Species Status Assessment for the Apache Trout *Oncorhynchus apache*

Apache Trout. Credit: U.S. Fish and Wildlife Service

September 2022

ACKNOWLEDGEMENTS

The White Mountain Apache Tribe is acknowledged for the countless years of Apache Trout conservation and management on the Fort Apache Indian Reservation. In addition, past U.S. Fish and Wildlife Service, federal, state, and Tribal biologists are acknowledged for their dedication to promoting Apache trout conservation.

PREFACE

This Species Status Assessment (SSA) provides a science-based assessment of the species needs, current conditions, and future conditions of Apache Trout *Oncorhynchus apache*. The document was prepared by Trout Unlimited together with a core team of representatives from tribal, state, and federal agencies, while also engaging other experts for collaboration and document review.

Core Team

Dan Dauwalter, Trout Unlimited
Jess Newton, U.S. Fish and Wildlife Service
Tim Gatewood, White Mountain Apache Tribe
Zach Beard, Arizona Game and Fish Department
Ryan Follmuth, Arizona Game and Fish Department
Kaleb Smith, Arizona Game and Fish Department
Stephanie Coleman, U.S. Forest Service
Jerry Ward, U.S. Forest Service
Zachary Jackson, U.S. Fish and Wildlife Service
Rosalinda Gonzalez, U.S. Fish and Wildlife Service
Kirk Young, U.S. Fish and Wildlife Service

U.S. Fish and Wildlife Service Advisory Group

Ryan Gordon, U.S. Fish and Wildlife Service
Mary Richardson, U.S. Fish and Wildlife Service
Sarah Rinkevich, U.S. Fish and Wildlife Service

Reviewers and Collaborators

Matt Rustin, White Mountain Apache Tribe
Stuart Leon, White Mountain Apache Tribe
Julie Carter, Arizona Game and Fish Department
Mike Lopez, Arizona Game and Fish Department (retired)
Brian Giordano, formerly Arizona Game and Fish Department
Michael Anderson, formerly Arizona Game and Fish Department
Jeremy Voeltz, U.S. Fish and Wildlife Service
Jennifer Johnson, U.S. Fish and Wildlife Service
Angela Anders, U.S. Fish and Wildlife Service
Bruce Thompson, U.S. Fish and Wildlife Service

Yvette Paroz, U.S. Forest Service
Scott Grunder, U.S. Forest Service
Scott Bonar, University of Arizona
Matt Recsetar, University of Arizona
Jean Barney, Trout Unlimited
Helen Neville, Trout Unlimited

Recommended Reference

U.S. Fish and Wildlife Service. 2022. Species Status Assessment for the Apache Trout *Oncorhynchus apache*. U.S. Fish and Wildlife Service, Flagstaff, Arizona.

EXECUTIVE SUMMARY

This Species Status Assessment (SSA) provides a comprehensive review of the status, viability, and resiliency of the Apache Trout *Oncorhynchus apache*. It does so by using the U.S. Fish and Wildlife Service's SSA framework to describe the species, its life history and ecological needs, risks and threats, and conservation actions. Next it describes the species' current condition by quantifying key demographic and habitat factors central to the species' life cycle for each population, and then placing extant populations within the 3R framework of representation, redundancy, and resiliency. Last, the future condition of the species is viewed under five future condition scenarios over a 30-year timeframe (six generations of Apache Trout) that considers environmental change, including climate change, and levels of conservation action based on resource availability and policy. Some of these scenarios include future delisting and implementation of a Cooperative Management Plan for the Apache Trout by relevant action agencies to contrast their perceived impacts on the future status of the species.

The SSA was completed in September 2021. This document is a revision that updates the SSA to include all 2021 survey data, corrects errors (both data and display errors) and incorporates 2021 updates in data tables and figures (Tables ES1, ES2, 8, 9, and 11–15; Figures ES1, ES2, 18–22, 24, and 25), clarifies the scoring matrix (Table 13), and provides additional summarization (Tables 16–18).

Species Overview

The Apache Trout (family Salmonidae) is endemic to the White Mountain region of east-central Arizona. Historically the species occupied headwater streams in the White and Black rivers that are tributary to the Salt River, as well as headwater streams in the Little Colorado River basin. Streams in the San Francisco drainage were considered historical habitat in the past, but it was determined in the early 2000's that Gila Trout *O. gilae* most likely occupied that drainage. Researchers considered the historical range to be streams above 1,800–2,100 m in elevation, although the precise nature of historical occupancy is unknown.

The Apache Trout was formally described in 1972 when it was split from the Gila Trout and described as *Salmo apache* by Robert R. Miller, owing to fewer and larger spots than Gila Trout and a horizontal band across the eye absent in Gila Trout. All trout native to the Gila River basin prior to then were considered Gila Trout. Pacific trout were moved from the genus *Salmo* to *Oncorhynchus* in 1989 due to shared genetic and morphometric characteristics with that genus, and the Apache Trout received its current scientific name *Oncorhynchus apache*. The Apache Trout was listed as endangered under the Endangered Species Preservation Act in 1967 before being downlisted to threatened under the Endangered Species Act in 1975. There is no critical habitat designation for Apache Trout. The first Recovery Plan for the Apache Trout was developed in 1979, a revised plan was developed in 1983, and a second revision was completed in 2009. A main goal of the recovery plan is to reach 30 genetically pure populations of Apache Trout, with habitat sufficient to support self-sustaining populations.

Like most salmonids, the Apache Trout requires cold and clean water and access to spawning habitat that consists of gravels free of fine sediment, rearing habitat along stream margins and other areas containing velocity refuges, and cover elements (e.g., undercut banks, boulders) for juveniles and adults to seek refuge while they feed and grow. Apache Trout are opportunistic feeders and consume a wide variety of prey types, although the one diet study conducted to date showed they primarily consumed caddisflies and terrestrial insects in summer, and terrestrial insects and true flies in autumn. They can live to nine years of age, although five years is probably more common in most populations. A major threat to the genetic purity of Apache Trout populations is hybridization with nonnative Rainbow Trout *O. mykiss*, and to a lesser extent Cutthroat Trout *O. clarkii*. Nonnative Brook Trout *Salvelinus fontinalis* and Brown Trout *Salmo trutta* also pose threats through competition and predation. Isolation of Apache Trout populations above protective fish passage barriers, often in concert with mechanical or chemical removal of nonnative trout, is a common conservation action used to protect populations. The 2011 Wallow Fire impacted many Apache Trout populations and streams by way of subsequent ash and debris flows that resulted in direct mortality, compromised protective barriers, removed streamside vegetation important in shading streams, and otherwise altered physical habitat. Installation, maintenance, and repair of protective barriers, removal and suppression of nonnative species, protection and enhancement of physical habitat, and promotion of the species through development of recreational fisheries and education are important conservation actions for the species' long-term viability.

Species Needs

The Apache Trout has various needs to meet the life history requirements of individuals, populations, and the species. They are:

- Complex habitat (individual)
- Suitable water temperatures and water quality (individual)
- Flow regime (individual)
- Available habitat (patch size; population)
- Minimum population size and genetic diversity (population)
- Habitat connectivity and metapopulation dynamics (population)
- Ecological diversity (population)
- 3Rs: representation, redundancy, and resiliency (species)

Current Condition

The current condition of the Apache Trout is reflected in the representation, redundancy, and resiliency of 38 Apache Trout populations occupying 402 km of habitat. These populations are comprised of 30 genetically pure relict or replicate populations (281.5 km) and 8 populations (120.7 km) known (from genetic testing) or suspected to be hybridized (Table ES1). Of the 30 genetically pure populations, 17 are relict populations occupying 161.4 km of habitat and 13 are replicate populations occupying 120.1 km. Twenty-six genetically pure populations are protected by a barrier (231.2 km), 19 are free of nonnative trout (146.7 km), and 18 are protected above a barrier and are free of nonnative trout (141.2 km). An additional 6 unoccupied streams designated for recovery of the species and representing nearly 61 km of habitat are assessed within this SSA.

Table ES1. Number of genetically pure relict, replicate, and hybridized Apache Trout populations and unoccupied recovery streams, and amount of habitat available for each. Habitat km taken from high resolution (1:24,000) National Hydrography Dataset.

Type	Number of populations	Available habitat (km)
Genetically pure populations	30	281.5
Relict	17	161.4
Replicate	13	120.1
Genetically pure + protective barrier	26	231.2
Genetically pure + no nonnative trout	19	146.7
Genetically pure + barrier + no nonnative trout	18	141.2
Hybrid populations	8	120.7
Unoccupied recovery streams	6	60.6

Representation

Representation is a concept that reflects whether important ecological aspects of a species are present. For the Apache Trout, representation focused on a single ecological element – relict subbasin lineages. Representation of relict lineages was determined for six subbasins: Black River, Bonito, Diamond, East Fork White, Little Colorado River, and North Fork White. Relict populations native to these subbasins assumedly represent unique genetic lineages because stream fishes commonly show genetic structuring by drainage basins; however, this has not been thoroughly investigated for the Apache Trout and so representation and redundancy of relict populations native to subbasins is used as a surrogate. Representation of subbasin lineages, a surrogate measure of extant genetic variation, reflects the ability of the species to adapt to current and future ecological conditions. Within all genetically pure populations of Apache Trout, relict lineages are still extant and represented within five of the six subbasins. The Little Colorado River is the only subbasin with no extant relict populations, suggesting the loss of any unique genetic variation that may have historically been associated with that subbasin.

Redundancy

Redundancy reflects the number of times a representative ecological element is replicated across a species (or defined sub-unit of the species). Redundancy for the Apache Trout was based on replication of the representative relict subbasin lineages. Redundancy reflects that, for example, a population with an important representative ecological element may be lost via extirpation, but that representative element still exists for the species because it is replicated, and thus redundant, in other populations. For the Apache Trout, all extant subbasin lineages have been replicated at least once, indicating some level of redundancy exists among the remaining five extant relict lineages unique to the six subbasins in the historical range of the species. The East Fork White River relict lineage contains the highest level of redundancy with six replicates of relict populations being extant, four of which are replicated in other subbasins outside of the East Fork White River subbasin.

Resiliency

The current condition of extant Apache Trout populations and unoccupied recovery streams was characterized on a 4.0 grading scale to infer a level of resiliency. The current condition of populations was described using three demographic factors and six habitat factors. The demographic factors were:

genetic purity (known or suspected), adult (≥130-mm TL) population size (N), and recruitment variation (# size classes). The habitat factors were: stream length occupied (km), percent intermittency, maximum July temperature (°C), habitat quality (ranked 1 to 5), presence of nonnative trout (known or suspected), and functionality of protective barriers. The data ranges and values for these demographic and habitat factors were classified by Apache Trout experts into Very Poor, Poor, Fair, Good, and Very Good classes. A Delphi method was used whereby experts recorded the data thresholds or categories that best defined classes, while considering the scientific literature, via an anonymous survey, a discussion was held in which experts could clarify survey questions and view their responses in the context of a group summary, and then experts were administered the survey a second time, which allowed them to modify their responses if desired. Mean responses to the second survey were used to classify data ranges, and then classifications were used to grade each individual demographic and habitat factor on a 4.0 grading scale as: Very Poor = F (0.0 grade point equivalents), Poor = D (1.0), Fair = C (2.0), Good = B (3.0), and Very Good = A (4.0). Grades for each factor were used to compute a grade-point-average (GPA) for each set of demographic factors and habitat factors for each Apache Trout population, and then the demographic and habitat factors were averaged for an overall GPA for a population. The GPA of demographic factors, and overall GPA, for unoccupied streams was set to zero.

The current condition of the 38 Apache Trout populations (excluding the 6 unoccupied recovery streams) rated an average of 2.53 (B- average) on a 4.0 grading scale (Figure ES1; Table ES2). The 30 genetically pure populations that would count towards recovery averaged 2.91 (B average). Based on the demographic and habitat factor grade point equivalents for each population, Apache Trout populations were more often limited by demographic factors than habitat factors (Table ES2). Adult population size (≥130-mm TL) was most frequently the limiting demographic factor, as most populations were less than 500 adults and received lower grades accordingly. Unoccupied streams (e.g., Home Creek) had demographic GPAs of 0.00 (Table ES2). East Fork White River had the highest demographic GPA (4.00; Table ES2). Likewise, presence of nonnative trout was frequently a limiting habitat factor, although all habitat factors graded low for some populations except for maximum July temperature. Centerfire and Stinky creeks on the Apache-Sitgreaves National Forests (ASNF) had the lowest habitat factors GPA (1.33); Deep Creek (Fort Apache Indian Reservation; FAIR) had the highest habitat factor GPA (3.50; Table ES2).

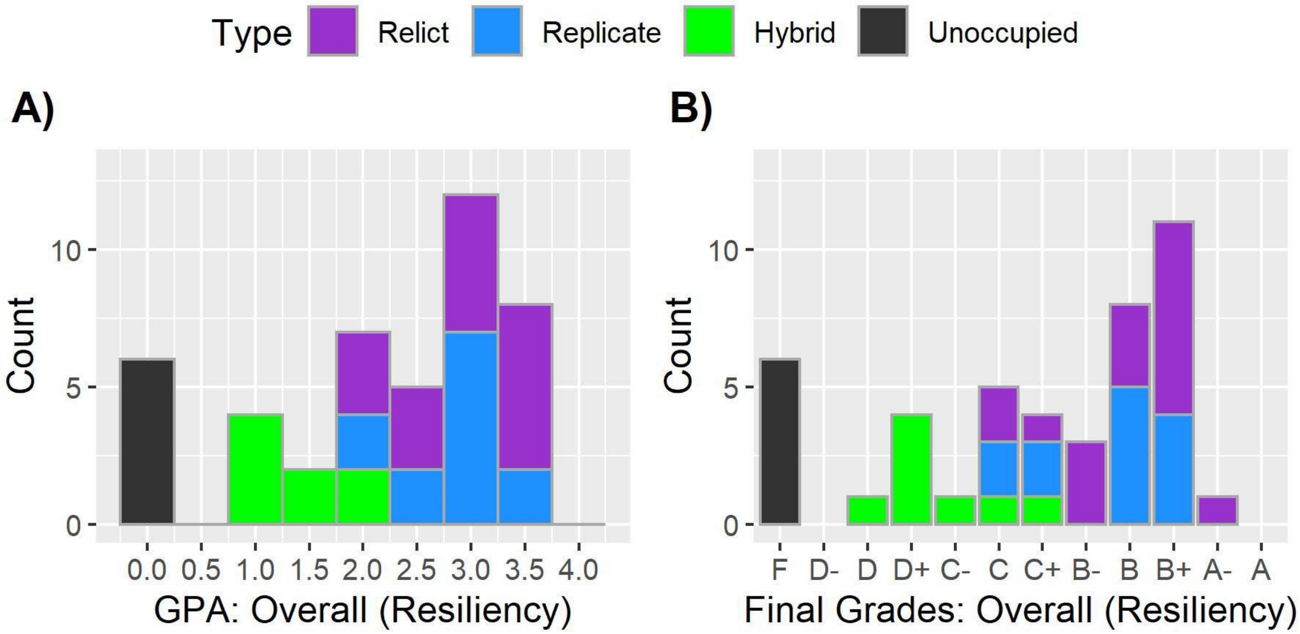

Figure ES1. A) Frequency of overall grade-point-averages (GPAs) and B) final grades for Apache Trout populations and unoccupied recovery streams, by type, in east-central Arizona.

Table ES2. Grade point equivalents for the three demographic factors [genetics (GEN), adult abundance (N), and recruitment (REC)] and six habitat factors [habitat kilometers (HKM), percent intermittency (INT), maximum July temperature (MJT), habitat quality (HQ), nonnative trout (NNT), and barriers (BAR), grade-point-averages (GPA) for all demographic and habitat factors combined (third- and second-to-last columns), and overall GPA (last column) for Apache Trout populations and unoccupied recovery streams in east-central Arizona. Rows with NA (gray) for all three demographic factors are unoccupied streams. Subbasins (SUB) noted in far left column; Black River (BR), Bonito (Bo), Colorado (CO), Little Colorado (LC), Diamond (DIA), East Fork White River (EFWR), and North Fork White River (NFWR). Color gradient shows low grade point equivalents (dark orange) to high grade point equivalents (white). Grade point equivalents are: 0.0=F; 1.0=D; 2.0=C; 3.0=B; 4.0=A. See Table 13 for GPA translations to letter grades.

