TWENTY-SIX

Fire and Climate Change

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The only thing that is constant is change.

HERACLITUS

The ecological impacts of climate change present major challenges for resource managers and policy makers in the state of California. State and federal agencies are now requiring that vulnerability to climate change be addressed in land and resource management plans, and major efforts are underway to augment resilience in California ecosystems (USDA 2012, Obama 2013, Cal-NRA 2014). One of the major effects of climate change in California will be its influence on ecological processes like fire (Westerling and Bryant 2008, Safford et al. 2012). Public and private lands in the state are experiencing increasingly large and destructive wildfires, from desert and Great Basin ecosystems, to southern California chaparral and the forested mountains in the north (Miller et al. 2009, Miller and Safford 2012, Barbero et al. 2014). The impacts of climate change on fire in California are accompanied by accelerating population growth in one of the largest and most complex wildland urban interfaces in the nation, and the impact of fire on human assets is rising and is projected to continue to rise as the climate warms (Bryant and Westerling 2014). It seems clear that climate change driven alterations in fire regimes will provoke great changes in California landscapes, and under even the best scenarios the momentum of these effects will not be curbed for many decades.

The influences of climate change on fire are both direct and indirect and have the potential to affect two of the three legs of the fire behavior triangle. Local weather and fuels are both largely controlled by macroclimate and its interactions with topography. It has been argued that climate change will principally modify fire through altering fuel condition, fuel volume, and fuel ignitions (Hessl 2011), suggesting that fire weather will play a less significant role than the fuel itself. Others argue that the role of climate varies depending on whether the system is mostly conditions-limited (e.g., fire weather dependent) or resource-limited (e.g., fuel dependent; Krawchuk and Moritz 2011). Either way, climate change is expected to have a significant impact on both the extreme weather conditions that drive large catastrophic wildfire and the production and drying of fuels that are necessary for fire spread. Climate change is likely to influence fire in three principal ways (Krawchuk and Moritz 2012): (1) direct effects of changes on fire weather conditions such as drought, high temperatures, winds, and their seasonality, (2) an indirect effect on fire through vegetation—that is, by climate altering the structure, abundance, and energetics of biomass to burn, and (3) through changes in ignition potential due to shifting spatial or temporal patterns of lightning and human behavior in response to factors such as climate policy and environmental management.

Our ability to model and infer the potential impacts of climate change on fire in California depends on our understanding of the relationship between fire, fire weather, and fuels. In this chapter, we outline what is known about the relationship between fire and climatic change, summarize modeled and other projections for future fire activity in California, and discuss potential feedbacks that may alter the fire landscapes that we currently manage.

Fire–Climate Change Interactions

All attributes of the fire regime are connected to climatic variability in some way. Indeed, while climate is only one leg of the fire behavior triangle, under some conditions its effect can be so pervasive that it overrides the other components that determine fire behavior. Climate properties that influence fire include temperature, precipitation, humidity, wind speed and direction, and lightning. Such properties vary spatially and temporally across orders of magnitude, ranging, as Gedalof (2011) notes, "from a sunfleck that might dry a few square meters for a minute or two, to a megadrought that might persist throughout a given region for decades or more." Gedalof (2011) provides a succinct summary of how climate variability affects fire, ranging from short-term controls on fine fuel moisture, ignition frequencies, and fire spread rates; to intermediate-scale (annual to interannual) effects on the abundance and continuity of fine fuels and the abundance and moisture content of coarser fuels; to long term (decadal to centennial) influences on the pool of species that can persist in a given location. Interactions between the physical characteristics of these species and more direct influences of climate on fire lead to the distinctive fire regime and vegetation structure that we consider "characteristic" of a place, and changes in these variables and their interactions can have major ecological implications.

The historical record demonstrates how these complex linkages between climate change and fire operate. Tree ring records and sedimentary charcoal make evident that fire frequency and area burned are closely linked with the duration, frequency, and intensity of droughts (Marlon et al. 2012). Historically, the periods of highest fire activity during the Holocene Epoch coincided with periods of drought and/or climatic change, for example during the Altithermal or Xerothermic Period (ca. 7,000–4,000 years ago) and the Medieval Droughts (ca. 900 to about 1350 AD) (Whitlock et al. 2003, Beaty and Taylor 2009). Similarly, fire activity increased markedly at the end of the Younger Dryas stadial (ca. 12,800–11,500 years ago; Berger 1990), when global temperatures are thought to have increased at rates at least as fast as the current ones (Marlon et al. 2009). Changes in fire regimes provoked, and were provoked by changes in vegetation. Ancient pollen assemblages in Sierra Nevada lakes and peaty soils show local and regional shifts from forest to shrubland or grassland and back, or cycling between groups of more moisture loving, fire intolerant species and more xeric, fire-tolerant species. These types of vegetation shifts fed back into important changes in burning conditions, as biomass became more or less flammable, and fuelbeds more or less dense and continuous (Safford and Stevens, 2017).

Current changes in global climates are writing the next chapter in this age-old saga. The ten warmest years in the formal human record system (1880 to present) have all occurred since 1990 (Jones and Palutikof 2006) and 2016 was the warmest year on record (www.noaa.gov). In the high California mountains, earlier spring snowmelt and warmer summer temperatures have increased the length of the growing season as well as the fire season (Westerling et al. 2006), less precipitation is falling as snow (Knowles et al. 2006), and there is an overall decline in snow accumulation at all but the highest elevations (Mote et al. 2005). In northern California forests as a whole, the influence of climate on fire size and annual burned area has increased by two to four times over the last century. Whereas temperature was the primary climate driver of these fire variables in the first half of the twentieth century, today it is the variability in precipitation—and primarily during the fire season, not before—that is the most important factor (Miller et al. 2009, 2012).

Climate Change Predictions for California

Many empirical or statistically based climate projections are available at global and continental scales, but there are fewer statewide or regional projections due to the difficulty of obtaining precisely downscaled climate data. Most global circulation models (GCMs) produce raster outputs on grids of >10,000 km^2 and downscaling introduces errors and uncertainty to the projections. Additionally, there are many different ways to downscale climate data and different downscaling techniques lead to disparate results, even from the same dataset. Precipitation is particularly difficult to downscale given high levels of uncertainty in how the mechanisms driving precipitation may change as a result of complicated feedbacks. For example, early models varied from a 26% increase to an 8% decrease in precipitation per 1°C (2.1°F) temperature increase in California (Gutowski et al. 2000). That said, efforts have been made to provide finer-scale climate projections, and every year there are more—and more trustworthy—data to support decision-making and adaptation efforts in California (Cayan et al. 2008a).

Cayan et al. (2008a, b) summarized climate scenarios and downscaled models for California from two of the models used in the Third and Fourth Intergovernmental Panel on Climate Change (IPCC) Assessments: the Parallel Climate Model (PCM; Meehl et al. 2003) and the National Oceanic Atmospheric Association (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL) model (Stouffer et al. 2006). These models were chosen because they met a series of conditions, including a minimum grid size and daily outputs, realistic simulations of historical climate, realistic representation of temporal and spatial variability in the California climate, and differing levels of sensitivity to greenhouse forcing (GFDL is much more sensitive to climate forcing than PCM and predicts greater warming). The models incorporate two greenhouse gas emission scenarios (B1—doubling of CO_2 emissions followed by decrease to below current by 2100, and A2—tripling of CO_2 emissions) (Cayan et al. 2008b), so there were four separate simulations carried out, ranging from moderate change compared to today (PCM-B1) to severe change from today (GFDL-A2). Outputs include projected precipitation and temperature, which are summarized below and in Table 26.1.

Process-based hydrologic models are an alternative approach that provides projections that are spatially relevant to ecological processes and can reconcile precipitation inconsistencies across climate models. Hydrologic models incorporate runoff, recharge and soil properties, creating a more holistic picture of water availability in ecosystems. Examples include the Basin Characterization Model (BCM; Flint et al. 2013) and the Variable Infiltration Capacity Hydrologic Model (Nijssen et al. 1997, Liang et al. 1994), both of which link climate and hydrologic models and output historical and future climate datasets. The historical component of the dataset allows for robust model validation that is not as easily accomplished with statistical models (Cuddington et al. 2013). Below we summarize projected climate data (Cayan et al. 2008b) and report the results of the BCM process-based hydrologic model for California (Thorne et al. 2015). BCM also uses the GFDL and PCM models used in the IPCC.

Temperature

By 2100, Cayan et al.'s (2008b) simulations project mean annual temperature will rise by 1.5°C to 4.5°C (34.7°F to 40.1°F) in California; three of the four simulations project greater temperature increases in summer than in winter (Table 26.1). These projections fall within the spread of future temperature projections from most other climate modeling exercises (c. 2°C to 7°C [4.2°F to 14.8°F]; Dettinger 2005). "Cool" summers will largely be a thing of the past by the second half of the century. The number of extremely hot days (those that fall above the 99.9th percentile of days between June 1 and September 30, using 1961–1990 as the reference period) is projected to rise by 50 to 500 times (to up to 23% of days) by 2100 in northern California, and slightly less dramatically in southern California; oceanic influences will reduce warming near the coast (see Cayan et al. 2008b for details). These results parallel those of most other published climate change predictions for California (e.g., Gutowski et al. 2003, Hayhoe et al. 2004).

