Adaption Strategy / Approach: Limit expansion of sites and pioneering of new sites.		
Strategy Objective: Coordinate (e.g., with other agencies and the public); reduce stressors/threat.		
Tactic	Specific Tactic – A Educate the public and post signs to prevent expansion of dispersed recreation sites in riparian areas.	Specific Tactic – B Design measures for resource protection, such as blocking access to riparian areas, and revegetating impacted areas.
Tactic effectiveness (risks)	Moderate	Moderate
Implementation urgency	Near term (ongoing to long term)	Near term (ongoing to long term)
Where can tactics be applied? (geographic)	Riparian areas on federal lands	Riparian areas on federal lands
Opportunities for implementation	Federal, state, tribal, and private partnerships	Federal, state, tribal, and private partnerships
Cost	Moderately expensive	Moderately expensive
Barriers to implementation	Social	Social; recognizing treaty rights to maintain access to traditional family use areas

Table 10A.15—Adaptation options that address climate change effects on recreation in the Western Subregion.

Sensitivity to climatic variability and change: Cultural/heritage recreation and tourism (e.g., Nimiipuu Trail and Lewis and Clark Trail) and associated scenic driving recreation will likely be affected by increased wildland fire with changing climate.		
Adaption Strategy / Approach: Manage vegetation to limit wildfire impacts on recreation and tourism.		
Strategy Objective: Promote resiliency.		
Tactic	Specific Tactic – A Reduce stand density, and vary age class and species composition through vegetation management and/or prescribed fire.	Specific Tactic – B Re-establish native vegetation (e.g., forbs, grasses, and conifers such as whitebark pine); slow spread and reduce populations of invasive species.
Tactic effectiveness (risks)	High to moderate	Moderate to low
Implementation urgency	Near term	Near term
Where can tactics be applied? (geographic)	Within scenic corridors	Within scenic corridors
Opportunities for implementation	Tribal partnerships and collaborative partnerships	Cross-regional genetics improvement programs; federal, tribal, state, and private partnerships
Cost	Moderately expensive	Expensive
Barriers to implementation	Some (opponents to vegetation management as a tool)	Some (difficulty with implementation success)

Table 10A.16—Adaptation options that address climate change effects on recreation in the Western Subregion.

Sensitivity to climatic variability and change: Seasonality of whitewater rafting will likely shift with changing climate and timing of peak flows.		
Adaption Strategy / Approach: Increase management (primarily permitting) flexibility.		
Strategy Objective: Promote resiliency.		
Tactic	Specific Tactic – A Vary permit season to adapt to changes in peak flow and duration.	Specific Tactic – B Educate the public about changes in peak flows and permitting.
Tactic effectiveness (risks)	Moderate	High to moderate
Implementation urgency	Mid term	Mid term
Where can tactics be applied? (geographic)	Permitted rivers	Permitted rivers
Opportunities for implementation	Agency partnerships	Agency partnerships
Cost	Low	Low
Barriers to implementation	Social	Social

Table 10A.17—Adaptation options that address climate change effects on recreation in the Western Subregion.

Sensitivity to climatic variability and change: Winter recreation (ice fishing, cross-country skiing, snowmobiling) will be at risk with increased temperatures.		
Adaption Strategy / Approach: Increase management (primarily permitting) flexibility.		
Strategy Objective: Promote resiliency.		
Tactic	Specific Tactic – A Maintain current infrastructure and expand facilities in areas where concentrated use increases (anticipate additional use as lower elevation areas [Missoula] have reduced snowpacks).	Specific Tactic – B Conduct safety education for increased risk (avalanche potential and thinning ice sheets).
Tactic effectiveness (risks)	Moderate	Moderate
Implementation urgency	Near term	Near term
Where can tactics be applied? (geographic)	Snow play areas and major lakes	Snow play areas and major lakes
Opportunities for implementation	Fees	Partnerships
Cost	Moderately expensive	Low
Barriers to implementation	Social; expense	Social (people do not always listen)