SUB	Stream	GEN	N	REC	HKM	INT	MJT	HQ	NNT	BAR	DGPA	HGPA	OGPA
BR	Bear Wallow	4	2	4	4	4	4	2	1	3	3.33	3.00	3.16
BR	Centerfire	1	NA	NA	4	0	3	1	0	0	1.00	1.33	1.17
BR	Conklin	NA	NA	NA	2	1	4	1	4	3	0.00	2.50	0.00
BR	Fish	1	3	3	4	2	4	2	0	1	2.33	2.17	2.25
BR	Hannagan	NA	NA	NA	2	1	4	1	1	1	0.00	1.67	0.00
BR	Hayground	1	NA	NA	2	4	4	1	0	0	1.00	1.83	1.42
BR	Home	NA	NA	NA	3	0	4	1	4	3	0.00	2.50	0.00
BR	Paddy	0	NA	3	3	4	4	3	0	1	1.50	2.50	2.00
BR	Snake	1	NA	NA	1	0	4	2	1	1	1.00	1.50	1.25
BR	Soldier	4	3	4	0	4	4	2	4	3	3.67	2.83	3.25
BR	Stinky	1	NA	NA	1	1	4	2	0	0	1.00	1.33	1.17
BR	Thompson-up	4	0	0	0	3	4	4	4	3	1.33	3.00	2.16
BR	WFBR-low	1	NA	NA	4	3	3	2	0	3	1.00	2.50	1.75
BR	WFBR-up	4	3	4	4	2	4	3	2	3	3.67	3.00	3.34
Bo	Big Bo-low	4	NA	NA	4	3	4	4	1	0	4.00	2.67	3.34
Bo	Big Bo-up	4	3	4	1	3	4	4	4	3	3.67	3.17	3.42
Bo	Boggy/Lofer	4	2	4	4	2	4	3	4	3	3.33	3.33	3.33
Bo	Crooked	4	2	4	2	2	4	3	4	4	3.33	3.17	3.25
Bo	Flash	4	1	3	2	1	4	4	4	4	2.67	3.17	2.92
Bo	Little Bo	4	2	4	3	2	4	4	1	3	3.33	2.83	3.08
Bo	Squaw	4	3	4	3	2	4	4	1	2	3.67	2.67	3.17
CO	North Canyon	4	2	2	0	4	4	4	4	3	2.67	3.17	2.92
LC	Coyote/Mamie	NA	NA	NA	3	1	4	1	4	3	0.00	2.67	0.00
LC	EFLC-low	NA	NA	NA	2	4	4	2	0	0	0.00	2.00	0.00
LC	EFLC-up	4	1	4	2	4	4	2	4	3	3.00	3.17	3.08
LC	Mineral	4	0	0	1	4	4	1	4	3	1.33	2.83	2.08
LC	Rudd	NA	NA	NA	3	2	4	1	4	3	0.00	2.83	0.00
LC	SFLC	3	3	4	2	4	4	2	4	3	3.33	3.17	3.25
LC	WFLC	4	2	3	3	4	4	3	0	3	3.00	2.83	2.92
DIA	Coon	0	0	0	1	1	4	2	1	1	0.00	1.67	0.84
DIA	Coyote	4	0	1	1	3	4	3	1	2	1.67	2.33	2.00
DIA	Little DIA	4	2	3	2	1	4	2	1	1	3.00	1.83	2.42
DIA	Moon	4	1	4	2	1	4	2	1	1	3.00	1.83	2.42

DIA	Sun	4	1	4	2	1	4	2	1	1	3.00	1.83	2.42
EFW	Deep	4	3	3	3	3	4	4	4	3	3.33	3.50	3.42
EFW	EF White	4	4	4	2	3	4	4	4	3	4.00	3.33	3.66
EFW	Elk Canyon	4	0	3	1	2	4	4	4	3	2.33	3.00	2.66
EFW	Firebox	4	0	0	1	2	4	3	4	1	1.33	2.50	1.92
EFW	Marshall Butte	4	1	3	1	2	4	4	4	3	2.67	3.00	2.84
EFW	Rock	4	2	2	3	1	4	3	1	2	2.67	2.33	2.50
NFW	Ord	4	3	4	1	3	4	4	4	3	3.67	3.17	3.42
NFW	Paradise	4	0	4	1	3	4	3	4	3	2.67	3.00	2.84
NFW	Smith	4	0	2	0	4	4	3	1	3	2.00	2.50	2.25
NFW	Wohlenberg	4	1	3	1	3	4	4	4	3	2.67	3.17	2.92

The current status of the Apache Trout is a result of management actions taken to protect populations by isolating them above protective fish passage barriers and removing nonnative trout that hybridize with, compete with, and predate upon Apache Trout. Likewise, habitat conditions continue to recover in streams impacted by the 2011 Wallow Fire, and barriers have been constructed, replaced, or maintained since then to achieve the current condition of the species although there are opportunities to continue to improve its condition and resiliency.

Future Conditions

The future condition of the Apache Trout as a species was assessed by characterizing the importance of future threats and conservation actions to species viability and resiliency, as well as determining the future condition of each Apache Trout population or unoccupied recovery stream based on five future scenarios that represent a 30-year timeframe.

The importance of various demographic, habitat, climate, and nonnative species threats, as well as conservation actions, to Apache Trout viability was assessed by querying Apache Trout experts through a survey instrument. Conservation funding, barrier construction, chemical (piscicide) and sustained mechanical (electrofishing) removal of nonnatives, increased frequency and severity of wildfire, and low flows were considered to be most important to the viability of Apache Trout. The small geographic range of Apache Trout makes the species especially susceptible to the threat of a large catastrophic wildfire. Water use, increased monsoon rains, and chemical pollution were considered least threatening to viability among the 37 threats and actions considered.

Five probable future scenarios over a 30-year timeframe (six generations of Apache Trout) were developed that considered environmental conditions, including climate change, and levels of conservation action based on availability of resources and policy. Some of these scenarios account for future delisting and implementation of a Cooperative Management Plan for the Apache Trout by relevant action agencies to assess their perceived effect on the future condition of the species. The future condition of each Apache Trout population or unoccupied recovery stream given each future scenario was characterized—using the 4.0 grading scale described above—through elicitation from Apache Trout experts using the Delphi method. The Delphi method consisted of each expert grading (i.e., assigning a GPA) the future condition of each population or unoccupied stream for each scenario. The experts were then convened by conference call to discuss the survey results, and the experts were given a second survey that allowed them to change their responses based on the discussion. The future scenarios were:

Scenario #1 (Reduced Management, No Delisting, No CMP): Recovery and management actions are reduced to minimal levels because of funding reductions and some program dissolution. Proactive, adaptive management, and voluntary actions are substantially reduced.

Scenario #2 (Sustained Management Until Delisting, No CMP): Recovery and conservation actions continue at levels from 2000–2020 that are beneficial to the species for the first 10 years, at which time Apache Trout are delisted but without a Cooperative Management Plan in place.

Scenario #3 (Sustained Management, No Delisting or Delisting with CMP): Recovery and conservation efforts continue at levels from 2000–2020 that are beneficial to the species, at which time Apache Trout are either not delisted, or the species is delisted but management levels are maintained with a Cooperative Management Plan in place. This scenario represented the status quo scenario with approximately the same amount of resources and management action as a 2000–2020 baseline.

Scenario #4 (Increased Management, Delisting, with CMP): Recovery and conservation efforts continue but at levels increased slightly from 2000–2020 that are beneficial to the species. Management actions continue and some become effective at reducing some threats.

Scenario #5 (Greatly Increased Management, Delisting, with CMP): Improved efficiency in recovery actions, due to science and technology, result in many secured populations free of nonnative trout, including several metapopulations with high resilience and improved effectiveness of recovery and conservation actions before and after de-listing. Additional funding becomes available due to the Cooperative Management Plan agreement in place and new legislation resulting in more funding for fish habitat projects.

Future Viability

Experts predicted that the future condition of the Apache Trout, after 30 years, would decrease under Scenarios #1 and #2 (Figure ES2). Experts thought that the future condition of the species would remain approximately the same under Scenario #3. This scenario represented the status quo scenario, sustained management with no delisting or delisting with a Cooperative Management Plan in place, with approximately the same amount of resources and management action as a 2000–2020 baseline, thus highlighting the impact of ESA listing, or in the event of delisting, implementation of a Cooperative Management Plan. If more resources were to become available (Scenarios #4 and #5), or new science and technology would also come online to improve management efficiency (i.e., Scenario #5: Greatly Increased Management), the condition of the species would improve overall. Even under Scenario #1, a pessimistic scenario with reduced management, it is unlikely that all populations would become extirpated and the species would become extinct. However, the future condition of the Apache Trout will depend upon continued management to achieve Scenarios #2, #3, #4, or #5, especially management focused on protecting populations from nonnative trout. Species experts also thought that Scenarios #1 and #5 were mostly unlikely to occur over the next 30 years (and 100 years; see Appendix A.), which further suggests that the Apache Trout is and will remain a conservation reliant species.

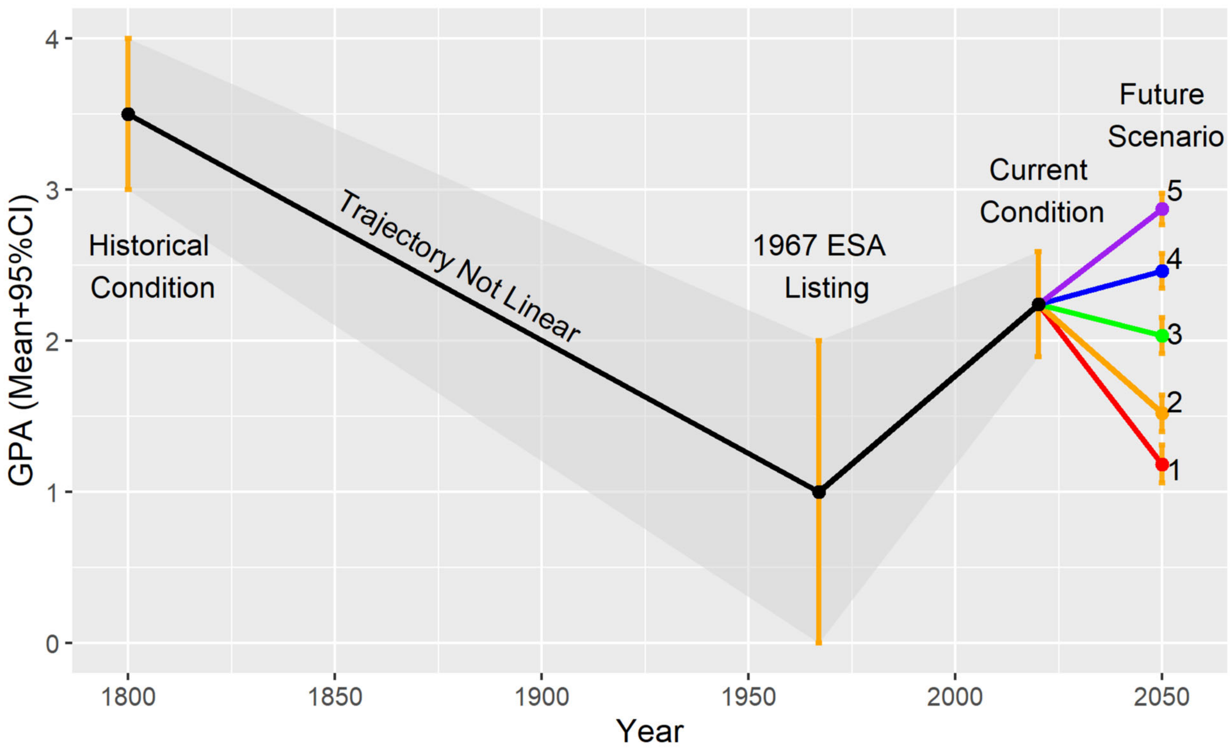

Figure ES2. Overall mean (±95%CI and 95% confidence band) future Grade Point Average (GPA) for the Apache Trout, as elicited from Apache Trout experts, in response to five future conditions scenarios. There were nine experts (N=9) for Apache-Sitgreaves National Forests streams, and seven experts (N=7) for Fort Apache Indian Reservation streams. Historical 1800 and 1967 GPAs (and error) were approximated using best professional judgement.

TABLE OF CONTENTS

A 2017 monitoring survey for Apache Trout on the South Fork Little Colorado River, east-central Arizona. Credit: D. Dauwalter.

INTRODUCTION

Overview and Report Organization

The U.S. Fish and Wildlife Service's (USFWS) Species Status Assessment (SSA) framework outlines a process for describing a species' ecological needs, a species' current condition, and a species' future condition (Smith et al. 2018), and this document does that for the Apache Trout *Oncorhynchus apache* using the best available science, data, and expert judgement (Murphy and Weiland 2016; USFWS 2016). A main goal of this SSA for the Apache Trout is to clearly characterize the species' viability based on the known and presumed ecological effects, controlling factors, and risks and threats, while also highlighting key uncertainties. The species ecological needs are outlined through a review of the scientific literature and most recent data collected on the species and populations where possible, while also drawing on the knowledge of Apache Trout experts when species-specific science and data do not exist. The 3 R's of representation, redundancy, and resiliency are also drawn upon to describe the Current Condition of the Apache Trout. The resiliency component of Apache Trout Current Condition is framed using a 4.0 grade scale—an easily understood and widely used concept—that is understandable to scientists, resource managers and administrators, and the general public. The Current Condition draws upon information on demographic factors and habitat factors known to be important to Apache Trout viability. The Future Condition draws upon a set of five future scenarios that account for exogenous factors such as future climates and varying levels of management action, funding availability, science, and technology, as well as the judgement of Apache Trout experts on the future condition of populations under each scenario.

Species Status Assessment (SSA) Framework

The purpose of the Endangered Species Act is to conserve threatened and endangered species and the ecosystems they require to persist (ESA 1973, as amended). Decisions that support the ESA require a science-based assessment of the species' risk of extinction. Species Status Assessments (SSAs) provide exactly that, a science- and conservation-based assessment of the status of a species that is independent of ESA decision processes or policies (USFWS 2016; Smith et al. 2018).

The SSA Framework was developed to provide improved consistency and transparency in species status assessments (USFWS 2016; Smith et al. 2018). As such, the SSA Framework has three successive stages: 1) Species Needs: the documentation of the species' life history and ecological relationships with its ecosystem; 2) Species Current Condition: a description of the current condition (status) of the species and the hypothesized causes for the current condition; and 3) Species Future Condition: forecasts of the species' future condition that describes the ability of the species to maintain viable populations in the wild given anticipated stressors and conservation actions under various scenarios and timeframes. An SSA represents the compilation and analysis of the-best available information for a species and is independent from policy and regulation (Smith et al. 2018).

CONTRIBUTION FROM EXPERTS

Experts on Apache Trout comprise the Core Team involved in all aspects of this Species Status Assessment, but experts on Apache Trout and trout native to the western U.S. outside of the Core Team were also engaged. These latter experts were engaged formally during surveys, such as those which used the Delphi method (see section titled "Species Current Condition"), and these included past employees of agencies engaged in Apache Trout conservation and management. Other experts were engaged at various points for review of the SSA document, as well as for data analysis and interpretation. These experts are listed at the beginning of the document (Reviewers and Collaborators), as well as in certain sections as appropriate.

SPECIES OVERVIEW

Species Description and Taxonomy

The Apache Trout *Oncorhynchus apache* (Figure 1) is one of several taxa of southern Pacific trouts. Pacific trout were moved from the genus *Salmo* to *Oncorhynchus* in 1989 due to shared genetic and morphometric characteristics with that genus (Smith and Stearley 1989; USFWS 2016). Pacific salmon and Pacific trout (both *Oncorhynchus*) split from a common ancestor 15–20 million-years-ago (MYA), Rainbow Trout *O. mykiss* and Cutthroat Trout split 10 MYA, and Apache Trout, Gila Trout *O. gilae*, and Mexican Golden Trout *O. chrysogaster* are closely related to an ancestral Rainbow Trout lineage and are considered to be the most divergent group of trout with some of the longest isolation from all evolutionary lines of Rainbow Trout (Whiteley et al. 2019); some have in the past proposed that these later species should be considered subspecies of Rainbow Trout (Behnke 2002). Apache Trout and Gila Trout are monophyletic, with an estimated divergence time of 0.66 MYA (range: 0.15 and 1.3 MYA; Wilson and Turner 2009), and are believed to have derived from a common ancestor that gained access to the Gila River from the Gulf of Mexico (mid- to late- Pleistocene); they are more closely related than the four major lineages of Cutthroat Trout (Behnke 1992; Trotter et al. 2018).