TABLE 26.1

Temperature and precipitation changes from GFDL and PCM B1 and A2 simulations for northern and southern California

Mean values are for historical period (1961–1990). Changes between successive 30 year periods are shown in columns for the models and emission scenarios. Units are °C for temperature, mm for precipitation, and % for precipitation changes. Tables are reproduced with permission from Cayan et al. (2008b)

	Mean 1961–1990		2005–2034 change				2035–2064 change				2070–2099 change			
			GFDL		PCM		GFDL		PCM		GFDL		PCM	
	GFDL	PCM	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
Northern California														
Annual °C	9.3	8	1.5	1.4	0.5	0.5	2.3	2.2	1.3	0.8	4.5	2.7	2.6	1.5
Annual °C (JJA)	21.5	17.9	2.1	1.7	0.9	0.6	3.4	2.6	1.7	1.1	6.4	3.7	3.3	1.6
Annual °C (DJF)	−0.46	0.08	1.4	1.3	0.1	0.7	1.7	2.1	0.9	2.4	3.4	2.3	2.3	1.7
Annual mm/%	1098	750	+0.3	+2	−0.4	+7	−3	−2	−2	+3	−18	−9	−2	0
Summer mm/%	14	14	−29	+28	+28	+44	−67	−13	+35	−18	−68	−43	−30	−4
Winter mm/%	649	386	−1	−5	−5	+13	+6	−0.1	−5	−2	−9	−6	+4	+4
Southern California														
Annual °C	12.2	14.3	1.3	1.3	0.5	0.6	2.3	2.1	1.2	0.8	4.4	2.7	2.5	1.6
Annual °C (JJA)	23.2	23.4	1.7	1.6	0.4	0.5	3.1	2.3	1.3	0.8	5.3	3.2	2.6	1.5
Annual °C (DJF)	2.4	5.4	1.0	1.0	0.2	0.7	1.7	1.6	1.0	0.6	3.3	2.0	2.4	1.6
Annual mm/%	537	342	−6	−2	+7	+18	−2	−11	+7	−2	−26	−22	+8	+7
Summer mm/%	7	5	+49	−13	−7	+6	−60	−50	+35	+33	−44	−63	−11	+2
Winter mm/%	320	187	−0.7	+0.8	+1	+32	+9	−9	+6	−6	−2	−26	+8	−0.8

Precipitation

The simulations run by Cayan et al. (2008b) suggest that California's Mediterranean-type precipitation regime will not change, with most of the precipitation continuing to fall in the months between November and May. Cayan et al.'s (2008b) simulations do not project increased monsoonal influence in California, but drivers of interannual monsoonal variability in North America are poorly understood and difficult to model (Adams and Comrie 1997). Overall precipitation is also not expected to change much, with slight increases or no change under the PCM simulations, and 10% to 20% decreases under GFDL. Earlier summaries of different climate change models and simulations suggested broadly similar patterns, with most simulations showing no change or modest increases in annual precipitation in California by 2100 (Gutowski et al. 2000, Hakkarinen and Smith 2003, Maurer 2007). While results do not suggest significant change in annual precipitation, Cayan et al.'s (2008b) simulations project an increase in the frequency and intensity in extreme precipitation events in northern California, but not much change in southern California (which is already characterized by a preponderance of such events; Dettinger et al. 2011). Interannual to decadal variability in precipitation is projected to continue to be very high (California supports the highest interannual variability in precipitation in the United States [Dettinger et al. 2011]), and Cayan et al.'s (2008b) simulations do not suggest a change in the broad periodicity of the El Niño Southern Oscillation (ENSO), which is an important driver of climate variability in California, especially in the south. Note that, like the North American monsoon, it is very difficult to model climate change impacts on the ENSO system because it is a highly dynamic process influenced by both atmospheric and ocean circulation patterns (Diaz et al. 2001). Changes in ENSO patterns would affect precipitation differently in the northern and southern regions of California as a function of the ENSO dipole (Brown and Comrie 2004).

Snow Accumulation

Although overall precipitation averages may not change, higher temperatures will influence the amount of precipitation that falls as snow and accumulates on the ground. Current trends in increasing snow:rain ratios (Mote et al. 2005) are projected by Cayan et al. (2008b) and Thorne et al. (2015) to continue and accelerate. In California, April 1 snowpack (defined as snow-water equivalent, SWE) has declined by an average of 10 mm (0.4 in) annually, with large declines in the Cascade Range (–33 mm [–1.3 in]) and the Sierra Nevada (–29 mm [–1.1 in]; Fig. 26.1). Cayan et al. (2008b) and Thorne et al. (2015) project further losses in April 1 SWE across northwestern California, the Modoc Plateau and the Sierra Nevada. By 2100, Cayan et al. (2008b) project decreases in SWE of 32% to 79% (compared to today), with the largest losses at elevations <2,000 m (6,561 ft); snow loss in the Sierra Nevada will be greatest in the northern and central part of the range because elevations there are much lower than in the south.

Climatic Water Deficit

In the semiarid landscapes of western North American, water availability is a major driver of ecosystem distribution and condition (Major 1988, Loik et al. 2004). In terms of water availability in ecosystems, it is probably less valuable to consider changes in precipitation or temperature independently and more valuable to consider how the integration of water and energy manifest into climate conditions that are actually experienced by plants. Climatic water deficit (CWD; potential evapotranspiration minus actual evapotranspiration) is a climate variable that represents available water for plant use by incorporating precipitation and temperature into one "biologically relevant" measure (Stephenson 1998). CWD has been used as a metric for understanding water balance, drought stress, and fire vulnerability in ecosystems throughout California and the western United States. Since the period 1951–1980, the average annual CWD has increased (i.e., water is less available) in California by an average of 17 mm, but this change is less than one standard deviation from the historical record, and trends have been geographically variable. For example, much of northwestern California and parts of the Sierra Nevada west slope have experienced increasing water availability (decreasing CWD), due to precipitation increases over the period that have counteracted warming temperatures (Thorne et al. 2015; Fig. 26.2). Future changes under the BCM scenarios are projected to increase CWD by 40 mm to 160 mm (1.6 in to 6.3 in) in most of California, depending on the simulation and the location. The largest projected changes will occur east of the Sierra Nevada-Cascades crest. Many of these changes will depart from the historical record by between 1.5 and 2 standard deviations, implying a very significant decrease in water availability by the end of the century (Fig. 26.2; Thorne et al. 2015).

Projected Climate Change Impacts on California Fire Regimes

The combined effects of changing temperatures and shifts in the timing and magnitude of precipitation will undoubtedly alter California fire regimes. In many montane forests, a century of fire exclusion has resulted in the accumulation of fuels such that uncharacteristic weather conditions can more quickly accelerate a small fire event into a major wildfire. A majority of future fire models agree that changes in climate will directly and indirectly increase the frequency and area burned across most of the western United States, including California (Lenihan et al. 2008, Gedalof 2011, Westerling et al. 2011, Safford et al. 2012). It has been notably more difficult to predict changes in fire severity and intensity because of nonlinear relationships and complex feedbacks between vegetation, climate, and fire (Flannigan et al. 2009, van Mantgem et al. 2013), but most models project increases in fire severity/intensity as well, depending on the fire regime and vegetation type in question (Lenihan et al. 2003b, Flannigan et al. 2013). Undoubtedly, changing fire regimes will alter vegetation composition and structure and the water balance as well (Miller and Urban 1999), ultimately altering fuel conditions. In some cases, decreases in fire activity are projected in certain components of the fire regime towards the end of the next century due to ecosystem transitions caused by originally increased fire activity and/or from altered species composition (i.e., woody vegetation to grass). It is important to remember that most models that project future fire activity are built on empirical relationships between past climate and fire, and then these relationships are applied to future climate scenarios. Empirical models assume stationarity in the fire-climate