Apache Trout taxonomy has evolved over time due to advances in molecular techniques and phylogenetic analyses. These advances have led to a better understanding of the Apache Trout's relationship to other closely related species and ancient ancestors, and, not surprisingly, the species has been renamed several times. Native trout have been known to scientists to occur in the White Mountains of Arizona since at least 1873. Specimens collected from the White River were first described as Colorado River Cutthroat Trout *O. c. pleuriticus* (Cope and Yarrow 1875; as cited in USFWS 2009), and specimens collected from the Little Colorado River were referred to as *Salmo mykiss pleuriticus* (Jordan and Evermann 1896; as cited in USFWS 2009). However, it was not until 1972 that the Apache Trout was originally described as *Salmo apache* owing to fewer and larger spots than Gila Trout and a horizontal band across the eye absent in Gila Trout (Miller 1972). At that time, the Apache Trout was split out from Gila Trout (described in Miller 1950), which is what all trout native to the Gila River basin had been referred to prior to that time (Miller 1972). The Apache Trout was renamed *Oncorhynchus apache* when Pacific trouts were reclassified to *Oncorhynchus* (Smith and Stearley 1989). Behnke (1992) referred to Apache Trout and Gila Trout as subspecies of the same species (*O. gilae apache* and *O gilae gilae*, respectively), and the Apache Trout trinomial was recognized by the American Fisheries Society in 2004 (Nelson et al. 2004); however, the American Fisheries Society now recognizes Apache Trout as *O. apache* in the 7th Edition of Common and Scientific Names (Page et al. 2013). The common name Arizona Trout was originally linked to *Salmo apache*, but in 1980 the American Fisheries Society accepted the species' common name change to Apache Trout (Robins et al. 1980).

Figure 1. The Apache Trout. Credit: Arizona Game and Fish Department.

Listing Status and Recovery Planning

The Apache Trout was listed as endangered under the Endangered Species Preservation Act in 1967 (March 11, 1967, 32 FR 4001; USFWS 1967) before being downlisted to threatened under the Endangered Species Act in 1975 (July 16, 1975, 40 FR 29863; USFWS 1975) after successful culturing in captivity and discovery of additional populations; The downlisting rule included a 4(d) rule which allows Arizona Game and Fish Department to establish and regulate sport fishing opportunities on non-tribal lands. The White Mountain Apache Tribe regulates take and sport fishing for Apache Trout on the Fort Apache Indian Reservation (FAIR). There is no critical habitat designation for Apache Trout because listing and reclassification occurred before the 1978 and 1982 amendments to the Endangered Species Act that provides for critical habitat designations.

The first Recovery Plan for the Apache Trout was finalized in 1979 (USFWS 1979), and a revised plan was finalized in 1983 (USFWS 1983). A second revision was completed in 2009 (USFWS 2009). The recovery goal of the 2009 Recovery Plan, which is generally consistent with the 1979 and 1983 plans (USFWS 1979; USFWS 1983), is to: "implement necessary actions to delist Apache Trout." The primary objective of the recovery plan is to: "establish and/or maintain 30 self-sustaining discrete populations of pure Apache Trout within its historical range." The recovery criteria for when Apache Trout should be considered for removal from the List of Threatened and Endangered Species (delisting) are (USFWS 2009):

- Habitat sufficient to provide for all life functions at all life stages of 30 self-sustaining discrete populations of pure Apache Trout has been established and protected through plans and agreements with responsible land and resource management entities. These plans will address and serve to remedy current and future threats to Apache Trout.
- Thirty discrete populations of pure Apache Trout have been established and determined to be self-sustaining. A population will be considered self-sustaining by the presence of multiple age classes and evidence of periodic natural reproduction. A population will be considered established when it is capable of persisting under the range of variation in habitat conditions that occur in the restoration stream (Propst and Stefferud 1997).

- Appropriate angling regulations are in place to protect Apache Trout populations while complying with Federal, State, and Tribal regulatory processes.
- Agreements are in place with USFWS, AZGFD, and White Mountain Apache Tribe (WMAT) to monitor, prevent, and control disease and/or causative agents, parasites, and pathogens that may threaten Apache Trout.

The last 5-year review for Apache Trout was completed in 2010 (USFWS 2010). Drawing from the Revised Recovery Plan (USFWS 2009), the 5-year review stated implementation of actions in the 1983 Revised Recovery Plan (USFWS 1983) resulted in amelioration of most significant threats to the species. Three of five listing factors were no longer considered a threat: 1) overutilization, 2) inadequacy of regulatory mechanisms, and 3) diseases and pathogens were of minor concern (into the future). Some habitat improvement projects have been completed and management plans are in place to protect, maintain, and improve riparian and instream habitat. However, the 5-year review found that certain threats to the species still existed. Some conservation barriers isolating Apache Trout populations from nonnative salmonids had been compromised, and those habitats were subsequently invaded. Other populations with sympatric nonnative salmonids required nonnative suppression and removal, others had been hybridized, and a few more existed in small habitats. Together these issues restricted the number of genetically pure, self-sustaining populations from reaching recovery criteria. A 'No Change' in the species status was recommended (USFWS 2010).

Historical Distribution

The Apache Trout is endemic to the White River, Black River, and the Little Colorado River drainages in the White Mountains of east-central Arizona although the exact historical distribution is not known with certainty (Figure 2). The general native distribution is confirmed by extant pure and hybrid populations and historical fish collections (Rinne 1985; Loudenslager et al. 1986; Carmichael et al. 1993). Early European settlers in the White Mountains reported the presence of yellow-bellied, speckled trout, with some photographic evidence of large catches from streams around Springerville, Arizona (likely Becker Creek; USFWS 1983). Rinne and Minckley (1985) reconstructed historical collections and noted the lower elevational limits of Apache Trout to be from 1,800 to 2,100 m. Estimates based on field sampling, physical characteristics, and geographic information system (GIS) mapping, suggested that the Apache Trout occupied between 965 and 1,320 km of streams above 1,800 meters elevation in these drainages (USFWS 2009).

The Apache Trout is considered native to the headwaters of the Little Colorado River. Original specimens in the Little Colorado River headwaters were called Colorado River Trout *Salmo mykiss pleuriticus* (Jordan and Evermann 1896), now referred to as the Colorado River Cutthroat Trout *O. c. pleuriticus* (Behnke 1992). In the past it had been speculated that Apache Trout colonized the Little Colorado River through a transbasin canal diverting water from the Black River to Colter Reservoir in the Little Colorado River drainage (Miller 1961); however, the canal was built in 1897 (Miller 1972) whereas Apache Trout were first collected prior to 1886 (Jordan and Evermann 1896), thus suggesting they are native to the basin (USFWS 2009).

The Blue River and San Francisco River drainages were once considered to be historical habitat of the Apache Trout but are now considered to be historical Gila Trout habitat based on early fish collection records, current distribution of relict Gila Trout lineages, and distribution of Gila Trout × Rainbow Trout hybrids (USFWS 2003). Likewise, questions have arisen as to why Apache Trout never occupied the

Verde and Agua Fria drainages that are considered historical Gila Trout habitats; specimens from Oak Creek (Verde River) in the 1800's were called the Verde Trout that resembled Gila Trout but also contained Apache Trout characteristics, suggesting the fish found there may be a natural hybrid morphotype. Specimens from Sycamore Creek in the Agua Fria River drainage were identified as Gila Trout x Rainbow Trout hybrids (Behnke and Zarn 1976).

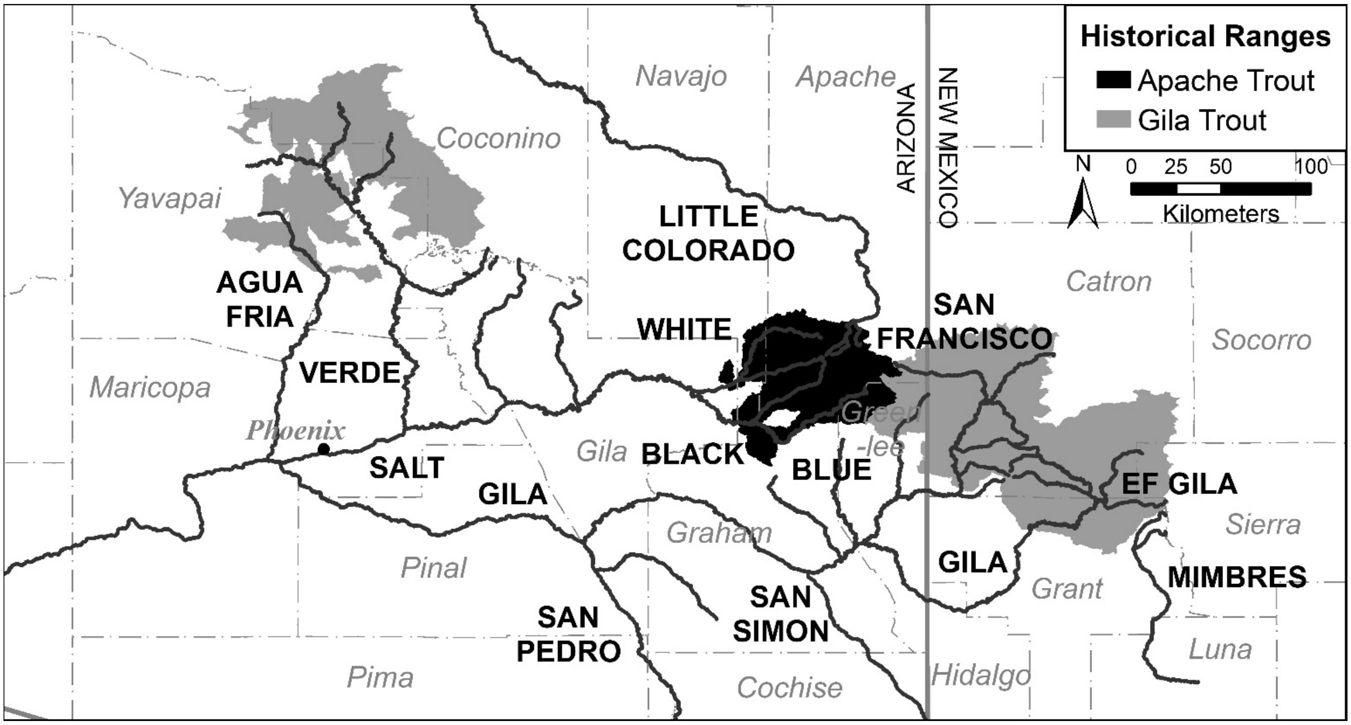

Figure 2. Historical distribution of Apache Trout and Gila Trout in Arizona and New Mexico.

Native trout specimens from the Gila River basin, except the Salt River above the barrier falls in Salt River Canyon, have been identified as Gila Trout or Gila Trout × Rainbow Trout hybrids. As summarized in the 2009 Recovery Plan (USFWS 2009), a 1973 specimen from Chitty Creek, an Eagle Creek tributary, that is currently lost was tentatively identified as a Gila Trout × Rainbow Trout hybrid (from W.L. Minckley and R. Miller, personal communication cited in USFWS 2009), although some have claimed Chitty Creek fish were a subspecies of Apache Trout (Kynard 1976). Collection and genetic testing of specimens from Chitty Creek around 1990 showed fish currently occupying Chitty Creek to be Rainbow Trout (Dowling and Childs 1992; Genetic Analysis 1994). Specimens collected by F.W. Chamberlain in 1904 from KP Creek, a tributary of the Blue River (San Francisco River drainage), exhibited spotting patterns similar to Apache Trout but showed "hybrid" influence (Miller 1972) and purportedly had a distinct red band rarely seen in Apache Trout.

At the time of the 1983 Recovery Plan there were only 14 known populations of Apache Trout occupying less than 48 km of habitat (USFWS 1983). At the time that the 2009 Revised Recovery Plan was finalized, there were 28 populations within the historical range (USFWS 2009). The current status of Apache Trout populations is discussed in the section titled "Species Current Condition."

Life History

The Apache Trout is one of several southern species of Pacific trout that currently are recognized as a separate species (Whiteley et al. 2019). The ecology of Apache Trout is, consequently, similar to other *Oncorhynchus* trout species, but there is also some uniqueness due to interspecific differences in the species' ecology and environment within its historical range (White, Black, and Little Colorado rivers in Arizona; Behnke 2002).

Feeding

Like most trout occupying small headwater streams, the Apache Trout has been described as an opportunistic feeder, although only one study has characterized the species' feeding ecology. In Big Bonito Creek, Apache Trout consumed primarily caddisflies (Trichoptera; 43–54%) followed by terrestrial insects (32–33%) in the summer, and terrestrial insects (45%) followed by true flies (Diptera; 34%) in fall, although only 9 fish diets were examined in fall; mayflies (Ephemeroptera), stoneflies (Plecoptera), and beetles (Coleoptera) were also consumed in smaller percentages (Harper 1978). Individuals 6–9-cm total length (TL) consumed more mayflies than those ≥15-cm TL, and individuals ≥15-cm TL consumed more caddisflies (Harper 1978). In an unpublished study, Apache Trout 5–17-cm TL collected by AZGFD from Mamie Creek (Apache-Sitgreaves National Forests [ASNF]) exhibited diets similar to those reported in Big Bonito Creek, although larger individuals consumed more mayflies (Ephemeroptera; unpublished data reported in USFWS 2009).

Growth

Three studies have evaluated the age and growth of Apache Trout. Apache Trout were collected from upper Big Bonito Creek upstream from the Hurricane Creek confluence between 2,500 and 2,745 m elevation in 1974 and 1975, where maximum temperatures were 21°C and 17°C, respectively (Harper 1976; Harper 1978). Otoliths were removed from 37 fish and photographed against a black background, and photographs were used to count annuli for age and to back-calculate TL at each annulus (Tesch 1971; Williams and Bedford 1974). Length at the first annulus (age 1) ranged from 33–51-mm TL, and the oldest individual was age 5 (Table 1). Apache Trout collected from the East Fork White River in 2017 were commonly 10–30 mm longer at a given age (estimated using otoliths) than those from Big Bonito Creek based on back-calculated lengths at age, and the maximum age observed was 9 (Table 1; Quist et al., in press). Although speculative, differences in length at age and growth increments likely reflect differences in thermal regimes between the headwaters of Big Bonito Creek (mean July =12.8°C) and the lower East Fork White River (mean July = 13.6°C). Porath et al. (2010) report on age and growth of Apache Trout (aged using scales) from streams in the Pinaleño Mountains (Graham County, AZ); these streams are now considered historical habitat of, and are occupied by, Gila Trout.

Apache Trout from Big Bonito Creek grew slowly. Fry were 20 to 22-mm TL upon emergence, and during capture in fall were only 45-mm TL (Harper 1978). Growth to annulus 1 (age 1) averaged 11 to 29-mm TL from 1970 to 1975, and from ages 2 to 5 average annual growth ranged from 25 to 50-mm TL (Table 2). In Firebox Creek, Apache Trout emerged from the gravel in July at 15-mm TL and dispersed at 25-mm TL (Wada 1991). In Squaw and Flash creeks, Apache Trout implanted with passive integrated transponder (PIT) tags grew from 0.10 mm/day and 0.17 g/day in 1997 (June to August), but only grew 0.05 mm/day in length and 0.03 g/day in weight in 1998 when flows were high (Kitcheyan 1999).

Table 1. Mean back calculated length (TL in mm) at age (annulus formation) from otoliths for Apache Trout from Big Bonito Creek (BBC), Arizona collected in July 1974 and August and October 1975 (Harper 1976; Harper 1978) and East Fork White River (EFWR), Arizona collected in 2017 (Quist et al., in press).

Year Class	Sample size (n)	Age-1	Age-2	Age-3	Age-4	Age-5	Age-6	Age-7	Age-8	Age-9
BBC–1970	2	51.0	95.0	129.5	160.0	210.0				
BBC–1971	13	35.5	84.2	121.1	--					
BBC–1972	11	43.9	90.7	*118.3	*139.0					
BBC–1973	4	40.0	76.5	98.5						
BBC–1974	7	45.7	84.9							
BBC–1975	24	33.0								
EFWR–2009	1	61.0	101.8	144.2	166.9	178.1	191.1	202.5	211.1	222.0
EFWR–2010	2	34.2	80.9	109.6	136.4	153.9	175.3	196.4	209.9	
EFWR–2011	10	61.6	100.7	125.2	141.5	153.8	164.6	173.9		
EFWR–2012	16	59.3	100.9	124.8	141.4	153.2	163.0			
EFWR–2013	27	63.2	119.6	149.7	167.6	181.3				
EFWR–2014	52	54.1	104.1	134.7	158.2					
EFWR–2015	70	50.2	99.1	125.4						
EFWR–2016	75	60.9	110.9							

*sample size was n = 4 fish for these ages

Table 2. Mean growth in length (mm) between annuli in Apache Trout from Big Bonito Creek, Arizona collected from 1970 to 1975 (Harper 1976; Harper 1978).

Year Class	Age-1	Age-2	Age-3	Age-4	Age-5
1970	29.0	44.5	34.0	30.0	50.0
1971	13.5	48.6	36.9		
1972	21.0	46.8	27.5	20.8	
1973	18.0	36.5	22.0		
1974	23.0	39.0			
1975	11.0				
Mean	19.3	43.0	30.0	25.4	50.0

Survival

Survival of Apache Trout is typical of other trout. In Squaw and Flash creeks, annual survival across all ages was estimated to range from 48% to 74% (1996 to 1998; Table 3) based on catch-curve analysis using data from Kitcheyan (1999). These are similar to annual survival rates of other trout in the interior western U.S. (Carlson and Rahel 2010; Gresswell 2011). There have been no comprehensive studies of seasonal survival of Apache Trout. Often trout have high mortality during the spawning season, but also during summer in some systems where temperatures approach lethal limits (Carlson and Rahel 2010; Gresswell 2011). Survival of age-0 Apache Trout is also unknown, although it appears cold temperature may limit juvenile occupancy (Appendix C. Climate Influences on Apache Trout Distribution and Identification of Climate Resilient Habitats). Recruitment of Cutthroat Trout has been shown to be limited when streams have less than 900 degree days (number degrees Celsius above 0°C for each 1 day period) due to very low survival of fry smaller than 30–35-mm TL entering the winter (Coleman and Fausch 2007). More research is needed on seasonal survival, especially in winter, of Apache Trout.

Table 3. Age structure (catch by age) and annual survival of Apache Trout from Squaw and Flash creeks, Arizona from 1996 to 1998 (from Table 8 in Kitcheyan 1999). Values represent counts of fish within each age class by year. Instantaneous mortality (Z) was calculated using catch-curve analysis with age-1 fish omitted (Ricker 1975). Annual survival was computed as: $S = e^{-Z}$.

	Squaw Creek			Flash Creek		
Age (TL)	1996	1997	1998	1996	1997	1998
1 (<84 mm)	21	5	26	35	45	32
2 (85–128 mm)	47	1	95	125	58	128
3 (129–182 mm)	49	8	12	90	33	70
4 (183–229 mm)	12	13	7	16	2	11
>4 (>230 mm)	0	4	5	2	0	0
Total	129	32	144	268	138	241
Z	0.30	NA	0.41	0.61	0.73	0.53
S	0.74	NA	0.67	0.54	0.48	0.59

Note: NA indicates that the metric could be computed due to increasing catch by age

Reproduction

Apache Trout spawn from March through mid-June in White Mountain streams. In Big Bonito Creek, redds (spawning beds or depressions) were observed during the descending limb of the hydrograph from 30 May to 18 June, 1975 when daily maximum temperatures were 8.0 and 11.2°C, respectively (Harper 1976; Harper 1978). Redds were constructed from the middle of the stream to as close as 24 cm to the streambank in substrates ranging from 1 to 32 mm in diameter, water depths ranging from 19 to 27 cm, velocities ranging from 1.42 to 3.11 cubic meters per second (cms), and in areas with daylong illumination (Harper 1976). Wada (1991) suggested that spawning and rearing habitat was limited in Paradise, Ord, and Big Bonito creeks, but not in Firebox and Sun creeks, based on physical habitat surveys.

Apache Trout are thought to become reproductively mature at ages 2 or 3. Apache Trout were examined for eggs from 16 to 23 June, 1975 in Big Bonito Creek and East Fork White River, where it was revealed that 17 of 19 females were classified as spent (all eggs laid), while the remaining two partially-spent females retained 54 and 57 eggs (Harper 1976; Harper 1978). The smallest mature female was 130 mm (unstated but presumably total length), and the smallest male observed (visibly spilling milt) was 145 mm, which corresponds with age-3 fish (Table 1).

Fecundity of Apache Trout is related to fish size, as in other fishes (Harper 1976). Miller (1972) reported that female Apache Trout generally contain from 200 to 600 eggs. Apache Trout from Big Bonito Creek ranging in size from 130 to 200-mm TL produced from 72 to 240 eggs per female (Harper 1976). Data from Figure 6 in Harper (1976) were used to estimate the total length-fecundity relationship, which was estimated to be: # Eggs = $0.005 \cdot TL^{1.97}$ (R^2=0.675; Figure 3). Once eggs are deposited in the gravel they hatch after approximately 30 days and emerge after approximately 60 days (Harper 1978). Two redds excavated in Big Bonito Creek contained 43 and 67 eggs. This is less than the total eggs per female, which led Harper (1978) to suggest that Apache Trout do not deposit all eggs in a single redd.

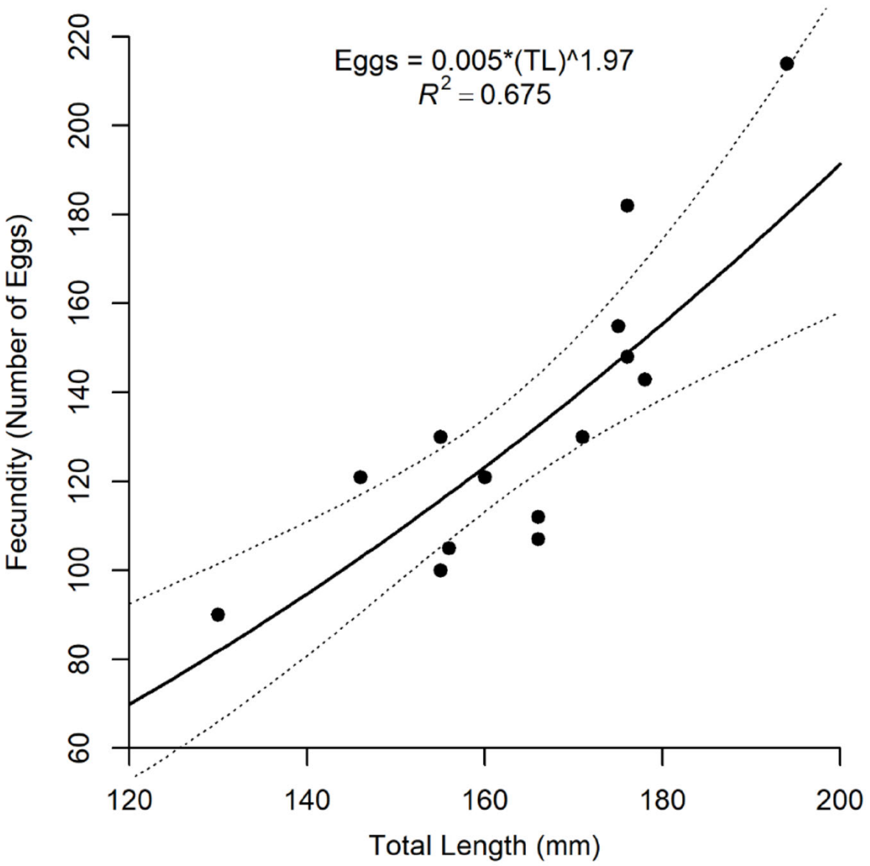

Figure 3. Relationship between Apache Trout [presumably] total length (TL mm) and fecundity (number of eggs) with 95% confidence (not prediction) intervals (Harper 1976). Data were digitally extracted from Figure 6 in Harper (1976), and then used to estimate the total length-fecundity relationship.

Movement

A few studies have been conducted on Apache Trout movement, and several others have anecdotally noted small-scale pool-to-pool movements (Wada et al. 1995). In Squaw Creek, a majority of 20 PIT-tagged Apache Trout >150-mm TL had relocated within 0.75 km of their release site from June to August. The maximum distance moved was 2.1-km upstream and 2.4-km downstream, although movement may have been restricted by barriers (Kitcheyan 1999). In Big Bonito Creek, Apache Trout were sedentary; the 41 tagged adults moved less than 0.1-km (Harper 1978). One Apache Trout (195-mm TL) tagged below the protective barrier on Fish Creek as part of a barrier evaluation study was collected 8 km upstream during an unrelated fish survey during the 3-year study period (AZGFD unpublished data reported in Avenetti et al. 2006). Fry migrating in Big Bonito Creek generally moved downstream at night from August to October (Harper 1978).

Habitat

Apache Trout currently occupy headwater streams upstream of natural and artificial barriers, which likely reflects a truncated distribution from historical distributions due to nonnative trout, habitat alterations, and other factors (USFWS 2009). Consequently, habitat use and selection by Apache Trout reflect the fact that studies have been conducted mostly in small headwater streams. Habitat use and selection patterns are commonly influenced by what habitat is available, and habitat available to the Apache Trout is based on stream size and the historical ecology of the region, including underlying geology, that may have a controlling influence on stream habitats (Long et al. 2006).

Underlying Geology as a Habitat Template

Bedrock and surficial (unconsolidated sediments) geology impart systemic controls on geomorphology, hydrology, and other aspects of aquatic ecosystems (Knighton 1998), and so it is important to recognize the geologic setting of streams within the historical range of the Apache Trout in the White Mountains (Figure 4). Mount Baldy represents an extinct volcano and thus has on its upper flanks felsic volcanic rocks, termed the Mount Baldy Formation, that also include glacial deposits in five valleys on Mount Baldy's northern flank (Long et al. 2006). The Springerville Quaternary Basalt is to the north, Tertiary mafic rocks are to the south, and Tertiary sedimentary rocks also occur. Felsic magmas tend to produce steep lobes whereas mafic magmas tend to form flatter flows. Valleys on lower slopes of Mount Baldy are filled with poorly sorted sand, gravel, and boulders shed from Mount Baldy. Drainages flowing south and west from Mount Baldy have incised into canyons cut into older mafic rocks mixed with volcanic clastic deposits. South-east sloping drainages flow onto expansive plateaus and canyons formed from the Tertiary mafic flows. The region north and east of Mount Baldy is comprised of cinder cones and the younger Springerville volcanic field. To the east, Coyote and Mamie creeks flow off the Escudilla Mountains that have a mafic summit and clastic sandstones, mudstones, and conglomerates down slope.

Land Use Impacts on Aquatic Habitat

Aquatic ecosystems are intricately linked across spatial scales (watershed → stream reach → microhabitat), and because of these linkages land cover and use within a watershed influences instream habitat and water quality (Frissell et al. 1986), including in stream habitats occupied by Apache Trout. As such, ungulate grazing, logging, and other land uses have impacted Apache Trout habitat and were cited in the original ESA listing as reasons for the decline of Apache Trout (in addition to nonnative species; USFWS 1983). In study of 143 sites across the White Mountains within Apache Trout historical habitat, Clarkson and Wilson (1995) found that trout standing crop (biomass) was primarily influenced by metrics reflecting ungulate grazing: streambank damage by ungulates, and channel width. Long and Medina (2006) reanalyzed the same data, but also considered geologic variation, and found that geology was a much better predictor of trout biomass than were the grazing indicators used in the original study that subsequently showed no effect in the reanalysis of the data. Other researchers have found streams to be wider from livestock use, but mixed effects of livestock impacts on stream substrates including fine sediments (Rinne 1988; Rinne 1990). However, fine sediments have been shown to be negatively associated with trout populations (Rinne and Medina 1988), and fine sediments have been shown to embed spawning substrates and negatively impact emergence of Apache Trout from spawning gravels (Rinne 2001). The impact of ungulate grazing on stream habitat and populations of Apache Trout, and the magnitude of those effects when they occur, appear to be dependent on the landscape context (geology, topography, etc) in which each stream is set, and further research is needed to reveal in what contexts are impacts the highest and what streams may be most resilient to ungulate use.

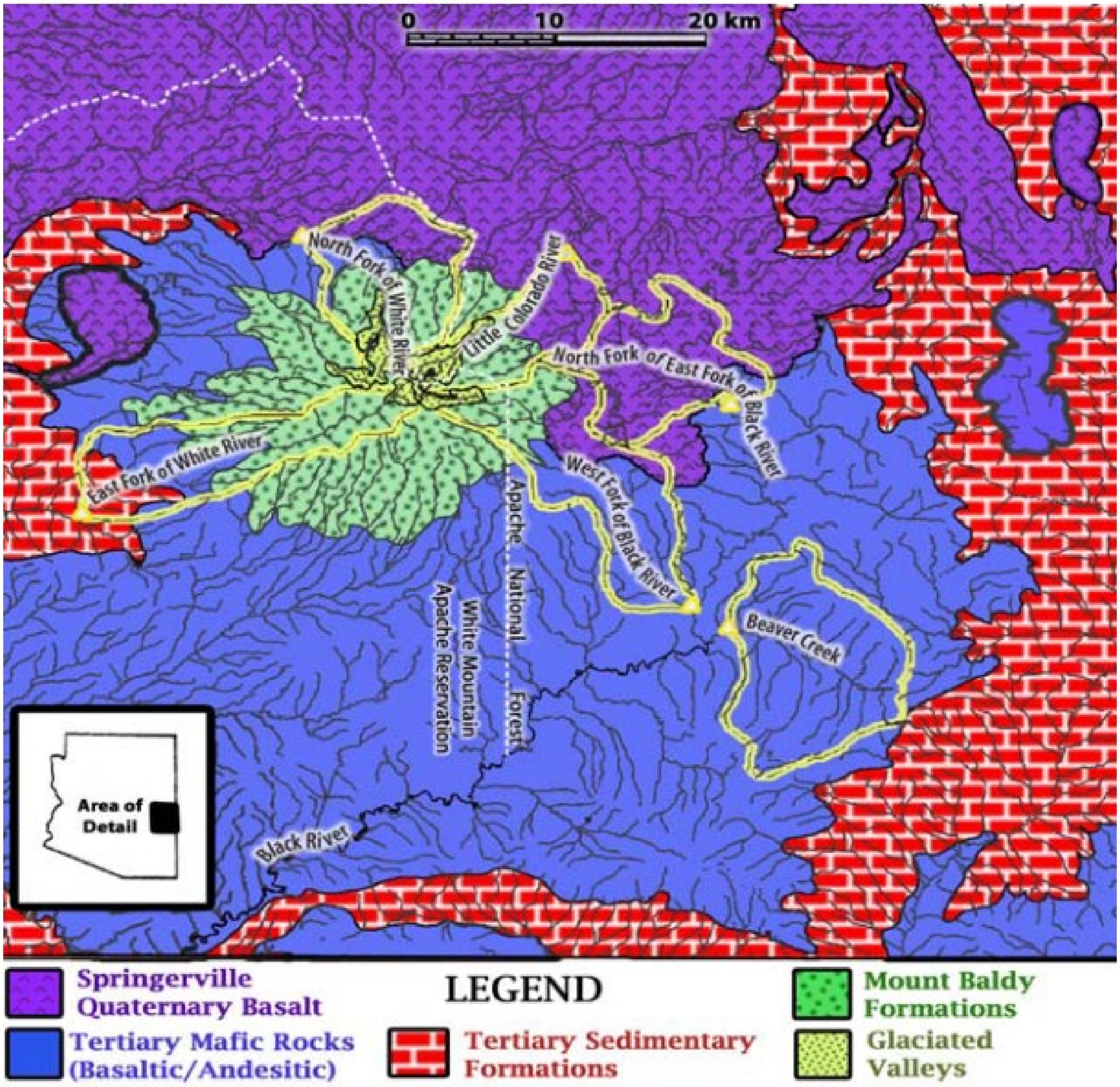

Figure 4. Geology of the White Mountains region in east-central Arizona, with six gaged watersheds outlined. From Long et al. (2006) with permission.

Logging and associated road building were also implicated in the decline of Apache Trout during the species' original ESA listing (USFWS 1983). Logging can impact aquatic habitats by fragmenting stream systems with poorly design road networks and road-stream crossings, and it can result in high levels of fine sediment inputs therefore increasing substrate embeddedness (Eaglin and Hubert 1993). While no specific studies have been done on the effects of logging, including historical logging, on Apache Trout habitats, the effects were purported to be many, including: changes to riparian corridors, stream morphology, erosion potential, increased susceptibility to flood effects, reduced quality of spawning substrate, altered streamflows, elevated temperatures, and decreased stream productivity and Apache Trout food supply (USFWS 2009). Reservoir construction, agriculture, and broader road construction have also been implicated in causing damage to Apache Trout habitats (USFWS 2009).