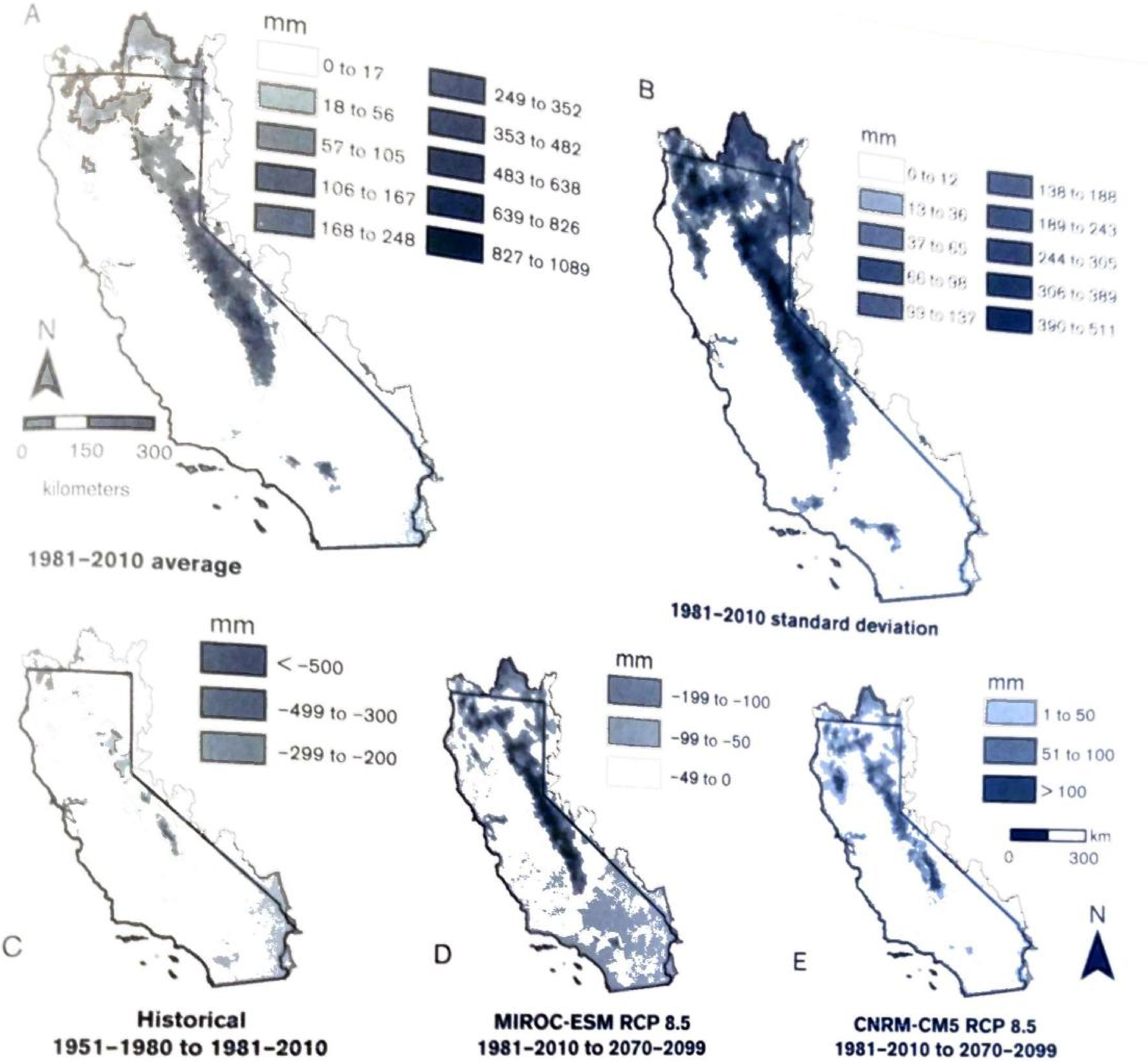

FIGURE 26.1 Historical and projected April 1 Snow Water Equivalent. Figure reproduced with permission from Thorne et al. (2015).

relationship and presume the relationship between a fire regime attribute and a climate variable will remain quantitatively similar into perpetuity. This is not always a valid assumption given that the relationship between climate and fire is specific to vegetation on the landscape that is burning (Littell et al. 2009, Hessl 2011), and future vegetation assemblages may be very different from those today or in the past (Williams and Jackson 2007). Here we summarize this literature, and differentiate projections for forest, shrubland, and grassland ecosystems where the research results permit.

Vegetation Shift Impacts on Fire Frequency and Probability

Miller and Urban (1999) conducted simulations of future fire regimes and species composition across an elevational gradient in the southern Sierra Nevada. Their results highlighted how strongly fire activity depends on not just the abundance but the composition of fuel. In the two lowest elevation sites in the analysis (yellow pine and mixed conifer forests), fire frequencies increased during the first century of simulation, but then declined gradually as woody biomass was consumed and then disappeared altogether from the ecosystem. At the end of their 400 year simulations, woody biomass decreased at the lower elevation (1,800 m [5,905 ft]) site from ~200 mg ha^{-1}to 0 mg ha^{-1}, providing minimal fuel for consumption. Under Miller and Urban's (1999) most extreme scenario, forest fuels at this elevation were completely replaced by grassy fuels and fire frequency increased. At the middle elevation (2,200 m [7,218 ft]) site, biomass loss was high but not as extreme as at the 1,800 m (5,905 ft) site, and fire frequencies remained similar to baseline conditions although fire area decreased with the decrease in biomass. The highest elevation (2,600 m [8,530 ft]) site, which is currently in red fir forest but was predicted to transition to a mixed conifer composition, experienced very large increases in fire frequency. Results from Miller and Urban (1999) predict significant transitions in the fire regime that are largely driven by changes in fuel characteristics—lower elevation woody ecosystems will contain more flashy fuels which will increase fire frequency and higher elevation forests will experience more frequent fire as species composition shifts toward more flammable, fire-prone species.

The Changed Climate Fire Modeling System (CCFMS; Fried and Torn 1990) links GCMs to local weather, fire records, population density, fuel type, and slope to simulate area burned and the number of potential escaped fires (their model

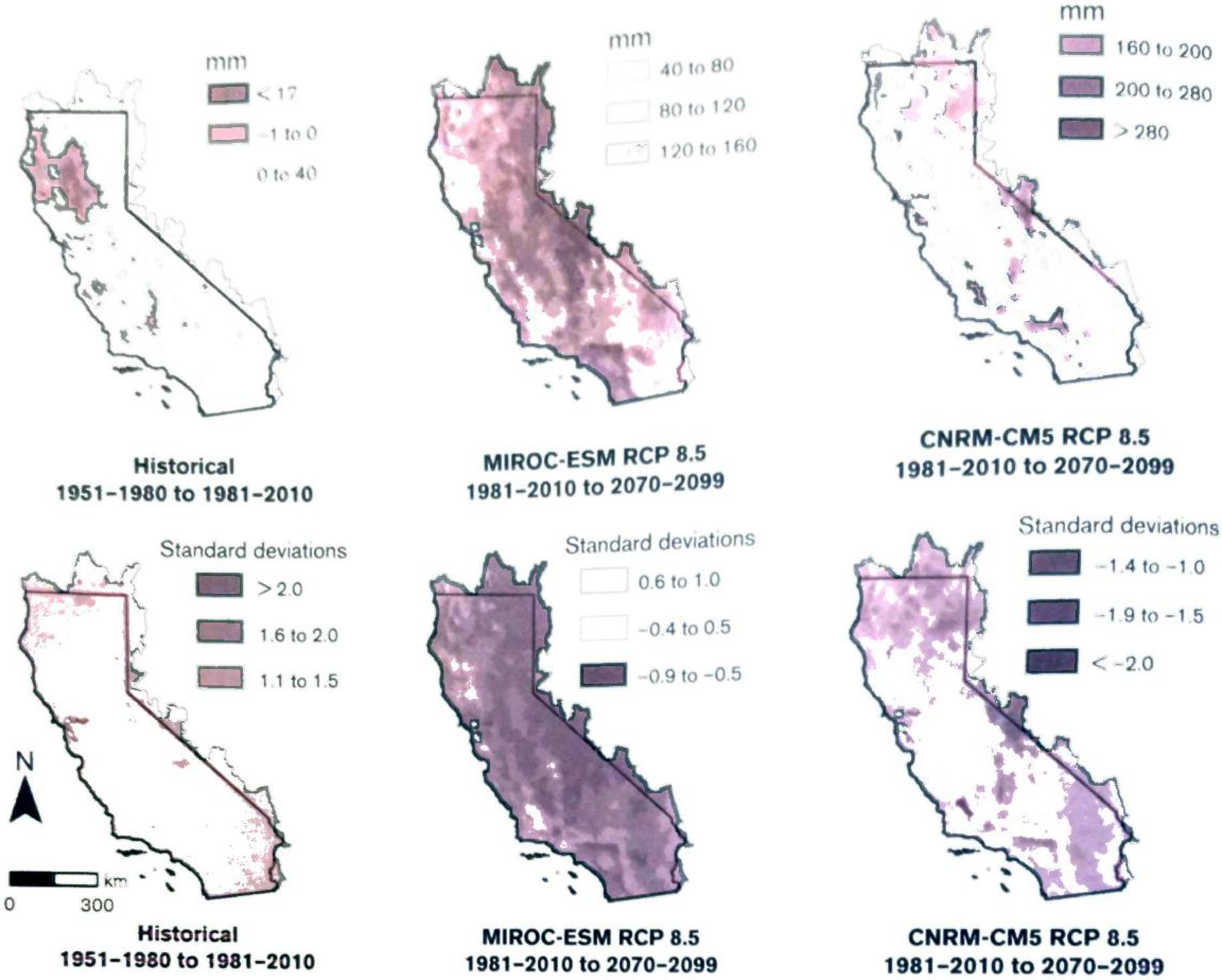

FIGURE 26.2 Climatic water deficit (CWD; potential evapotranspiration—actual evapotranspiration) modeled with the Basin Characterization Model. Historical and future values are displayed as differences between two time periods (top panels). Data is alternatively displayed as standard deviations to better show variability and significant departure from historical conditions (bottom panel). Under the warmer and drier scenario (GFDL) CWD will increase by more than one standard deviation throughout the entire state. Under the warmer and wetter scenario (PCM) CWD will increase by one standard deviation in the eastern regions of the state. Figure reproduced with permission from James Thorne.

includes the effects of fire suppression). Fried et al. (2004) applied the model to northern California under a future climate with twice the atmospheric CO_2 as today. Their projections suggested that climate change will lead to increases in the frequency of weather conditions that are associated with high fire risk and therefore increases in the frequency of fire events. Like Miller and Urban (1999), Fried et al.'s (2004) results underlined the key role that fuel type plays in driving ecosystem response to climate change. Areas vegetated with grass and shrubs were projected to experience many more escaped fires under warming, but the lack of a crown fire module probably led to an underestimate of the number of escapes in forest fuels. Fried et al. (2004) projected that the number of escaped fires would increase by 125% in the Sierra Nevada and 51% in the south Bay Area, but there was no projected change in the North Coast region because of the slower wind speeds and higher humidities produced from the downscaled GCM. Because the CCFMS model does not include any internal feedbacks from fire to vegetation, Fried et al. (2004) underlined that their results represented the minimum expected change.

Krawchuk and Moritz (2012) developed fire projections for California using statistical relationships that relate fire counts and climate variables (e.g., precipitation seasonality, maximum temperature, CWD) to determine the probability of fire under future climate scenarios. In Krawchuk and Moritz's (2012) model, future fire probability varied along two primary axes: (1) the climate scenario used (different GCMs), and (2) the primary limiting factor of the fire regime (fuel-quantity or "burning condition," the latter driven by fuel moisture and climate). Under warmer and drier scenarios, fire probability was not projected to increase in regions where lack of fuel is a major limitation to burning (e.g., deserts of southeastern California and unforested parts of the Modoc Plateau), but the converse was true for the warmer and wetter climate scenarios. In fuel-rich ecosystems, there was agreement between GCMs that future changes in climate will result in increased fire probability. Increases in area burned were projected in northwestern California, the Cascade Ranges and the Sierra Nevada, whereas decreases in area burned were projected for the Mojave and Sonoran Deserts (Krawchuk and Moritz 2012). Mean fire return interval was also modelled and, in general, was reduced across the state suggesting more frequent fire.