Temperature

The Apache Trout, like most salmonids, is a cold-water obligate. Several laboratory and field studies have evaluated the temperature tolerance and preferences of the Apache Trout.

Laboratory — Laboratory studies of Apache Trout thermal tolerance have typically focused on a few key thermal tolerance metrics: LT50, CTMax, and Survival. These metrics are defined as:

- **LT50**: Median temperature lethal to 50% of individuals.
- **CTMax**: Critical Thermal Maximum: median (or mean) temperature at which fish loses equilibrium for 30 seconds. This metric is often used for at-risk species because they often recover when returned to cooler water (Lee and Rinne 1980).
- **Survival**: Percent (%) of individuals surviving over a defined time period.

The thermal tolerance of fishes is, in part, based on previous thermal experience (Johnstone and Rahel 2003), and studies often evaluate thermal tolerance at different acclimation temperatures. One laboratory study showed Apache Trout 150–200 mm TL had a CTMax of 28.5°C when acclimated at 10°C and a CTMax of 29.4°C when acclimated at 20°C (Lee and Rinne 1980). In another study, Apache Trout critical thermal maxima (CTMax) was observed to be 30.5°C for fry and 29.7°C for adults (200-220 mm TL) when acclimated at 18°C (Recsetar et al. 2012). When daily temperatures were cycled (±3°C from a mean temperature) to mimic the diurnal temperature cycles of streams, CTMax was found to decrease from that at static temperatures in one study (Lee and Rinne 1980), but LT50 was found to increase slightly under fluctuating temperatures (Recsetar and Bonar 2013). Survival of eggs and larva decreases considerably above 15–18°C (Recsetar et al. 2014), and fry survival decreases considerably above 22°C (Recsetar et al. 2014). Lethal temperatures at 50% survival (LT50) were estimated to be 17–18°C for eggs and larva over 14 days and 23°C for fry over 30 days (Recsetar and Bonar 2013).

Field observations — In the field, there have been many observations of temperature in streams occupied by Apache Trout, and one study has explicitly evaluated how Apache Trout select temperatures *in situ*. Petre and Bonar (2017) evaluated habitat use and selection by Apache Trout in three streams that originate at the highest elevations and represent some of the most intact riparian and instream habitat on the ASNF (J. Ward, ASNF, pers. comm). Apache Trout occupancy throughout each stream was documented using snorkeling and pre-positioned aerial electrofishing from 24 May to 14 June, 2012. They also recorded temperature continuously every 20 min from May to December 2012. At the time of capture, Apache Trout occupied habitats with temperatures of 17.8 ± 2.7°C (mean ± SD) in the West Fork Black River (WFBR), 17.1 ± 2.1°C in the West Fork Little Colorado River, and 13.6 ± 3.4°C in the East Fork Little Colorado River. From these observations, Petre and Bonar (2017) combined data across streams to develop generalized thermal habitat suitability criteria. Optimal temperature ranges at the time of capture were defined as 13.3 to 18.9°C, and suitable temperatures at capture were 10.4 to 21.1°C. Optimal maximum temperatures observed across the study period were defined as 20.1 to 22.9°C and suitable maximum temperatures were 17.1 to 25.9°C, although maximum temperatures at a location did not necessarily occur at the time of capture when fish may no longer have occupied that location. No Apache Trout were observed at locations with a summer maximum daily temperature above 26°C. The authors concluded that temperature is likely a limiting factor for Apache Trout (Petre and Bonar 2017).

Temperature of Apache Trout habitats — Thermographs have been deployed in select Apache Trout streams to continuously measure temperature and characterize their thermal profile. From 2012 to 2018, thermographs were placed on Apache Trout streams on the ASNF and represent 49 site-years (number of sites × number of years) of data (Figure 5; J. Ward, ASNF, unpublished data). These data show Apache Trout streams to typically be warmest before monsoon rains begin (~late June, early July). There is a strong relationship between mean August and mean July temperatures in these streams, and mean July is, on average, warmer than mean June and mean August in most streams (Figure 6). Mean July temperatures in these streams range from 11.5 to 18.5°C, and they can fluctuate daily by up to 19.2°C (Figure 6; Table 5). All temperature monitoring sites exceeded 23°C in at least one year (Table 5), which is the upper limit of maximum daily temperatures considered optimal for Apache Trout >120-mm (Petre and Bonar 2017) but is a temperature at which 50% of fry mortality and 100% of egg/larva mortality occurs (Table 4; Recsetar et al. 2014). Thirteen stream-years had exceeded the maximum daily temperature of 26°C, which is the upper range of suitable temperature criteria for Apache Trout >120-mm TL (Petre and Bonar 2017) and a temperature at which fry survival is very poor to non-existent (Table 4; Recsetar and Bonar 2013; Recsetar et al. 2014). The maximum average weekly maximum temperature (MWMT), a weekly metric that better integrates thermal experience than does a single day, was 26°C or higher in three streams (Double Cienega, Fish, and West Fork Black) in two years (2015 and 2018), suggesting that most exceedances of 26°C occur only one to a few days in a row. In winter, Harper (1978) noted that severe winter conditions with heavy snow and cold temperatures can result in anchor ice and ice bridges in Apache Trout streams, which can create harsh winter conditions for fish (Brown et al. 2011), but little is known about winter ecology of the Apache Trout.

Table 4. Apache Trout thermal tolerance metrics by fish size, acclimation temperatures, and evaluation time periods. Note: For thermal metric CTMax, size class Fry, total length 40 and for size class adults, total length 200mm, minimum and maximum sizes evaluated, and mean CTMax was estimated using linear regression across fish lengths (40 to 200-mm TL).

Thermal Metric	Size class	Total Length (mm)	Acclimation °C (time)	Timeframe	Temperature °C	Survival (%; mean ± SD)	Reference
CTMax	Fry	40	18°C (14-d)	↑0.3°C/min	30.5°C	not applicable	(Recsetar et al. 2012)
CTMax	[Sub]adults	100–140	13–15°C (12-d)	↑2–3°C/2-d	22–23°C	not applicable	(Alcorn 1976)
CTMax	Adults	150–200	10°C (14-d)	↑0.2°C/min	28.5 ± 0.35°C	not applicable	(Lee and Rinne 1980)
CTMax	Adults	150–200	10°C (14-d)	↑1°C/2-d (±3°C)	24.0 ± 3.0°C	not applicable	(Lee and Rinne 1980)
CTMax	Adults	150–200	20°C (14-d)	↑0.2°C/min	29.4 ± 0.21°C	not applicable	(Lee and Rinne 1980)
CTMax	Adults	200	18°C (14-d)	↑0.3°C/min	29.7°C	not applicable	(Recsetar et al. 2012)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	15°C	76.0 ± 8.5%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	18°C	36.7 ± 26.3%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	21°C	13.9 ± 9.8%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	24°C	1.1 ± 1.9%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	27°C	0.0 ± 0.0%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	15 ± 3°C	68.1 ± 30.2%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	18 ± 3°C	62.2 ± 13.5%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	21 ± 3°C	27.8 ± 30.8%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	24 ± 3°C	0.0 ± 0.0%	(Recsetar and Bonar 2013)
Survival	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	27 ± 3°C	0.0 ± 0.0%	(Recsetar and Bonar 2013)
Survival	Fry	33–41	14°C (14-d)	30-d	16°C	73.3 ± 30.6%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	19°C	53.3 ± 33.4%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	22°C	88.9 ± 13.9%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	25°C	0.0 ± 0.0%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	28°C	0.0 ± 0.0%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	16± 3°C	66.7 ± 13.4%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	19± 3°C	73.3 ± 11.5%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	22± 3°C	91.1 ± 7.7%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	25± 3°C	1.1 ± 1.9%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	19± 6°C	88.9 ± 10.2%	(Recsetar et al. 2014)
Survival	Fry	33–41	14°C (14-d)	30-d	22± 6°C	60.0 ± 10.0%	(Recsetar et al. 2014)
LT50	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	17.1°C	50%	(Recsetar and Bonar 2013)

LT51	Eggs/larva	Eggs/larva	15°C (12-h)	14-d	17.9 ± 3°C	50%	(Recsetar and Bonar 2013)
LT52	Fry	33–41	14°C (14-d)	30-d	22.8°C	50%	(Recsetar et al. 2014)
LT53	Fry	33–41	14°C (14-d)	30-d	23.1°C ± 3°C	50%	(Recsetar et al. 2014)

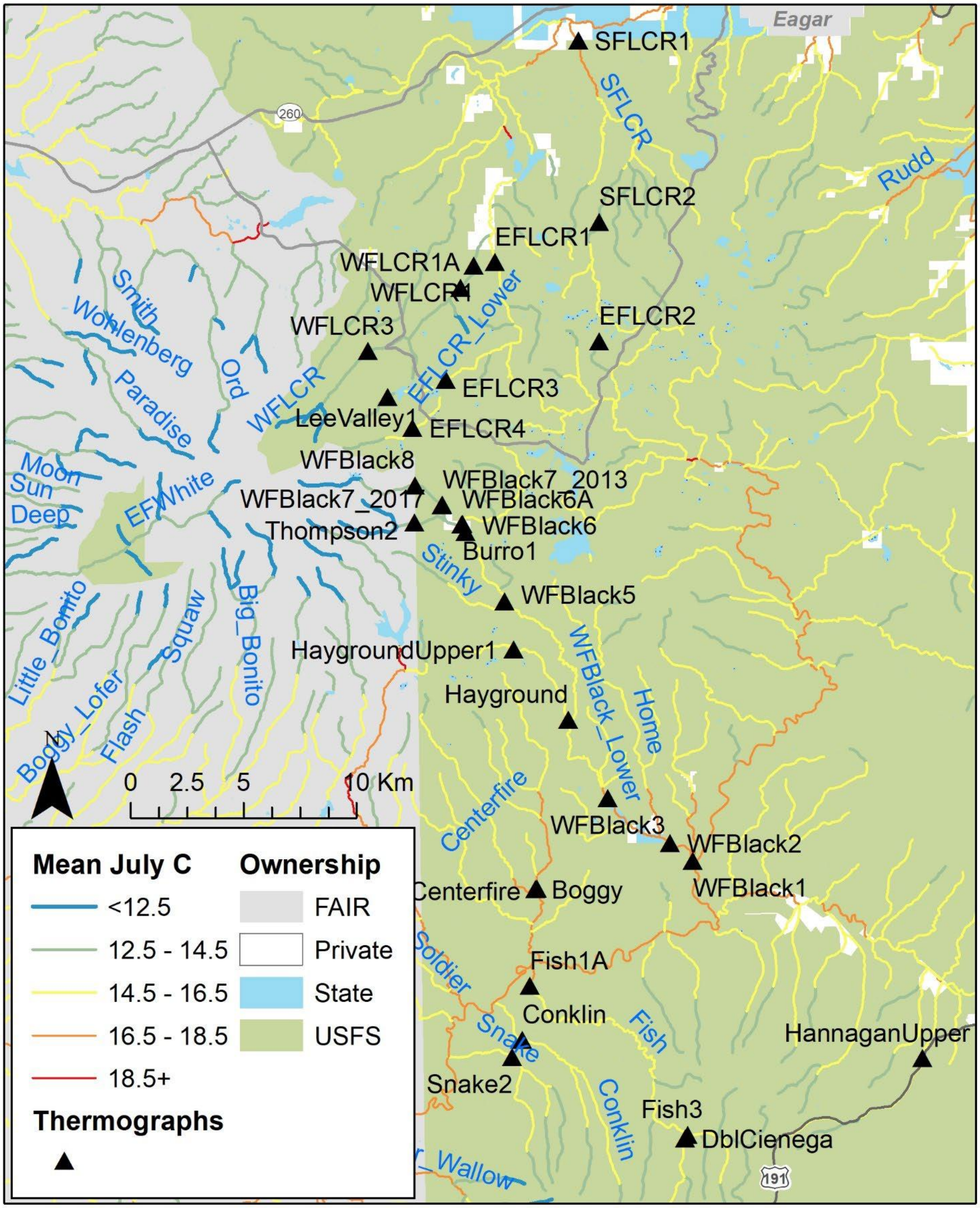

Figure 5. Map showing location of thermographs on Apache Trout streams on the ASNF (data credit: J. Ward, ASNF) and mean July stream temperatures predicted by the NorWeST model. Apache Trout streams labeled in blue.

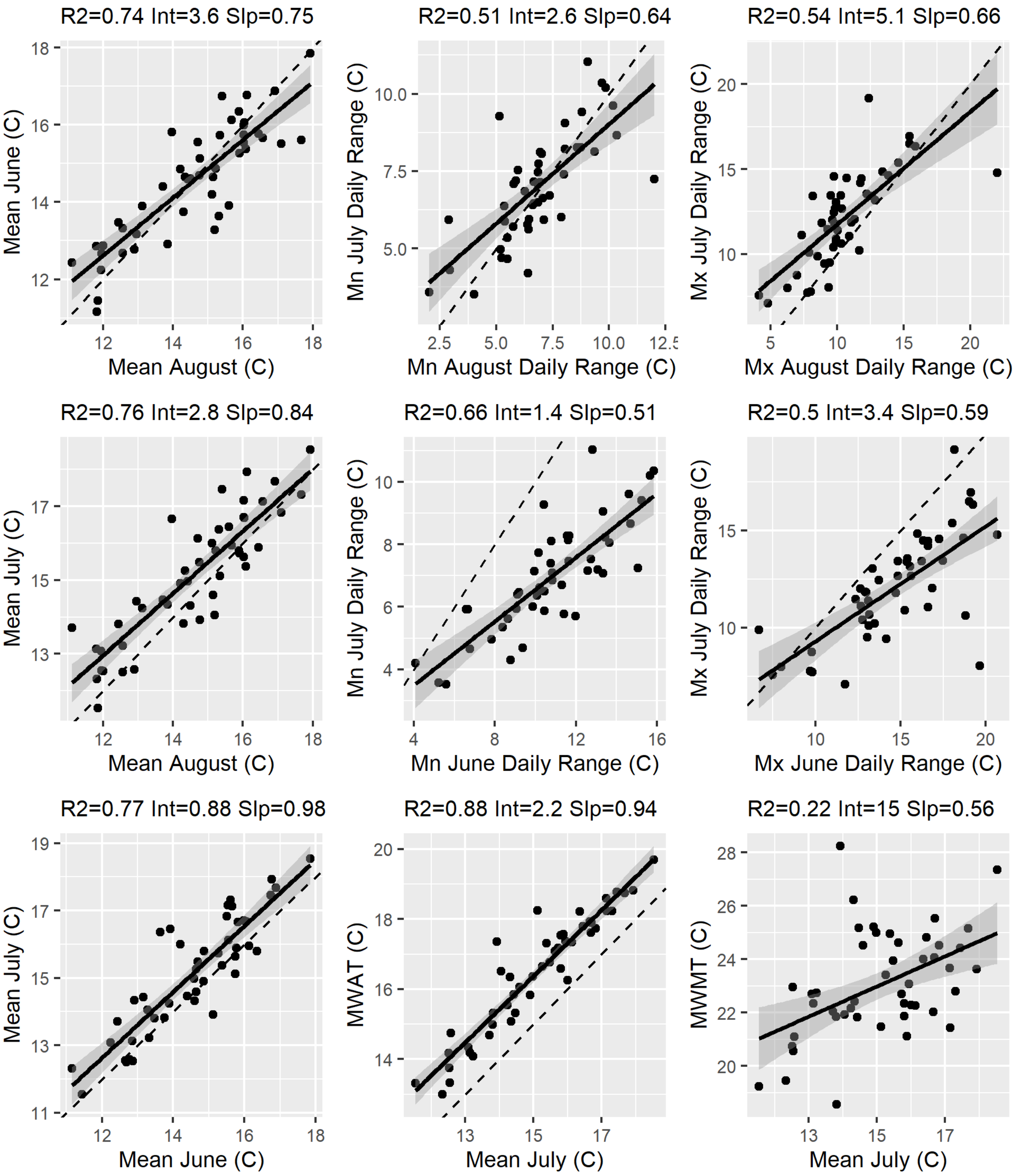

Figure 6. Relations between temperature metrics: mean monthly, mean daily ranges, maximum daily ranges, maximum average weekly average (MWAT), and maximum average weekly maximum (MWMT) for summer months (June, July, August) in Apache Trout streams in the ASNF (data from J. Ward, ASNF). N = 49 unique site-years; dashed line represents 1:1, solid black line is fitted linear regression line, and grey bands is 95% confidence interval. R2=R^2, Int=Intercept, and Slp=Slope coefficient from the linear regression.

Table 5. Mean and maximum July monthly temperatures by monitoring year; maximum, mean, and SD of daily temperature ranges (daily maximum-minimum) in July by year; number of days exceeding 23 and 26°C within the year; and maximum average weekly average (MWAT) and maximum average weekly maximum (MWMT) temperatures in July by year in Apache Trout streams in the ASNF (data from J. Ward, ASNF). N = 49 unique site-years. See Figure 5 for site locations.

Site name	Year	Mean July (°C)	Max July (°C)	Max July Range (°C)	Mean July Range (°C)	SD July Range (°C)	Days 23 °C+	Days 26 °C+	MWAT (°C)	MWMT (°C)
Boggy	2015	16.8	18.3	8	4.7	1.8	5	1	17.7	24.5
Centerfire	2015	17.3	18.5	10.6	5.9	2.2	13	0	18.2	22.8
Conklin	2014	17.9	19.4	9.5	6.8	1.7	18	0	18.8	23.6
Conklin	2015	15.9	18.5	10.4	6.5	2.1	7	0	17.4	23.1
Coyote1	2015	15	18.5	14.6	7.5	2.8	12	3	16.4	25
Coyote2	2015	15.7	19.1	13	6.4	2.6	9	1	17.2	22.7
DblCienega	2015	14.3	17.3	16.3	8.7	3.4	31	6	16.4	26.2
DblCienega	2018	16.4	18.5	19.2	11	4	24	2	17.8	24.8
EFLCR1	2013	15.5	17.7	13.5	7.5	2.7	14	2	16.8	23.9
EFLCR1	2014	15.3	17.5	11.1	7.1	2.3	17	0	16.7	23.4
EFLCR1	2015	14.6	17.5	13.4	5.8	2.9	12	0	16.1	24.5
EFLCR2	2014	16.4	19.7	13.2	8.3	2.6	12	2	18.2	24
EFLCR2	2015	15.4	19.4	14.5	6.7	3.2	12	4	17.3	25
EFLCR3	2014	16.1	18.7	7.1	4.3	1.4	1	0	17.3	22.3
EFLCR3	2015	15.1	19.3	7.6	3.6	1.6	1	0	18.3	21.5
EFLCR3	2016	16.7	18.5	8.8	5.9	1.9	0	0	17.9	22
Fish3	2015	13.9	17.6	14.8	7.2	3.2	49	21	17.4	28.2
Fish3	2018	17.5	19.4	11.9	8.1	2.2	30	0	18.8	24.4
HannaganUpper	2017	16	16.8	11.4	7.7	1.9	3	0	16.3	22.3
HannaganUpper	2018	15.8	17.1	11.1	6.4	2.2	1	0	16.6	22.4
Hayground	2015	15.6	18.8	13.5	7.4	2.7	20	3	17.1	24.6
HaygroundUpper1	2018	16.7	19.2	14.5	9.1	2.8	26	3	17.9	25.5
LeeValley1	2014	13.1	15.6	14.6	9.4	2.8	5	0	14.3	22.7
Mineral1	2018	17.1	19	10.7	7.1	2.2	23	0	18.6	23.7
SFLCR1	2014	17.2	18.9	7.7	5	1.5	0	0	18.2	21.4
SFLCR1	2015	15.9	19	7.8	4.7	1.6	0	0	17.6	21.1
SFLCR2	2014	13.8	16.2	12	8.1	2.3	1	0	15	21.9
SFLCR2	2015	14.1	16	10.2	6	2	4	0	16.5	21.9
Snake2	2015	15.8	17.8	9.9	4.2	1.8	1	0	17.5	21.9
Thompson2	2014	13.8	16.2	12	8.1	2.3	1	0	15	21.9
Thompson2	2015	12.5	15.8	12.7	6.5	2.7	0	0	14.2	20.7
WFBlack1	2013	14.4	16.9	11.8	7.1	2.5	4	0	15.8	21.8
WFBlack2	2017	17.7	19.7	13.4	8.3	2.9	46	3	18.7	25.2
WFBlack2	2018	18.5	20.7	15.4	9.6	2.7	78	22	19.7	27.4
WFBlack3	2017	16.7	18.7	12.4	6.6	2.7	12	0	17.6	24.1
WFBlack5	2015	13.8	17.4	8	3.5	1.7	0	0	15.3	18.6
WFBlack6	2017	14.3	16.1	14.8	8.1	3.2	2	0	15.1	22.4
WFBlack6	2018	14.9	16.6	16.5	10.2	2.7	28	0	15.8	25.2
WFBlack6A	2018	14.5	16.1	16.9	10.3	2.6	25	0	15.3	25.2

WFBlack7_2013	2014	13.1	15.6	10.9	7.2	2.3	1	0	14.2	22.3
WFBlack7_2013	2015	11.5	15.5	11.8	5.3	2.8	0	0	13.3	19.2
WFBlack7_2013	2016	13.7	15.3	13.4	9.3	3.2	0	0	14.7	22.1
WFBlack7_2013	2017	12.3	13.7	12	5.9	2.6	0	0	13	19.4
WFBlack7_2017	2018	13.2	14.8	12.7	7.2	2.3	3	0	14.1	22.7
WFBlack8	2018	12.5	13.9	10.1	5.9	2	0	0	13.3	20.6
WFLCR1	2013	14.4	16.9	11.8	7.1	2.5	4	0	15.8	21.8
WFLCR1	2014	14.2	16.4	9.4	5.7	2.1	0	0	15.5	22.2
WFLCR1	2015	12.6	16.7	11.5	5.6	2.6	1	0	14.7	21.1
WFLCR3	2018	12.5	14.2	14.2	8.2	2.5	6	0	13.8	23

Water quality

Apache Trout stream water quality is representative of small, high elevation headwater streams in the White Mountains of Arizona. These streams flow through geology that ranges from the glaciated valleys and felsic geology of Mount Baldy, Quaternary basalts and mafic rock surrounding Mount Baldy, and Tertiary sedimentary geologic formations to the east (Long et al. 2006). Water quality ranges from neutral to slightly acidic, with low alkalinity and conductivity. Dissolved oxygen ranges 4.9 to 15 ppm (Table 6).

Table 6. Water quality of Apache Trout streams in Arizona measured once per week during summer in 1989 (all streams) and 1990 (Sun and Firebox only).

Stream	Dissolve oxygen (ppm)	pH	Alkalinity ($CaCO_3$ mg/L)	Conductivity (mmhos/cm)	Reference
Firebox	4.9–7.0	7.1–7.8	13–73	30–42	Wada 1991
Sun	6.4–15.0	7.4–7.9	10–15	31–35	Wada 1991
Paradise	7.8–10.0	6.0–7.5	40–50	34–41	Wada 1991
Ord	8.1–9.0	6.4–7.0	40–40	34–35	Wada 1991
Big Bonito	8.1–11.0	5.9–7.0	40–40	32–32	Wada 1991

Physical habitat

In addition to temperature, numerous studies have documented elements of physical habitat needed by the Apache Trout to fulfill its life history requirements – reproduce, feed, seek cover, rest, and grow. These are summarized in Table 7.

Table 7. Habitat needs of Apache Trout by life stage by activity. Note: for eggs, emergence takes approximately 60 days, Fry's are <100 mm in total length, Juveniles are 100 to 130 mm in total length, and Adults are ≥130-mm in total length.

Stage: Activity	Resource Needs	References
Eggs	Gravels (8–32 mm); few fine sediments (<2 mm)	(Harper 1976; Rinne 2001)
Eggs	Water temperature: optimal <15°C; suitable <17°C	(Recsetar and Bonar 2013)
Eggs	Dissolved oxygen: 2–9 mg/L	(Rombough 1986; Ciuhandu et al. 2007)
Fry: Feed	Insects (terrestrial/aquatic)	(Harper 1976)
Fry: Rest/Grow	Water temperature: optimal: 10–21°C (Critical Thermal Max. 30°C)	(Lee and Rinne 1980; Recsetar et al. 2014)

Fry: Rest/Grow	Low velocity (Fry <25 mm TL: <5 cm/s; Larger Fry: <17 cm/s)	(Wada 1991; Cantrell et al. 2005)
Fry: Rest/Grow	Shallow water (10–20 cm); stream margins	(Kitcheyan 1999)
Juveniles: Feed	Insects (terrestrial/aquatic)	(Harper 1976)
Juveniles: Feed	Temperature: <20°C	(Alcorn 1976)
Juveniles: Rest/Grow	Water temperature: optimal: 10–23°C (Critical Thermal Max. 30°C)	(Lee and Rinne 1980; Recsetar et al. 2012; Recsetar et al. 2014; Petre and Bonar 2017)
Juveniles: Rest/Grow	Gravel or larger substrate	(Petre and Bonar 2017)
Juveniles: Rest/Grow	Larger streams with deep, narrow channels	(Cantrell et al. 2005)
Juveniles: Rest/Grow	Pools and eddys	(Wada 1991; Cantrell et al. 2005)
Juveniles: Rest/Grow	Optimal depth 15–32 cm (need >3cm)	(Petre and Bonar 2017)
Juveniles: Rest/Grow	Optimal velocity 0.00–0.12 m/s (suitable: <0.22 m/s)	(Petre and Bonar 2017)
Juveniles: Rest/Grow	Instream and overhead cover (overhanging vegetation, debris, boulders)	(Kitcheyan 1999; Cantrell et al. 2005; Petre and Bonar 2017)
Adults: Feed	Insects (terrestrial/aquatic)	(Harper 1976)
Adults: Feed	Temperature: <20°C	(Alcorn 1976)
Adults: Rest/Grow	Water temperature: optimal: 10–21°C (Critical Thermal Max. 30°C)	(Lee and Rinne 1980; Recsetar et al. 2012; Recsetar et al. 2014; Petre and Bonar 2017)
Adults: Rest/Grow	Gravel or larger substrate	(Petre and Bonar 2017)
Adults: Rest/Grow	Larger streams with deep, narrow channels	(Cantrell et al. 2005)
Adults: Rest/Grow	Pools and eddys	(Wada 1991; Cantrell et al. 2005)
Adults: Rest/Grow	Optimal depth 15–32 cm (need >3cm)	(Kitcheyan 1999; Petre and Bonar 2017)
Adults: Rest/Grow	Optimal velocity 0.00–0.12 m/s (suitable: <0.22 m/s)	(Petre and Bonar 2017)
Adults: Rest/Grow	Instream and overhead cover (overhanging vegetation, debris, boulders)	(Mesick 1988; Cantrell et al. 2005; Petre and Bonar 2017)
Adults: Spawn	Initiate at 8°C	(Harper 1976)
Adults: Spawn	Small to medium gravels (8–32 mm)	(Harper 1976)
Adults: Spawn	19–27 cm water depth	(Harper 1976)
Adults: Spawn	1.4–3.1 meters per second	(Harper 1976)

There have been several studies of habitat use and selection by Apache Trout. Fry have been described to use low velocity, shallow areas in miniature pools within runs or along pool margins in Sun and Firebox creeks (Wada 1991). Juvenile Apache Trout also use shallower and faster habitats than adults (Kitcheyan 1999; Cantrell et al. 2005). In Squaw and Flash creeks, mean (± SD) water depths used by juveniles was 16.1 ± 0.7 cm, whereas adults used 26.5 ± 2.1 cm. Mean velocities used by juveniles was 0.14 ± 0.14 m/s versus 0.09 ± 0.02 m/s for adults. In Firebox Creek, Apache Trout biomass was higher in deeper pools with more instream cover, and within pools Apache Trout used deeper areas than predicted based on availability (Wada et al. 1995). Apache Trout biomass was also higher in deeper pools in Paradise Creek, but not Ord, Sun, or Big Bonito creeks (Wada 1991).

Associations between Apache Trout and cover have been variable among studies. Juvenile Apache Trout in Squaw Creek, but not Flash Creek, showed an association with cover, whereas adult Apache Trout in Flash and Squaw creeks showed no close association with cover (Kitcheyan 1999). In Firebox Creek, Apache Trout biomass was higher in deeper pools with more instream cover (Wada 1991; Wada et al. 1995). Significant associations between biomass and cover were not observed in Sun Creek (Wada

1991). In Coyote, Mineral, WFBR-Thompson, Soldier, and Coleman creeks, Apache Trout >100-mm TL selected areas with more overhanging vegetation, wood, and boulders (Cantrell et al. 2005); juveniles <100-mm TL showed no association with cover. In a more recent study, Apache Trout in the WFBR, West Fork Little Colorado River, and East Fork Little Colorado River were also shown to select slow deep areas (pools) with instream (wood, undercut banks) and overhead cover (e.g., overhanging vegetation; Petre and Bonar 2017).

Associations and interactions with other species

Apache Trout are part of a native fish community that includes Specked Dace *Rhinichthys osculus*, Desert Sucker *Catostomus clarkii*, and Bluehead Sucker *C. discobolus* (Clarkson and Wilson 1995). Roundtail Chub *Gila robusta* have been observed to prey upon Apache Trout and other fishes and displace them to shallow areas of a stream when present (Cope and Yarrow 1875; as cited in Miller 1972).

Rainbow Trout *O. mykiss*, Cutthroat Trout *O. clarkii*, Brown Trout *Salmo trutta*, and Brook Trout *Salvelinus fontinalis* have all been stocked in east-central Arizona streams at least since the early 1900's (Rinne 1996). Cutthroat Trout were reported to be stocked by mule train as early as the late 1800s (USFWS 1983), and hatchery and management records show Cutthroat Trout to have been stocked since 1920 to 1942 (USFWS 2009). Rinne (1996) gives an overview of nonnative fish introductions into Arizona.

Nonnative trout have been shown to negatively impact Apache Trout. Other *Oncorhynchus* species are closely related to the Apache Trout and have been shown to hybridize with them, and several studies have evaluated the extent of their hybridization. Carmichael et al. (1993) found that only 11 of 31 populations within the historical range of Apache Trout lacked evidence of hybridization in 10 alleles. Cutthroat Trout alleles only were found in four populations, both Cutthroat Trout and Rainbow Trout alleles were found in two populations, and the remaining hybridized populations had Rainbow Trout alleles. Some researchers have suggested that hybridization with Rainbow Trout may be regulated by assortative mating and selective gene expression (Dowling and Childs 1992). Pure populations of Apache Trout are typically above 2,100-m elevation and often above natural barriers (waterfalls) that prohibit invasion of nonnative trout into those habitats, which, when coupled with closed access to fishing, have resulted in several relict populations of Apache Trout remaining free of hybridization. The 2009 Recovery Plan suggested that this may have prevented the species' extinction (USFWS 2009). In a genetic assessment of Gila Trout and Apache Trout, Wares et al. (2004) concluded that conservation efforts and recovery programs have been successful in maintaining the genetic integrity of both species.

Nonnative trout have also impacted Apache Trout through competition and predation (Rinne and Minckley 1985), as is common to trout native to the western United States (Dunham et al. 2002a; Hansen et al. 2019). As one example, Brown Trout are sympatric with Apache Trout in several streams and are a known factor threatening Apache Trout (Clarkson and Wilson 1995; USFWS 2009). The impact, in part, is due to behavior and habitat use. Apache Trout often use open water more so than Brown Trout (Wada 1991), possibly because Brown Trout can feed efficiently under low intensity light conditions (Robinson and Tash 1979). This may be why Apache Trout have been shown in experimental studies to abandon cover when food abundance is low (Mesick 1988). While this may limit the realized niche of Apache Trout adults, the impacts to Apache Trout populations are more likely to be realized at the juvenile life stage through predation.

SPECIES ECOLOGICAL NEEDS

The Apache Trout, like all species, is comprised of populations that are made up of individuals. Thus, it has needs at the scale of the species, populations, and individuals (Figure 7). For example, individuals need spawning habitat to reproduce successfully, and populations need a population growth rate (i.e., lambda) that is stable or increasing for long-term population viability; or, if population growth rate is negative it is only so for a short period of time (e.g., 1–2 years). Populations need high growth rate potential to be resilient (e.g., rebound) from high mortality events (e.g., drought years, wildfires, pathogens). And the viability of a species is dependent on having multiple resilient populations. Thus, there are needs at the individual, population, and species level, and these needs may be habitat-, demographic-, or resilience-based to ensure the species is viable. These needs, whether habitat-, demographic-, or resiliency-based could be at risk from various threat factors listed in the section "Risks Factors". The Risk Factors may be limiting factors themselves or they may interact with other factors to limit population growth rate or the carrying capacity of the habitat (Figure 8). Many needs of Apache Trout are common to all trout in the interior western U.S, although there are often subtle differences among species and subspecies (Behnke 2002). These needs are initially discussed in a synthesis of the broader western native trout scientific literature, but they are then discussed in the specific context of Apache Trout as a unique species and in relation to Apache Trout-specific science when it is available.