Batllori et al. (2013) used maximum entropy modeling to investigate the outcomes of warmer-drier climate scenarios vs. warmer-wetter scenarios with respect to fire occurrence in the world's five Mediterranean-type climate regions. Results for California suggested that under either type of climate scenario, fire probabilities would likely increase over the coming century on 60–80% of the landscape (depending on the scenario and the time period) and decrease on 15–30% of the landscape. Parts of the state that experienced increases or decreases in fire probability changed depending on the climate scenarios however, and Batllori et al. (2013) ascribed this to differences in the way climate and fire interact in fuel- and condition-limited ecosystems.

Burned Area

In Miller and Urban's (1999) model, area burned at their 1,800 m (5,905 ft) and 2,200 m (7,218 ft) sites rose strongly during the first century of their climate change simulations, but then decreased over time as woody biomass was gradually lost. At the lowest site, little woody biomass remained at the end of their simulation and the abundance of grassy fuels led to a large increase in area burned. At the 2,200 m (7,218 ft) site, fire area decreased as biomass was lost over time (Miller and Urban 1999). The red fir forest site at 2,600 m (8,530 ft) experienced very large increases in area burned.

McKenzie et al. (2004) calculated correlations for the twentieth century between mean summer temperature and precipitation and annual burned area for 11 western states, and then used regression to project burned area into the future under two climate scenarios. They found strong relationships between their summer climate variables and fire area for all states but California and Nevada, and concluded that most of the western United States was likely to experience large increases in annual area burned by wildfire in the twenty-first century. However, they conclude that "fire in California and Nevada appears to be relatively insensitive to summer climate, and area burned in these states may not respond strongly to changed climate." This curious statement appears to result from McKenzie et al.'s (2004) combination of southern and northern California into a single dataset. Southern and northern California (with the Tehachapi Mountains being the boundary) each contribute about half of California's total burned area in an average year, but general fire–climate relationships in the two regions are very different (Safford and Van de Water 2014). McKenzie et al.'s (2004) analysis thus buries the relatively strong relationship that exists between fire and summer climate variables in the Sierra Nevada, Klamath Mountains and North Coast Range (Westerling et al. 2006; Miller et al. 2009, 2012; Keeley and Syphard 2015) under the southern California fire–climate relationship, which is essentially independent of summertime temperature or precipitation (Keeley 2004). In summary, changes in summer temperature and precipitation may not have strong effects on southern California fire area, but McKenzie et al.'s (2004) predictions for the western United States in general are certainly valid for most of the assessment area.

The MC1 Dynamic General Vegetation Model is a dynamic vegetation model that simulates physiognomically defined vegetation types; the movement of carbon, nitrogen, and water through ecosystems; and fire. Unlike most other models described here, MC1 incorporates feedbacks between fire and vegetation, and temporal changes in fuel loadings and types can be accounted for. Lenihan et al. (2008) simulated the responses of vegetation distribution, carbon, and fire to climate change in California using MC1. Fire events were determined as a function of moisture content of the largest dead fuels and fire spread thresholds, and the occurrence of fire was limited to extreme events only. Lenihan et al. (2008) found that the average annual area burned across the state was 9–15% higher at the end of the twenty-first century than under current conditions. Greater burned area was strongly driven by the increasing area of grassland promoted by both climatic and fire effects, especially in the central and southern coasts, Modoc Plateau and lower elevation Sierra Nevada. Regional variations in projected fire activity were dependent on vegetation productivity and the distribution of woodlands and grasslands. Lenihan et al. (2008) conclude that increases in burning will have serious consequences for carbon storage as grasslands replace woodlands in many parts of California. In Yosemite National Park, Lutz et al. (2009) used a statistical model to predict that annual burned area would increase by around 20% by 2020–2049 due to projected decreases in snowpack in mid- and high-elevation forests.

Modeling reported by the National Research Council (NRC 2011) projected that, compared to the average of the 1950–2003 period, median annual area burned would increase by over 300% for the northern California mountains with a 1°C (2.1°F) increase in average temperature; increases in over 200% were projected for vegetation of the Central Valley and foothills, and over 70% for the southern California deserts; coastal California south of San Francisco was not modeled. Over time, the report noted that extensive warming and wildfire could ultimately exhaust much of the fuel for fire in some regions, as forests were completely burned (NRC 2011).

Westerling et al. (2011) modeled burned area across California under a range of future climate and development scenarios. They found that, under the most realistic future climate and emissions scenarios and compared to the average of the period 1960–1990, projected area burned by wildfire increased by over 200% by 2085 for most of the forested area of northern California. Middle and higher elevation forests were among the most severely impacted, with some future climate scenarios producing increases in burned area of more than 300%. Naturally vegetated areas in most of central and southern coastal California was projected to see increases of around 100% in annual burned area, except for the southeastern deserts, where burned area remained steady or dropped (Westerling et al. 2011).

Fire Intensity and Severity

The MC1 dynamic vegetation model was used to model vegetation and fire response to two different GCM-based future climate scenarios specific to California (Lenihan et al. 2003a, b). One of the mid-stream outputs of the model is fireline intensity. Under the warmer-wetter climate scenario (Hadley CM2), fireline intensity was projected to increase in grass-dominated systems, to slightly increase in desert and shrubland ecosystems, and to remain steady or slightly increase in most forested ecosystems. Under the warmer-drier future scenario (PCM), simulations projected that increased fire frequency and area burned would remove woody vegetation from coastal areas, the Klamath Mountains and the North Coast Ranges. Ultimately, the reduction or absence of woody material was projected to result in lower fireline intensities.

Flannigan et al. (2000) modeled the seasonal severity rating (SSR)—a measure of the difficulty of fire control—across North America under two GCM scenarios for the year 2060, and found that SSR increased by an average of 10% under both scenarios for California. Flannigan et al. (2013) linked the Canadian Forest Fire Weather Index to three GCMs and predicted the Cumulative Severity Rating (CSR), a fire danger metric based on weather conditions, for the northern and southern hemispheres for the periods 2041–2050 and 2091–2100. They projected that by 2100 severity as measured by CSR would increase by around 10% in California. In Yosemite National Park, the total area burned at high severity in mid- and high-elevation forests was projected by Lutz et al. (2009) to increase 22% between the current (1984–2005) and mid-21st century (2020–2049) periods, due mostly to declines in snowpack.

Van Mantgem et al. (2013) showed that high prefire CWD increases the probability of postfire tree mortality, thus—aside from their well-known effects on fuel moisture—climate warming and increasing growing season drought can enhance fire severity independently of fire intensity. This suggests that future fire severities could be even higher than predicted by fire–climate modeling studies.

Fire Season

Changes in the length and character of the fire season can be attributed to decreases in the snow:rain ratio and the increased incidence of extreme temperatures. The snow:rain ratio has been decreasing across California in the past 75 years (Safford et al. 2012) and combined with warming temperatures, these negative trends in snow amount and storage result in earlier drying of fuels and a lengthening of the fire season. Current trends and projections of future patterns in the snow:rain ratio and snowpack persistence thus portend longer fire seasons (Mote 2006, Mote et al. 2005, Safford et al. 2012, Westerling et al. 2006). Collins (2014) showed that since 1992, 17% to 20% and 8% to 12% of days in the fire season exceeded the 90th and 95th percentile, respectively, in terms of fire weather thresholds. Collins (2014) suggests that extreme weather in a given fire season controls growth of individual fire events and therefore the increased incidence of extreme fire weather (one characteristic of the fire season) is contributing to increases in area burned.

A number of authors have used fire–climate models to project changes in the duration and timing of the fire season as climate warming continues. The Keetch–Byram Drought Index was modelled under a number of different future GCM-based scenarios as a proxy for "wildfire potential" (Liu et al. 2010). Fire season was projected to become a couple of months longer for much of the contiguous United States, including California, by the end of the twenty-first century. Flannigan et al. (2013) projected that fire season length would increase by more than 20 days for all of northern California by 2100. Yue et al. (2013) projected a median increase of more than three weeks in the fire season by the middle of the twenty-first century.

Fire Ignitions

Price and Rind (1994) simulated the distribution and frequency of lightning using downscaled GCMs for California. Results indicate that lightning frequency could increase by as much as 30% globally. Romps et al. (2014) found similar results, based on a simple linear relationship between lightning flash rate and the product of precipitation (per hour) × convective available potential energy (a measure of atmospheric convective instability). Results project a 12% average increase in lightning per 1°C [2.1°F] of temperature rise. By the end of the twenty-first century this could translate into 50% more lightning across much of the United States (Romps et al. 2014). Lightning strike densities (LSDs) are relatively low in California, but areas of high topography (especially in the Sierra Nevada) still see LSDs of 15 to 35 strikes yr^{-1} 100^{-1} km^{-2} (van Wagtendonk and Cayan 2008). The combination of greater lightning incidence, warmer climates, and drier fuels strongly suggests that fire activity will likely rise in most semiarid parts of California that support fuel, even where human ignitions can be reduced.

Fire Effects on Vegetation

Fire is a major driver of vegetation change in both space and time. The effects of fire on vegetation in California will depend greatly on precipitation trends, but Bachelet et al. (2007) note that in either wetter or drier conditions, forest could be notably reduced in much of the western United States in a warmer future. Under drier conditions, enhanced fire frequency could favor drought-tolerant grasses, which would further enhance ecosystem flammability and reduce woody cover. Under wetter conditions, expansion of woody plants might promote more intense fires and high mortality when drought conditions occur, ultimately reducing tree biomass. Bachelet et al. (2007) projected that most of California would see an increase in biomass consumption by fire during the twenty-first century, whether warming was extreme or moderate.

Using the same vegetation dynamics model as Bachelet et al. (2007), Lenihan et al. (2008) simulated the future distribution of terrestrial ecosystems in California under three GCM-based future climate scenarios. Fire drove grassland expansion into former shrublands and woodlands, even under the coolest and wettest future scenario; by 2099, under the warmest and driest scenario, grassland almost completely replaced shrublands on the Sierra Nevada west slope and also expanded greatly in the California Great Basin. Broadleaf woodland and forest replaced large areas of evergreen conifer forest under all three scenarios, with fire playing an important role in the transition, especially in the relatively warmer and drier scenarios (Lenihan et al. 2008). These types of vegetation transitions will have a major impact on fire regimes. For example, grasslands are characterized by flashy fuels that ignite easily and burn rapidly and propagate more grasslands, creating a positive feedback loop (the classic "grass-fire cycle").

Summary of Projected Climate Change Impacts

All the described climate models generally agree that fire frequency and area burned will increase in most California ecosystems. However, spatial variability in fire activity, burned area, and fire severity and intensity will depend on future precipitation patterns and the dynamic relationship among vegetation, fuels, and fire. The effects of climate change will likely vary for fire regimes that are driven principally by fuel quantity versus those driven principally by burning conditions (fuel quality) and climate. Even if increases in fire activity and burned area are in store for ecosystems at both

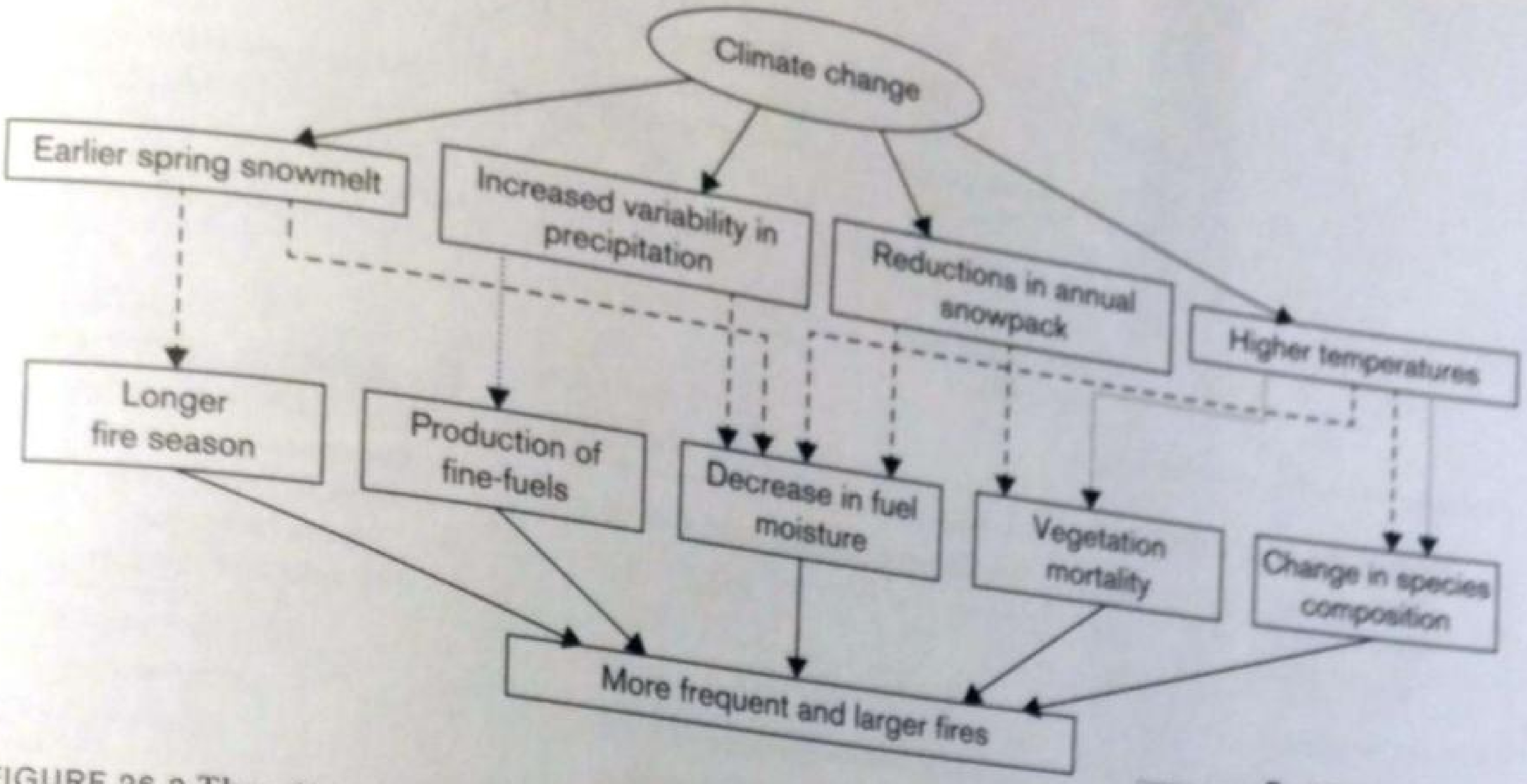

FIGURE 26.3 The effects of climate change will alter temperature and water availability in ecosystems, changing fuel availability and condition, all of which will lead to more frequent and larger fires. Major pathways of change will vary for fuels- versus conditions-limited ecosystems. Snowpack effects will be more significant for conditions-limited systems because most fuels-limited systems experience rain-dominated precipitation. Higher temperatures of course reduce fuel moisture in all systems, but fuel-limited systems are typically dry enough to burn in any given fire season, so the enhancement effect will be more limited than in conditions-limited systems which typically support heavier fuels.

ends of this spectrum, the mechanisms of change will differ (Fig. 26.3). For example, in California, where interannual variability in precipitation is extreme (Dettinger et al. 2011), further increases in precipitation variability could enhance an already prevalent pattern of very wet years catalyzing fine fuel production in fuels-limited regions, and subsequent very dry years leading to large areas burned. Alternatively, low precipitation years that occur simultaneously with projected higher temperatures will drive increased fire activity in conditions-limited systems where there is already abundant fuel (i.e., densely forested landscapes), independently of antecedent years.

Decreases in snowpack or earlier timing of spring snowmelt combine to decrease fuel moisture and increase the length of the fire season, leading to more fire in conditions-limited systems. Higher temperatures and greater water stress may result in vegetation mortality (Allen et al. 2010), creating fine fuels (in the short term) and coarse woody debris (in the medium and long term) for combustion that could promote fire activity or possibly augment the ecological effects of fire in either fuels- or conditions-limited systems. It is likely that increased variability in precipitation will affect the fire regime in non-forested regions of California the most through increases in fuel production, and that higher temperatures will affect all regions in California via fuel moisture reduction. Regional drought stress will lead to increased annual area burned when fuels are not limiting (via fuel moisture reduction) and will result in the addition of fuels (via mortality) in conditions-limited systems (Williams et al. 2013).

Inferences about future fire can also be made from our understanding of the relationship among fire, vegetation, and climate rather than relying on models. Annual area burned is driven largely by climate (Trouet et al. 2009, Keeley and Syphard 2015), especially spring-summer vapor pressure deficit (VPD) because VPD determines atmospheric moisture demand and therefore drives the reduction of fuel moisture (Williams et al. 2014). The frequency of high fire-weather indices is responsible for a lengthening of the dry season resulting in more fires later into the fall (Collins 2014). Antecedent climate also influences fire regimes as drought stress can result in the production of fine fuels that are available for the next year's fire season. Parks et al. (2014) demonstrate that area burned varies with actual evapotranspiration and that greater CWDs lead to more severe fires. Within a given ecosystem, fire severity also increases with fuel quantity (Parks et al. 2014, Steel et al. 2015). Importantly, the strength and sometimes the nature of these relationships can modulate across ecosystem types. The generalization about the differences between fuels-limited (fuel quantity) and conditions-limited (fuel quality and climate) ecosystems (Agee 1993, Mallek et al. 2013, Steel et al. 2015) is highly germane to considerations of the future in California. Overall, these mechanistic relationships between climate and fire are expected to hold into the future where, for example, an increase in spring-summer VPD would lead to increases in annual area burned. Projected extremes in weather and decreases in the snow:rain ratio both portend increases in fire activity under a changing climate. We can expect, therefore, changes in fire regimes commensurate with the magnitude of changes in climate variables.

Understanding how climate change interacts with fire in ecosystems with different fire regimes is fundamental to understanding how undesirable changes might be avoided, for example through fire and fuels management (Fig. 26.3).