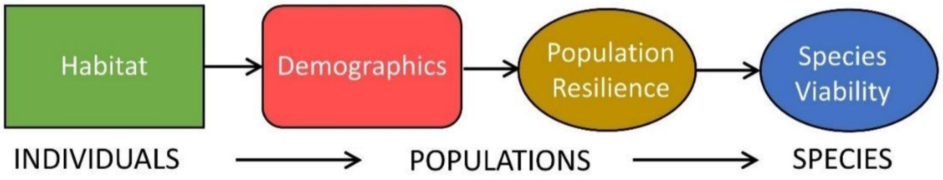

Figure 7. Simple conceptual framework of relationships between habitat, demographics, population resilience, and species viability and the level of biological organization to which they typically apply: individuals, populations, or species (USFWS 2016).

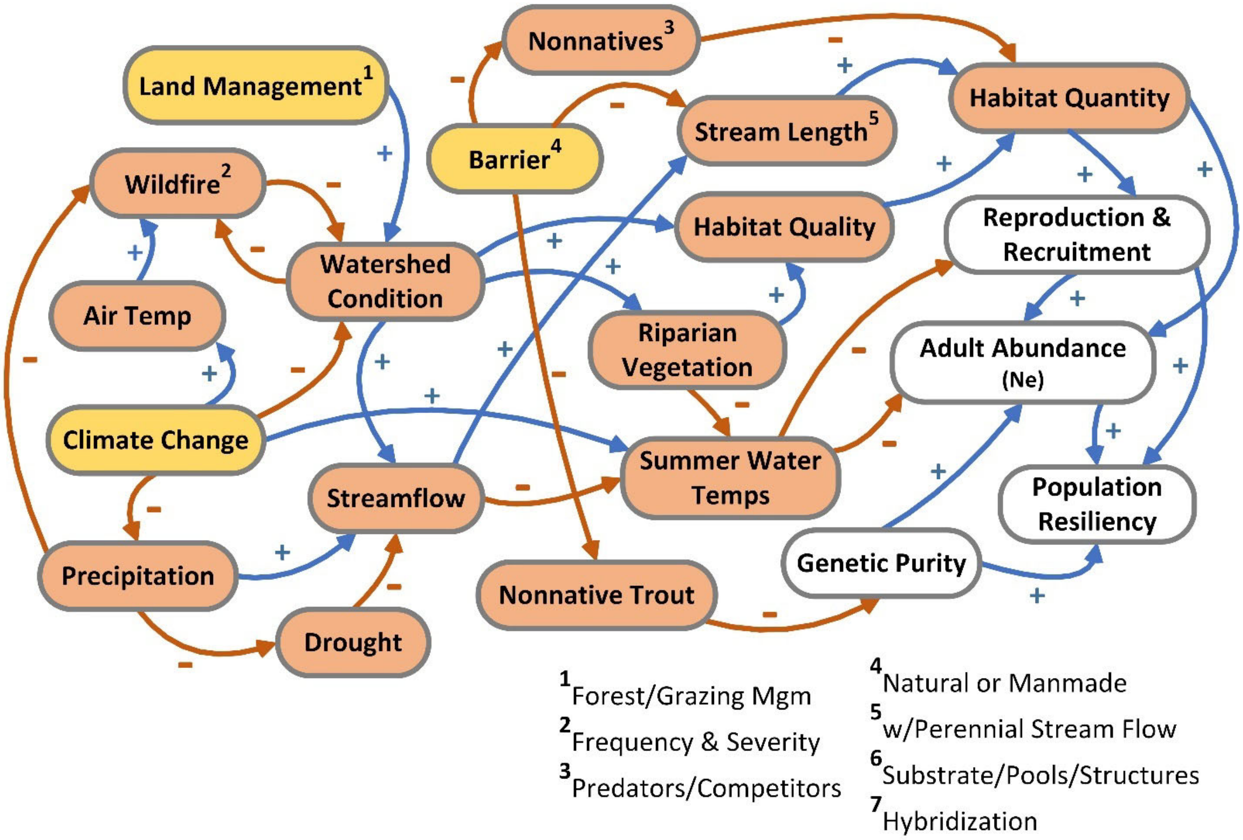

Figure 8. Core Conceptual Model describing the effects of key exogenous factors such as climate or resource management (yellow) on key habitat factors (brown), which in turn influences population demographics and resiliency (white). Blue arrows represent a positive effect (or association), and red arrows reflect a negative association.

Complex and Quality Habitat (Individual)

Complex habitat has many different definitions, but typically it is in reference to a diversity of instream cover types (e.g., boulders, wood, undercut banks) and stream channel morphology (e.g., well-developed riffle-pool sequences) when in the appropriate geomorphic setting along with other channel unit types (i.e., mesohabitat) such as eddy pools, runs, cascades, and more (Hawkins et al. 1993; Arend 1999). Complexity definitions are sometimes extended to include the presence of side channels and other geomorphic features in larger streams and rivers. These physical features are often dependent on intact riparian vegetation along stream margins, and a diversity of physical features often results in a diversity of microhabitats such as velocities and depths. A diversity of instream habitats can be used by diverse suites of species (Walrath et al. 2016) but also by different life stages of a single species such as trout that show shifts in habitat use as they grow (Horan et al. 2000). Cantrell et al. (2005) found that Apache Trout used areas of the WFBR that had more complex channel unit type (mesohabitat type) configurations that were difficult to distinguish as separate types (pools, runs, riffles, etc.) because of complex flow patterns and other features. Streams impacted from anthropogenic activities, such as improper livestock grazing, can often be incised with poor habitat complexity, and therefore poor suitability for diverse aquatic assemblages (Walrath et al. 2016). Despite this generalization, the degree of livestock impacts to Apache Trout streams has been debated because of the underlying influence of geology on stream sensitivity to disturbance (Clarkson and Wilson 1995; Long and Medina 2006).

Water Temperature and Quality (Individual)

Like other salmonids, the Apache Trout is a cold-water obligate, and laboratory studies have characterized the species' upper thermal tolerance. Early studies showed its thermal tolerance to be similar to other trout species native or introduced to the southwestern United States (Lee and Rinne 1980); however, much temperature-related research has been conducted in the last decade. The critical thermal maximum is <30°C for fry under the daily fluctuating temperatures that can be expected in stream systems in the White Mountains. Egg and larva survival decreases considerably at 18°C and warmer (Recsetar and Bonar 2013), and fry survival decreases considerably above 22°C (Recsetar 2011). More details on thermal tolerances, temperature needs, and temperature selection of Apache Trout are summarized in the section "Life History" above.

There is less information on the impacts of non-temperature related water quality on Apache Trout. Long et al. (2006) referenced some gray-literature water quality studies that showed higher nutrient enrichment, reflected by higher instream plant cover and potential productivity, in downstream reaches of White Mountain streams. Fine sediments can cause turbidity but can also embed spawning substrates and suffocate eggs in the gravel by limiting interstitial water movement and, thus, oxygen supply. Fine sediments have been shown to negatively impact egg and fry survival of Apache Trout (Rinne 2001). Other water quality constituents are not known to be limiting in Apache Trout streams.

Flow Regime (Individual)

Streamflows in the White Mountains reflect precipitation patterns, geology, and topography (Mock 1996; Long et al. 2006). Lithology (physical characteristics of rocks), along with precipitation, influences hydrologic regimes in the White Mountains through runoff and groundwater storage. This includes the timing and magnitude of peak flows that are important to spawning trout and low flows that can limit habitat volume during dry periods. Streams originating on Mount Baldy tend to have streamflows that peak later in spring due to snowmelt and maintain higher base flows than streams draining basaltic plateau areas (Long et al. 2006). Fractures and boundaries between volcanic flows can store and transport water through complex pathways. For example, springs can emerge at geologic boundaries, such as is observed on Soldier Creek, where a large source spring emerges at the transition between different mafic lava flows (Long et al. 2006). Glaciated valleys also act as groundwater reservoirs, can attenuate hydrographs, and result in higher baseflows with cooler temperatures during hotter summer months (e.g., Smith Creek).

The influence of hydrologic regimes on Apache Trout has not been widely studied. Harper (1978) found that Apache Trout spawning occurred on the descending limb of the hydrograph in the headwaters of Big Bonito Creek; spawning began at the end of May but primarily occurred during the first two weeks of June in 1975 when flows reached 100 cfs and temperatures were between 8 and 14°C. The broad nature of this pattern is unclear given that streamflow regimes are different among Apache Trout streams (Long et al. 2006). Low baseflows can influence the pool depth and volume that have been shown to be important to Apache Trout (Wada 1991; Wada et al. 1995), stream drying can cause direct mortality and render stream sections unsuitable (Wada 1991), and lower flows often correspond to higher temperatures that may be unsuitable (Recsetar et al. 2014; Petre and Bonar 2017).

Food Supply (Individual)

Apache Trout appear to have feeding habitats similar to those of other trout. Harper (1976) found that Apache Trout consumed a wide variety of aquatic insects, but they primarily consumed Tricoptera, Diptera, and terrestrial insects in Big Bonito Creek with small proportional differences between seasons and years. In laboratory experiments, Apache Trout 110-mm SL or smaller have been shown to emigrate from areas when starved for 10 d, and only after 41 to 73 d of starvation did larger Apache Trout 120 to 139-mm SL emigrate to other areas (Mesick 1988).

Patch Size (Population)

There have been many studies that suggest western native trout populations are more at risk of extirpation in small, isolated patches of stream habitat (versus larger, interconnected patches). For example, Peterson et al. (2014) found that Westslope Cutthroat Trout *O. c. lewisi* were more likely to persist in stream networks, often referred to as patches, isolated for up to 100 years (median 40 years) that had more stream length and higher habitat quality, but they were less likely to persist in higher elevation and higher gradient isolated networks. They found that when habitat was poor, 1.7 km of habitat was needed to achieve a long-term patch occupancy probability of 0.5, but that only 0.2 km of habitat was needed to achieve that same occupancy probability when habitat quality was high. Others have also found patch size, again defined as length of stream that is interconnected, to be a strong predictor of patch occupancy or persistence in Bull Trout *Salvelinus confluentus*, Lahontan Cutthroat Trout *O. c. henshawi*, and other trout species (Rieman and McIntyre 1995; Dunham and Rieman 1999; Hilderbrand and Kershner 2000; Dunham et al. 2002b; Harig and Fausch 2002).

Patch size is important because fish populations need access to different habitats to reproduce, feed and grow, and overwinter, and they need the ability to move between these habitats to remain viable (Fausch et al. 2002). These habitats used to meet life history requirements are sometimes located in the same habitat unit, such as a stream pool, and some species in some regions spend a majority of their lives in one pool (e.g., Brown Trout; Hoxmeier and Dieterman 2013). Other populations, such as some Bonneville Cutthroat Trout *O. c. utah* in the Bear River, make large migrations between tributary spawning areas and overwintering habitat in the Bear River mainstem to maximize growth and survival versus solely residing in small tributary streams year round (Carlson and Rahel 2010).

While the general scientific literature suggests that trout populations have a higher likelihood of persistence (viability) when they occupy larger habitat patches that does not mean that small populations occupying small habitat patches have never persisted over long time periods. In fact, some authors have questioned rules of thumb used to characterize trout population persistence because some small and isolated populations have persisted for 50–100 years whereas others have not, and this is likely due to the differing environments in which those populations live (less variable and fewer stochastic environments are more likely to have stable and persistent populations) and somewhat due to chance (Leasure et al. 2019). In modeling the viability of Lahontan Cutthroat Trout populations, small populations exhibited a wide range of 30-year extinction probabilities. This suggests that rules of thumb, while useful when better information or a mechanistic understanding are not available, should be used with caution (Figure 9; Neville et al. 2020).

Apache Trout historically occurred in tributaries of the Salt (White and Black rivers) and Little Colorado River basins (USFWS 2009), and although little is known about the species' historical fine-scale distribution and movement (including migration) patterns there was likely connectivity and exchange of individuals between some neighboring tributaries not isolated above natural barriers (e.g., waterfalls). Some tributaries, such as those flowing off the south flank of Mount Baldy, have historically and continue to harbor isolated Apache Trout populations (or sub-populations) upstream of natural waterfalls in small extents of stream habitat. These populations are a good example of small isolated and relict populations persisting over long time periods because they were located above natural waterfalls despite a high risk of extirpation due to isolation. In contrast, populations below the falls became extirpated due to nonnative trout invasions and subsequent hybridization, competition, and predation. The basaltic geologic formations on which the waterfalls occur are from the Quaternary period (~2.5 million years to present), but it is unclear how long the waterfalls have existed and whether it was after Apache Trout colonized habitat upstream of them. Some of those populations have since been extended downstream of those natural barriers to man-made barriers established to protect populations from nonnatives. Despite these examples, the influence of patch size on Apache Trout long-term population viability across the species' range has not been studied.

Population Size (N), Effective Population Size (N_e), and Genetic Diversity (Population – Resiliency)

Population Size (N)

Population size is related to habitat volume, and thus patch size (interconnected stream habitat length), and is a fundamental aspect of population resiliency and, thus, viability. Clearly a population is extirpated when there are zero individuals remaining, and large populations are less likely to reach zero near-term when confronted with demographic and environmental stochasticity. Small populations are also at risk to demographic stochasticity that may lead to a small population becoming smaller and smaller due to the randomness of births and deaths and sex ratios. Small populations also experience greater rates of genetic drift which may move them away from adaptively optimal characteristics. The risk of inbreeding depression (increased homozygosity across deleterious alleles), which can be more severe under stressful environmental conditions, is higher in small populations (Allendorf and Ryman 2002). Smallness can also lead to vortex effects where demographic and genetic stochasticity effects are exacerbated (Fagan and Holmes 2006) and stochastic events, such as stream drying, wildfire, or other disturbances, carry increased risks when they occur in small habitat extents occupied by few individuals. These reasons are why minimum viable population size is often equated to viability as a paradigm in conservation biology (Caughley 1994).

Many Apache Trout populations have small adult population sizes (<500 individuals); however, population extirpations have more often been due to stochastic events such as wildfire (and subsequent ash and debris flows) or functional extirpation due to introgression of nonnative alleles from hybridization (Table 9). Some small Apache Trout populations in streams with naturally low streamflows have become extirpated during droughts that reduced habitat capacity below viable levels. No evidence exists to directly link inherent inbreeding depression or demographic stochasticity to the extirpation of small Apache Trout populations, although it is difficult to attribute local extirpations to such mechanisms.