A Future with More Fire

Modeling results conclude that more and larger fires are highly probable with a warmer climate in the state of California. Such trends are already obvious. Recent examples of "megafires" (Stephens et al. 2014) in California include the Rim, King, and Rough fires in the Sierra Nevada, but record-breaking fires have also recently occurred in other western states such as Arizona, New Mexico, Oregon, and Washington. In the end, perhaps the key question is "what will our

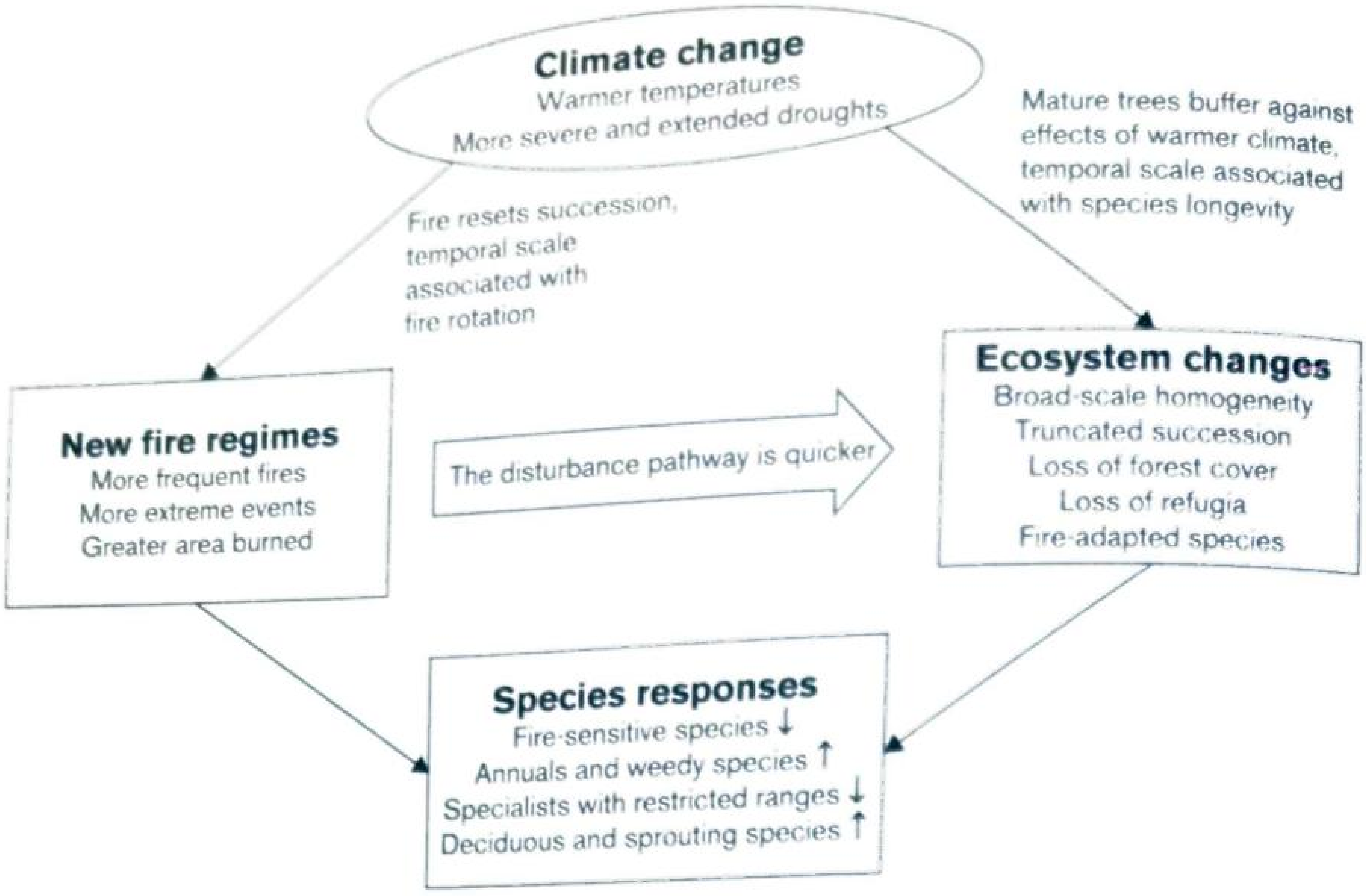

FIGURE 26.4 Changes in fire regimes will be the catalyst for ecosystem change. Fires modify landscapes on shorter temporal scales than climate change alone. Climatic conditions will likely be different after fire than when vegetation established, resulting in changes in species composition. Figure edited and reproduced with permission from Don McKenzie.

management landscapes look and act like if burned area and fire sizes increase as predicted?" It is likely that climate change will have its most dramatic effects on California landscapes through its direct and indirect connection to ecosystem-altering fire (Dale et al. 2001). When fires of novel sizes, or frequencies, or severities (and their combination) occur on landscapes, the likelihood of abrupt vegetation change or local extirpation is increased (Fig. 26.4). On this newly disturbed landscape, conditions—soil, light, nutrients, climate—may be vastly different from when the vegetation established. For example, many shrub-dominated landscapes in southern and eastern California have transitioned to annual grass dominated ecosystems as a result of steep positive trends in fire frequency driven by synergy among climate warming, droughts, ignitions, and invasive species (Keeley and Safford 2016). These trends, which are very difficult to reverse, are likely to accelerate and expand geographically.

In forested regions, areas dominated by long-lived conifers—which have experienced marked swings in climate over the centuries since they established—are being subjected to rapid increases in growing season temperatures and deeper late summer droughts. These conditions are already challenging for mature individuals, but when severe fires kill them, reestablishment of forest species is not a given, especially in the huge patches of stand-replacing fire that are more and more commonplace in California forest fires. This sort of dynamic is already apparent in lower elevation conifer forests in central and southern California and is at the heart of the major conifer forest loss projected by dynamic vegetation models (e.g., Lenihan et al. 2003a, 2008). These models also predict that oak species—which can resprout after fire—will largely benefit from these dynamics, and a trend toward higher hardwood density in lower elevation conifer forests is already apparent in the Sierra Nevada and southern California (Safford et al. 2012).

Increasing frequencies, areas, and severities of fire (which won't necessarily occur in tandem) are likely to alter more than just the overstory vegetation. More burning and more open vegetation stands created by increased burning will be less hospitable to species adapted to moist, cool habitats and more hospitable to drought-tolerant, sun-loving species (Stevens et al. 2015). Many invasive plants, mostly annual grasses but some forbs as well, will find it easier to expand into wildlands. Those that are highly flammable will further transform fire regimes and the ecological landscape. Animal species adapted to dense, old forest stands—spotted owls, fishers, goshawks—will find it increasingly difficult to locate suitable habitat, while animals preferring severely burned landscapes—many woodpeckers and other birds, certain rodents—will benefit (McKenzie et al. 2004, Mallek et al. 2013). As precipitation variability continues to increase, the effects of increased fire on soil erosion and sedimentation in streams are likely to become more pronounced, especially on steep less consolidated bedrock and where woody vegetation has been lost. If current and projected fire trends continue, smoke production will also rise, with the concomitant effects on human health and aesthetics.

Fires do not occur in isolation and are usually accompanied by other processes that may be intrinsic or extrinsic to the ecosystem. Climate change is documented to have impacts on forests through direct heat-related mortality (Bréda et al. 2006, Allen et al. 2010) or water stress (McDowell et al. 2008) and indirectly through the exacerbation of bark beetle outbreaks (Raffa et al. 2008), fungal diseases, and human-caused disturbances such as ozone pollution (Fowler et al. 1999). The co-occurrence of multiple stressors is known as a "stress-complex," where the cumulative impacts of multiple stressors can greatly alter ecosystem processes and patterns (McKenzie et al. 2008). For example, the combination of higher temperatures, longer warm seasons, and ozone can result in pine mortality and epidemic bark beetle outbreaks, resulting in further tree mortality (Fig. 26.5). Fire exclusion in the same forests leads to high stand densities which, coupled with increased fuel accumulation from increased tree mortality, can result in

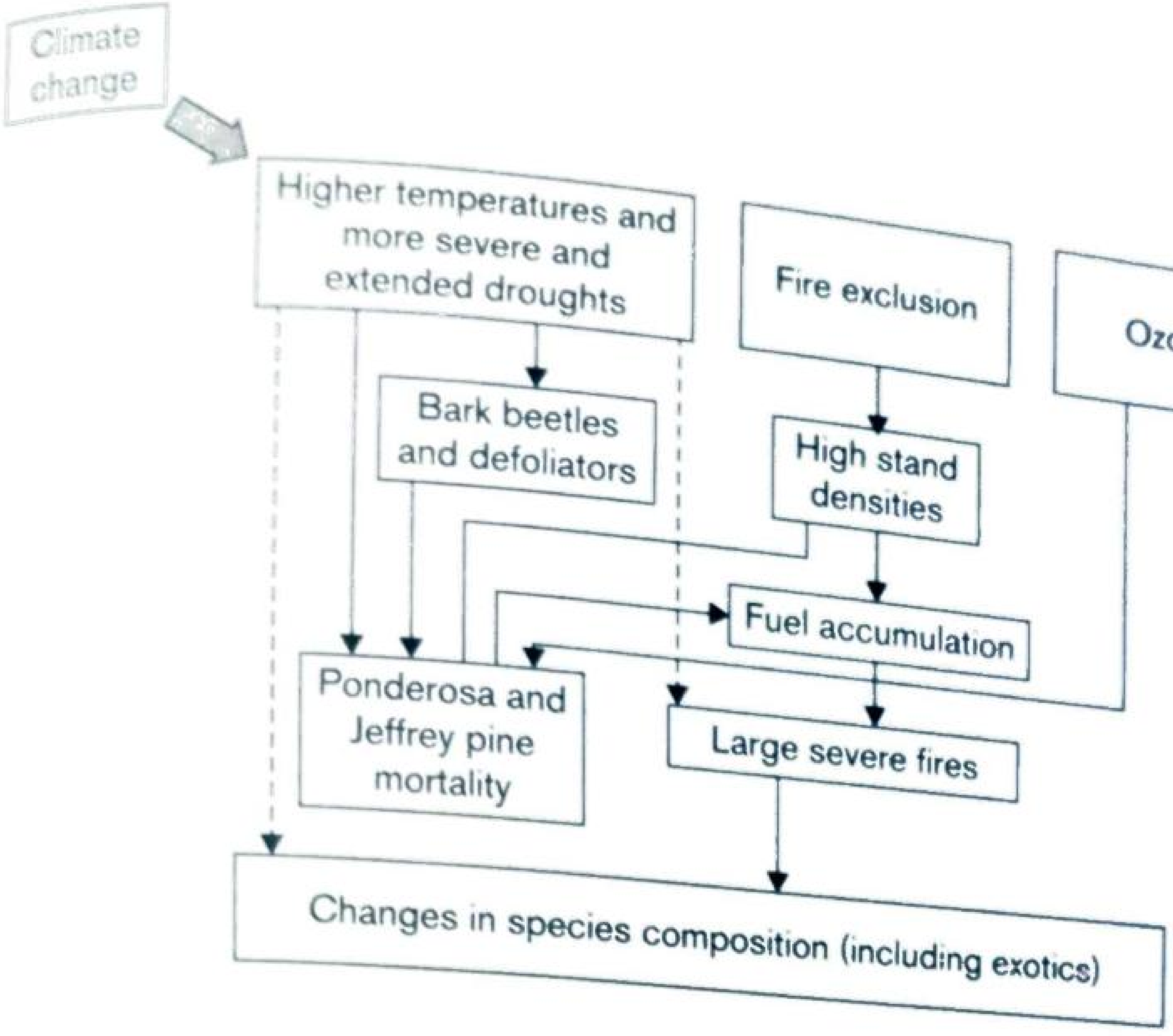

FIGURE 26.5 Example of a stress complex from Sierra Nevada forests. The combination of higher temperatures (imposed from climate change), fire exclusion, and ozone pollution result in multiple feedbacks triggering higher tree mortality and fuel accumulation that leads to larger wildfires. More severe droughts and wildfires can lead to a shift in species composition towards more annuals and fire-adapted species (including nonnatives). Figure reproduced with permission from McKenzie et al. (2008).

larger, more severe fires. All of these perturbations combine to alter species composition, potentially favoring nonnative species that are better adapted to higher fire frequencies or severities. We hypothesize that stress complexes will become more common under a changing climate (and an increasing human population), resulting in an increase in the frequency of ecological processes and an amplification of their effects.

References

Adams, D.K., and A.C. Comrie. 1997. The North American monsoon. Bulletin of the American Meteorological Society 78(10): 2197–2213.

Agee, J.K. 1993. Fire ecology of Pacific Northwest Forests. Island Press, Washington, D.C., USA.

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259: 660–684.

Bachelet, D., J.M. Lenihan, and R.P. Neilson. 2007. Wildfires and global climate change. The importance of climate change for future wildfire scenarios in the western United States. Pew Center on Global Climate Change, Arlington, Virginia, USA.

Batllori, E., M.A. Parisien, M.A. Krawchuk, and M.A. Moritz. 2013. Climate change-induced shifts in fire for Mediterranean ecosystems. Global Ecology and Biogeography 22: 1118–1129.

Barbero, R., J.T. Abatzoglou, E.A. Steel, and N.K. Larkin. 2014. Modeling very large-fire occurrences over the continental United States from weather and climate forcing. Environmental Research Letters 9: 124009.

Beaty, R.M. and A.H. Taylor. 2009. A 14 000 year sedimentary charcoal record of fire from the northern Sierra Nevada, Lake Tahoe Basin, California, USA. The Holocene 19(3): 347–58.

Berger, W.H. 1990. The Younger Dryas cold spell–a quest for causes. Global and Planetary Change 3: 219–237.

Bréda, N., R. Huc, A. Granier, and E. Dreyer. 2006. Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Annals of Forest Science 63: 625.

Brown, D.P., and A.C. Comrie. 2004. A winter precipitation 'dipole' in the western United States associated with mulitdecadal ENSO variability. Geophysical Research Letters 31: 1–4.

Bryant, B.P., and A.L. Westerling. 2014. Scenarios for future wildfire risk in California: links between changing demography, land use, climate, and wildfire. Environmetrics 25(6): 454–471.

Cal-NRA. 2014. Safeguarding California: reducing climate risk. State of California, Natural Resources Agency, Sacramento, California, USA. http://resources.ca.gov/docs/climate/Final_Safeguarding_CA_Plan_July_31_2014.pdf. Accessed July 22, 2015.

Cayan, D.R., A.L. Luers, G. Franco, M. Hanemann, B. Croes, and E. Vine. 2008a. Overview of the California climate change scenarios project. Climatic Change 87(1): S1–S6.

Cayan, D.R., E.P. Maurer, M.D. Dettinger, M. Tyree, and K. Hayhoe. 2008b. Climate change scenarios for the California region. Climatic Change 87(1): S21–S42.

Collins, B.M. 2014. Fire weather and large fire potential in the northern Sierra Nevada. Agricultural and Forest Meteorology 189: 30–35.

Cuddington, K., M.J. Fortin, L.R. Gerber, A. Hastings, A. Liebhold, M. O'Connor, and C. Ray. 2013. Process-based models are required to manage ecological systems in a changing world. Ecosphere 4(2): art20.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, and D. Simberloff. 2001. Climate change and forest disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. BioScience 51: 723–734.

Dettinger, M.D. 2005. From climate-change spaghetti to climate-change distributions for 21st century California. San Francisco Estuary and Watershed Science 3(1). http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4. Accessed July 22, 2015.

Dettinger, M.D., F.M. Ralph, T. Das, P.J. Neiman, and D.R. Cayan. 2011. Atmospheric rivers, floods and the water resources of California. Water 3: 445–478.

Diaz, H.F., M.P. Hoerling, and J.K. Eischeid. 2001. ENSO variability, teleconnections and climate change. International Journal of Climatology 21: 1845–1862.

Flannigan, M., A.S. Cantin, W.J. de Groot, M. Wotton, A. Newbery, and L.M. Gowman. 2013. Global wildland fire season severity in the 21st century. Forest Ecology and Management 294: 54–61.

Flannigan, M.D., B.J. Stocks, and B.M. Wotton. 2000. Climate change and forest fires. Science of the Total Environment 262: 221–229.

Flint, L.E., A.L. Flint, J.H. Thorne, and R. Boynton. 2013. Fine-scale hydrologic modeling for regional landscape applications: model development and performance. Ecological Processes 2: 25.

Fowler, D., Cape, J.N., Coyle, M., Flechard, C., Kuylenstierna, J., Hicks, K., Derwent, D., Johnson, C., and D. Stevenson. 1999. The global exposure of forests to air pollutants Water, Air & Soil Pollution 116: 1–2.

Fried, J.S., and M.S. Torn. 1990. Analyzing localized climate impacts with the Changed Climate Fire Modeling System. Natural Resource Modeling 4(2): 229–252.

Fried, J.S., M.S. Torn, and E. Mills. 2004. The impact of climate change on wildfire severity: a regional forecast for Northern California. Climatic Change 64(1): 169–191.

Gedalof, Z. 2011. Climate and spatial patterns of wildfire in North America. Pages 89–116, in: D. McKenzie, C. Miller, and D.A. Falk, editors. The Landscape Ecology of Fire. Springer, New York, New York, USA.

Gutowski, Jr. W.J., S.G. Decker, R.A. Donavon, Z. Pan, R.W. Arritt, and E.S. Takle. 2003. Temporal-spatial scales of observed and simulated precipitation in central US climate. Journal of Climate 16(22): 3841–3847.

Gutowski, W.J., Z. Pan, C.J. Anderson, R.W. Arritt, F. Otieno, E.S. Takle, J.H. Christensen, and O.B. Christensen. 2000. What RCM data are available for California impacts modeling? California Energy Commission Workshop on Climate Change Scenarios for California, 12–13 June, 2000. California Energy Commission, Sacramento, California, USA.

Hakkarinen, C., and J. Smith. 2003. Appendix I. Climate scenarios for a California Energy Commission study of the potential effects of climate change on California: summary of a June 12–13, 2000, workshop. Global climate change and California: potential implications for ecosystems, health, and the economy. Electric Power Research Institute, Palo Alto, California, USA.

Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider, K.N. Cahill, E.E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.S. Kalstein, J. Leniahn, C.K. Lunch, R.P. Neilson, S.C. Sheridan, and J.H. Verville. 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences 101: 12422.

Hessl, A.E. 2011. Pathways for climate change effects on fire: models, data, and uncertainties. Progress in Physical Geography 35: 393–407.

Jones P., and P. Palutikof. 2006. Global temperature record. Climate research unit, University of East Anglia. http://www.cru.uea.ac.uk/cru/info/warming/. Accessed July 22, 2015.

Keeley, J.E. 2004. Impact of antecedent climate on fire regimes in coastal California. International Journal of Wildland Fire 13(2): 173–182.

Keeley, J.E., and H.D. Safford. 2016. Fire as an ecosystem process. Chapter 3 in: H.A. Mooney and E. Zavaleta, editors. Ecosystems of California. University of California Press, Berkeley, California, USA.

Keeley, J.E., and A. Syphard. 2015. Different fire-climate relationships on forested and no-forested landscapes in the Sierra Nevada ecoregion. International Journal of Wildland Fire 42: 27–36.

Knowles, N., M.D. Dettinger, and D.R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19: 4545–4559.

Krawchuk, M.A., and M.A. Moritz. 2011. Constraints on global fire activity vary across a resource gradient. Ecology 92: 121–132.

———. 2012. Fire and climate change in California. California Energy Commission. Publication number: CEC-500-2012-026. Sacramento, California, USA.

Lenihan, J.M., D. Bachelet, R.P. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climatic Change 87(1): S215–S230.

Lenihan, J.M., R. Drapek, D. Bachelet, and R.P. Neilson. 2003a. Climate change effects on vegetation distribution, carbon, and fire in California. Ecological Applications 13: 1667–1681.

Lenihan, J.M., R. Drapek, R.P. Neilson, and D. Bachelet. 2003b. Appendix IV. Climate change effects on vegetation distribution, carbon stocks, and fire regimes in California. 60 pp., in: Global climate change and California: potential implications for ecosystems, health, and the economy. Final report to California Energy Commission. Project 500-03-058CF_A04. Electric Power Research Institute, Palo Alto, California, USA.

Liang, X., D.P. Lettenmaier, E.F. Wood, and S.J. Burges. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research 99: 14415–14428.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western US ecoprovinces, 1916-2003. Ecological Applications 19: 1003–1021.

Liu, Y., S. Stanturf, and S. Goodrick. 2010. Trends in wildfire potential in a changing climate. Forest Ecology and Management 259: 685–697.

Loik, M., D. Breshears, W. Lauenroth, and J. Belnap. 2004. A multi-scale perspective of water pulses in 4396 dryland ecosystems: climatology and ecohydrology of the western USA. Oecologia 14: 269–281.

Lutz, J.A., J.W. van Wagtendonk, A.E. Thode, J.D. Miller, and J.F. Franklin. 2009. Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA. International Journal of Wildland Fire 18: 765–774.

Mallek, C.R., H.D. Safford, J.H. Viers, and J. Miller. 2013. Modern departures in fire severity and area vary by forest type, Sierra Nevada and southern Cascades, California, USA. Ecosphere 4(12): Art153.

Major, J. 1988. California climate in relation to vegetation. Pages 11–74 in M.G. Barbour and J. Major, editors. Terrestrial Vegetation of California. California Native Plant Society, Sacramento, California, USA.

Marlon, J.R., P.J. Bartlein, M.K. Walsh, S.P. Harrison, K.J. Brown, M.E. Edwards, P.E. Higuerea, M.J. Power, R.S. Anderson, C. Briles, A. Brunelle, C. Carcaillet, M. Daniels, F.S. Hu, M. Lavoie, C. Long, T. Minckley, P.J.H. Richard, A.C. Scott, D.S. Shafer, W. Tinner, C.E. Umbanhower, Jr. and C. Whitlock. 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences 106: 2519–2524.

Maurer, E.P. 2007. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada Mountains, California under two emissions scenarios. Climatic Change 82: S309–S325.

McDowell, N., W.T. Pockman, C.D. Allen, D.D. Breshears, N. Cobb, T. Kolb, J. Plaut, J. Sperry, A. West, D.G. Williams, and E. Yepez. 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytologist 178: 719–739.

McKenzie, D., Z. Gedalof, D.L. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18(4): 890–902.

McKenzie, D., D.L. Peterson, and J. Littell. 2008. Global warming and stress complexes in forests of western North America. Developments in Environmental Science 8: 319–337.

Meehl, G.A., W.M. Washington, T.M.L. Wigley, J.M. Arblaster, and A. Dai. 2003. Solar and greenhouse gas forcing and climate response in the twentieth century. Journal of Climate 16: 426–444.

Miller, C., and D.L. Urban. 1999. Forest pattern, fire, and climatic change in the Sierra Nevada. Ecosystems 2: 76–87.

Miller, J.D., and H.D. Safford. 2012. Trends in wildfire severity: 1984-2010 in the Sierra Nevada, Modoc Plateau, and southern Cascades, California, USA. Fire Ecology 8(3): 41–57.

Miller, J.D., H.D. Safford, M. Crimmins, and A.E. Thode. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12(1): 16–32.

Miller, J.D., C.N. Skinner, H.D. Safford, E.E. Knapp, and C.M. Ramirez. 2012. Trends and causes of severity, size, and number of fires in northwestern California, USA. Ecological Applications 22: 184–203.

Mote, P.W. 2006. Climate-driven variability and trends in mountain snowpack in western North America. Journal of Climate 6209–6220.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bulletin of American Meteorological Society 86: 39–49.

National Research Council [NRC]. 2011. Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia. The National Academies Press, Washington, D.C., USA.

Nijssen, B.N., D.P. Lettenmaier, X. Liang, S.W. Wetzel, and E.F. Wood. 1997. Streamflow simulation for continental-scale river basins. Water Resources Research 33: 711–724.

Obama, B. 2013. Preparing the United States for the impacts of climate change. Executive Order 13653, November 1, 2013. https://www.whitehouse.gov/the-press-office/2013/11/01/executive-order-preparing-united-states-impacts-climate-change. Accessed July 22, 2015.

Parks, S.A., M.A. Parisien, C. Miller, and S.Z. Dobrowski. 2014. Fire activity and severity in the western US vary along proxy gradients representing fuel amount and fuel moisture. PLOS One 9(6): e99699.

Price, C., and D. Rind. 1994. Possible implications of global climate change on global lightning distributions and frequencies. Journal of Geophysical Research 99(D5): 10823–10831.

Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. Bioscience 58: 501–517.

Romps, D.M., J.T. Seeley, D. Vollaro, and J. Molinari. 2014. Projected increase in lightning strikes in the United States due to global warming. Science 346: 851–854.

Safford, H.D., M.P. North, and M.D. Meyer. 2012. Climate change and the relevance of historical forest conditions. Pages 23–46, in: M.P. North, editor. Managing Sierra Nevada Forests. USDA Forest Service General Technical Report PSW-GTR-237. Pacific Southwest Research Station, Albany, California, USA.

Safford, H.D., and J.T. Stevens. 2017. Natural Range of Variation (NRV) for yellow pine and mixed conifer forests in the Sierra Nevada, southern Cascades, and Modoc and Inyo National Forests, California, USA. USDA Forest Service General Technical Report PSW-GTR-256, Pacific Southwest Research Station, Albany, California, USA.

Safford, H.D., and K.M. Van de Water. 2014. Using Fire Return Interval Departure (FRID) analysis to map spatial and temporal changes in fire frequency on National Forest lands in California. USDA Forest Service Research Paper PSW-RP-266, Pacific Southwest Research Station, Albany, California, USA.

Steel, Z.L., H.D. Safford, and J.H. Viers. 2015. The fire frequency-severity relationship and the legacy of fire suppression in California forests. Ecosphere 6(1): art8.

Stephens, S.L., M. Burrows, A. Buyantuyev, R.W. Gray, R.E. Keane, R. Kubian, S. Liu, F. Seijo, L. Shu, K.G. Tolhurst, and J.W. Van Wagtendonk. 2014. Temperate and boreal forest mega-fires: characteristics and challenges. Frontiers in Ecology and the Environment 12(2): 115–122.

Stephenson, N.L. 1998. Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. Journal of Biogeography 25: 855–870.

Stevens, J.T., H.D. Safford, S.P. Harrison, and A.M. Latimer. 2015. Forest disturbance accelerates thermophilization of understory plant communities. Journal of Ecology 103: 1253–1263.

Stouffer, R.J., A.J. Broccoli, T.L. Delworth, K.W. Dixon, R. Gudgel, I. Held, R. Hemler, T. Knutson, H. Lee, M.D. Shwarzkopf, B. Soden, M.J. Spelman, M. Winton, and F. Zeng. 2006. GFDL's CM2 global coupled climate models–Part 4: Idealized climate response. Journal of Climate 19: 723–740.

Thorne, J.H., R.M. Boynton, L.E. Flint, and A.L. Flint. 2015. The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. Ecosphere 6(2): 1–30.

Trouet, V., A.H. Taylor, A.M. Carleton, C.N. Skinner. 2009. Interannual variations in fire weather, fire extent, and synoptic-scale circulation patterns in northern California and Oregon. Theoretical and Applied Climatology 95(3–4): 349–360.

USDA. 2012. Planning rule. US Department of Agriculture, Forest Service, Washington, D.C., USA. http://www.fs.usda.gov/detail/planningrule/home/?cid=stelprdb5359471. Accessed July 22, 2015.

Van Mantgem, P.J., J.C.B. Nesmith, M. Keifer, E.E. Knapp, A. Flint, and L. Flint. 2013. Climatic stress increases forest fire severity across the western United States. Ecology Letters 16: 1151–1156.

Van Wagtendonk, J.W., and D.R. Cayan. 2008. Temporal and spatial distribution of lightning strikes in California in relation to large-scale weather patterns. Fire Ecology 4(1): 34–56.

Westerling, A.L., and B.P. Bryant. 2008. Climate change and wildfire in California. Climatic Change 87(1): S231–S249.

Westerling, A.L., B.P. Bryant, H.K. Preisler, T.P. Holmes, H.G. Hidalgo, T. Das, and S.R. Shrestha. 2011. Climate change and growth scenarios for California wildfire. Climatic Change 109(1): S445–S463.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313: 940–943.

Whitlock, C., S.L. Shafer, and J. Marlon. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. Forest Ecology and Management 178: 5–21.

Williams, A.P., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangodagamage, M. Cai, and N.G. McDowell. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. Nature Climate Change 3: 292–297.

Williams, A.P., R. Seager, A.K. Macalady, M. Berkelhammer, M.A. Crimmins, T.W. Swetnam, A.T. Trugman, N. Buenning, D. Noone, N.G. McDowell, N. Hryniw, C.I. Mora, and T. Rahn. 2014. Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States. International Journal of Wildland Fire 24: 14–26.

Williams, J.W., and S.T. Jackson. 2007. Novel climates, no-analog communities, and ecological surprises. Frontiers in Ecology and the Environment 5: 475–482.

Yue, X., L.J. Mickley, J.A. Logan, J.O. Kaplan. 2013. Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid 21st century. Atmospheric Environment 77: 767–780.