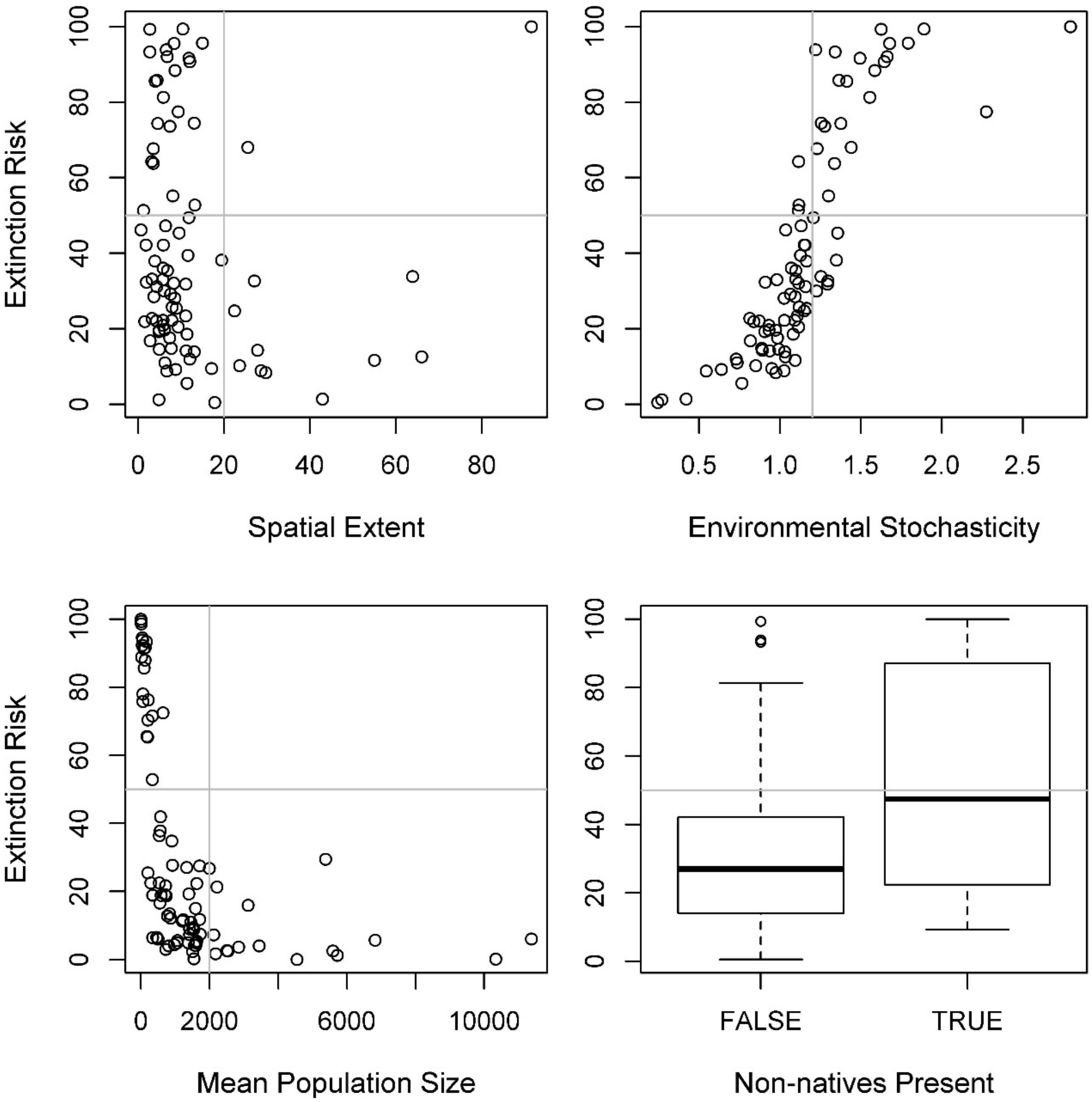

Figure 9. Lahontan Cutthroat Trout modeled extinction risks tended to be less than 50% in those populations with greater than 20 km of stream extent (top left), more than 2000 age-1 and older fish (bottom left), environmental stochasticity less than 1.2 (top right), or no nonnative trout (bottom right; from Neville et al. 2020).

Effective Population Size (N_e)

Effective population size (N_e) describes the size of an ideal population (random mating, equal sex ratio, discrete generations, and random variation in reproductive success) with the same rate of genetic exchange as the population under consideration (Waples 2002). The 50:500 rule has been widely used to inform conservation, including native trout conservation, and is based on the assertion that a N_e of 50 individuals is needed in a population to prevent inbreeding in the near term, and a N_e of 500 individuals is needed to maintain adaptive genetic variation over time. Some scientists have suggested that a 500:5,000 rule for minimum viable population size be used in place of the commonly used 50:500 rule although no single number or rule fits all species and populations (Traill et al. 2010; Brook et al. 2011). No studies have estimated N_e for Apache Trout or the ratio of N_e to adult population size, which would be needed to estimate the size of the breeding population from fish survey data.

Genetic Diversity

Genetic diversity is important because it increases the pool of alleles that may be valuable in resisting stressors (such as disease) while also providing flexibility to adapt to a changing environment. Carim et al. (2016) found that anthropogenically-isolated populations of Cutthroat Trout occupying <8 km of habitat had low genetic diversity compared to interconnected systems. However, even populations isolated due to natural geologic events (isolated at least tens of thousands of years ago) in up to 18 km of habitat had low genetic diversity that was likely driven by natural stochastic events (floods, drought, fire, debris and ice flows) within the isolated patch that resulted in genetic bottlenecks and genetic drift over longer time scales. Coastal Cutthroat Trout *O. c. clarkii* isolated above natural barriers for ~10,000 years showed reduced heterozygosity and allelic richness due to isolation, but loss was much higher (70 and 84%, respectively) in populations with small patch sizes (mean=1.3 km; Whiteley et al. 2010). Immigration, as discussed above, can increase genetic diversity as well, thus potentially improving demographic rates through a genetic rescue effect, as has been shown in some isolated eastern Brook Trout populations (Robinson et al. 2017). Other rules such as one-migrant-per-generation have been used as a rule of thumb to minimize loss of genetic diversity within populations and minimize divergence among subpopulations; however, some geneticists have recommended that a minimum of one and a maximum of 10 migrants per generation would be more appropriate (Mills and Allendorf 1996).

Apache Trout management has been successful in protecting relict populations from hybridization (see section "Genetic Factors (Population)"; Wares et al. 2004). However, genetic diversity within populations of the same lineages is low (Soldier [Apache 2] vs. Ord and EFWR [Apache 1] in Wares et al. 2004) despite being high among populations within lineages (12–56% of all genetic variation). The latter suggests some replicate populations were founded with only a few reproductively successful individuals, and that replicate populations should be founded or supplemented with more individuals to maintain 'cohesion' of lineages (Wares et al. 2004). Historically, population/lineage replications for Apache Trout typically have involved only a few hundred individuals at a time with no ongoing gene flow management after initial introduction and population establishment (in part for disease management purposes; see section "Species Current Condition").

Habitat Connectivity and Metapopulation Dynamics (Population – Resiliency)

Habitat Connectivity and Metapopulation Dynamics

Habitat connectivity is related to, and often defines, interconnected patch size but has the additional advantage of promoting metapopulation dynamics where populations interact through immigration and emigration processes. Small numbers of immigrants from nearby populations can have large benefits to the viability of trout populations (Hilderbrand 2003). In a study of Cutthroat Trout, Hilderbrand (2003) found that extinction risk of populations with 1,000 individuals decreased 3-fold and that extinction risk of populations with 500 individuals decreased 6-fold with immigration rates of 4 to 8 individuals per year; thus, small amounts of immigration can have large positive influences on population viability, illustrating the benefit of multiple, interacting populations on the landscape (e.g., metapopulations). Multiple populations aid viability at the species level because other populations can be used to rescue small populations or re-found them after individual populations are extirpated. This influence of immigration on population viability is built into metapopulation theory and is why some small populations can persist despite their smallness (Hanski 1999). Genetic considerations related to immigration are discussed below in the section "Genetic Factors (Population)."

Most Apache Trout streams have been intentionally isolated with fish barriers to protect populations from invading nonnatives downstream (Avenetti et al. 2006; Williams and Carter 2009). Thus, there is no connectivity among most populations, even within subbasins with shorter hydrologic distance between populations. However, there are some exceptions. For example, the upper WFBR is isolated above a protective barrier and contains multiple tributaries. Apache Trout occupy much of the interconnected habitat and are effectively managed as a metapopulation (Williams and Carter 2009). Other systems, such as lower Big Bonito Creek, is considered one Apache Trout population but may have small sub-populations occupying upstream portions of its three main tributaries: Big Bonito Creek, Hughey Creek, and Hurricane Creek. Likewise, Sun and Moon creeks are considered separate Apache Trout populations because their lower sections can become intermittent before they both flow into Christmas Tree Lake (a reservoir); Apache Trout in both streams occupy headwater reaches. In either case, the movement of Apache Trout between tributaries has not been studied, either through movement studies or genetic analysis, and it is unclear whether hydrologic connectivity results in population connectivity and facilitates metapopulation dynamics.

Recolonization After Disturbance

Connectivity also facilitates recolonization after stochastic disturbance events that can lead to extirpation of stream fish populations. Wildfires in the southwestern U.S. can cause direct fish mortality through superheating of water, although rare, and indirect mortality through low dissolved oxygen and other water quality problems stemming from ash flows. Wildfires can lead to flooding and channel-reorganizing debris flows after large rainfall events and cause indirect effects by altering resource availability and ecosystem characteristics (Gresswell 1999; Whitney et al. 2015). Trout populations, including Apache Trout, Gila Trout, and Rio Grande Cutthroat Trout *O. c. virginalis* in the southwestern U.S., have all experienced extirpations from wildfires (Brown et al. 2001; USFWS 2009; Propst 2020). In the upper Gila River, Whitney et al. (2016) found that availability of refugia from wildfire and debris flows varied among fish species (trout and non-trout species), and that re-colonization and recovery was dependent on stream networks being connected; they concluded that re-colonization and recovery of fish populations would be slow or non-existent in isolated streams or those fragmented by natural or man-made barriers. Rainbow Trout native to the Boise River basin (Idaho) showed that wildfires and channel-reorganizing debris flows can cause populations to exhibit different life-history characteristics, such as faster growth and earlier maturation from increases in stream temperatures, but do not pose as much of a long-term threat to genetic diversity as do barriers to dispersal and introductions of nonnative salmonids (Neville et al. 2009; Rosenberger et al. 2015). Human-assisted migration (not colonization outside of historical range), when done carefully, can replace or supplement immigration and recolonization processes (Hufbauer et al. 2015).

Williams and Carter (2009) noted that trout native to the southwestern U.S. are at increased risk because stochastic events (e.g., drought and wildfire) are becoming more frequent due to climate change. This risk is, in part, due to intentional isolation from nonnative species above protective barriers (Avenetti et al. 2006). Williams and Carter (2009) suggested that reconnecting or expanding habitat in isolated stream systems and facilitating metapopulation dynamics would improve population resiliency, but it is complicated due to the presence and threat of nonnative salmonids. Most Apache Trout populations are isolated above protective barriers in single-threaded stream systems. However, as mentioned above, there are some small interconnected systems occupied by Apache Trout populations. These populations should be more resilient because multiple tributaries increase the likelihood of refugia during stochastic disturbances, at least localized disturbances, and these refugia then facilitate recolonization to connected habitats without human assistance. Yet, the relatively small geographic range of the Apache Trout makes the species vulnerable to large catastrophic wildfires that are increasing in frequency in the Southwest (Figure 10, lower left panel). The 2011 Wallow Fire east of Mount Baldy burned 538,049 acres in Arizona and New Mexico (Figure 11, top panel). Today, 16 of 17 Apache Trout relict populations and 5 out of 8 genetically pure replicate populations occur within approximately 222,000 acres on the western side of Mount Baldy that is outside of the Wallow Fire perimeter and continues to have high risk of severe wildfire (Figure 11, top panel; Appendix B).

Ecological Diversity (Population)

Ecological diversity, which exists due to genetic diversity and environmental interactions, can increase a species' viability as it represents a phenotypic expression that may facilitate adaptation to novel or changing environments. For example, some native trout populations in the western U.S. have individuals that exhibit migratory tendencies and move within riverine environments (between headwaters and mainstems; termed *fluvial*) or between lakes and streams (to feed and grow versus spawn; termed *adfluvial*; Gresswell 2011). These movements to mainstem rivers and lakes are thought to provide growth advantages for individuals in the population (Hilderbrand and Kershner 2004). Higher growth rates and, thus, increased fecundity as a result of increased body size, leads to a higher population growth rate potential for migratory populations. Higher fecundity and reproductive potential allows them to take advantage of good environmental conditions or recover from stochastic events that cause population declines (i.e., increase resiliency to floods or fires; Hilderbrand and Kershner 2004). Other aspects of diversity, such as size or age at maturity, may also be considered as aspects of ecological diversity (Rosenberger et al. 2015).

Ecological diversity has not been well studied for Apache Trout, except for habitat use and selection. As highlighted above in section "Life History," habitat use and selection by Apache Trout has been studied across several stream systems albeit with different field sampling and analytical approaches. While habitat use, for example, has been shown to differ among Apache Trout populations, it is unclear whether these differences are due to ecological diversity or due to habitat availability and other features (e.g., streamflows) unique to each stream; habitat use and selection can be driven by habitat availability (Mysterud and Ims 1998). Little is known about age at maturity and movement from stream to stream (population to population) within connected drainage networks to understand how various aspects of ecological diversity relate to Apache Trout population and species viability.

3 Rs: Representation, Redundancy, and Resiliency (Species)

A species' biological condition can be evaluated in the context of representation, redundancy, and resiliency concepts from the conservation biology literature that apply at the population or species level – or sometimes both (USFWS 2016; Smith et al. 2018). Together they are often referred to as the 3 Rs, and when combined across all populations of a species they measure the viability of a species.

Representation

Representation is typically used in reference to how different and important aspects of the species are represented across the species as a whole or in a defined spatial unit (e.g., subbasin). Representation of important ecological elements of a species reflects a species' ability to adapt to changing environmental conditions over time as reflected in its breadth of genetic and ecological diversity. For example, a species might exhibit variation in age at maturity. Some populations may be early-maturing, and others may be late-maturing. One could presume that these two different life histories observed in different sets of populations adapted to their different local environments were both important to the viability of the species. It is therefore important to ensure that both life histories, early-maturing and late-maturing populations, are extant and represented across the species' range, or portions thereof (e.g., subbasin), because it allows the species the best chance to adapt to future, but unknown, environmental conditions. That is, it is best to save all the pieces to give a species the best chance of persisting into an uncertain future (USFWS 2016).

Redundancy

Redundancy refers to having more than one of each of the important representative elements of the species (USFWS 2016). Redundancy is important so that the species can withstand loss of a representative element with extirpation of a single population, such as during a catastrophic event (e.g., fire, drought), but that element is still represented in other populations because it is redundant across multiple populations. Going back to the previous example, multiple populations exhibiting early-maturing or late-maturing characteristics would indicate redundancy in the representation of the two variants of that important species trait. Multiple populations representing different genetic lineages could also be thought of in the context of redundancy whereby multiple neighboring populations are likely to have redundancy in the genetic representation of that species because neighboring populations within drainage basins typically have higher genetic similarity (Vrijenhoek et al. 1985).

Resiliency

Resiliency references the ability of a population to bounce back from disturbances or catastrophic events, and is often associated with population size, population growth rate, and habitat quantity (patch size) and quality (USFWS 2016).

Haak and Williams (2012) applied one version of the 3-R framework to different subspecies of Cutthroat Trout. They quantified the number of genetically pure populations, the presence of resident, fluvial, and adfluvial migratory life histories, the presence of populations occupying the periphery of the subspecies range (termed peripheral populations assumed to have distinct genetic characteristics from populations in more central, core habitats) as different representative elements of a subspecies. They used various combined measures of patch size and presence of migratory life histories to define population strongholds and metapopulations, which they then used to define population resiliency (defined by them as population persistence). Finally, they used the number of populations that met certain persistence, stronghold, or metapopulation criteria to quantify population redundancy by subbasin or a larger basin unit (e.g., geographic management unit). They suggested that the 3-R framework could inform a diverse management portfolio to help western native trout species and subspecies persist into an uncertain future (Haak and Williams 2012). The 3 Rs are applied to the Apache Trout in section “Species Current Condition”.

RISKS FACTORS AND CONSERVATION ACTIONS

Risk Factors

Various factors pose risks to Apache Trout viability at the population and species levels including climate change, nonnative species, genetics, and diseases.

Climate Change

The climate has changed when compared to historical records, and it is projected to continue to change due to increases in atmospheric carbon dioxide and other greenhouse gasses (USGCRP 2017). These climate changes have and will continue to impact aquatic ecosystems through increasing water temperatures, changing precipitation and streamflow regimes, and increasing the frequency and severity of wildfire. In the western U.S., snowpack has decreased, late-winter mean temperatures (January to March) have increased, and snowmelt run-off occurs earlier (Barnett et al. 2008); these are trends that are projected to continue into the future (Gonzales et al. 2018). Continuation of these changes is expected to influence the distribution and abundance of cold-water, stenothermic organisms such as salmonids (Kovach et al. 2016; Muhlfeld et al. 2019). For example, Wenger et al. (2011) used climate model projections to show that suitable habitat for Cutthroat Trout across the interior western U.S. will decrease by 50% by the 2080s due to increasing temperatures, changing flow regimes, and changing distribution of and interactions with nonnative species like Brook Trout.

The Southwest has the hottest and driest climate in the U.S. The U.S. Fourth National Climate Assessment suggests that warming temperatures will lead to decreasing snowpack, increasing frequency and severity of droughts, and increasing frequency and severity of wildfires, and these in turn will result in warmer water temperatures, reduced streamflows (especially baseflows), and increased risk of fire-related impacts to aquatic ecosystems (Gonzales et al. 2018; Overpeck and Bonar 2021). In fact, a recent study showed that the current drought is one of the worst in the last 1,200 years and it is exacerbated by climate warming. The study suggested climate warming will make droughts longer, more severe, and more widespread in the future (Williams et al. 2020). Another recent study showed an eight-fold increase in the amount of land burned at high severity during wildfires, including in the southwestern U.S., and suggested that warmer and drier fire seasons in the future will continue to contribute to high-severity wildfires where fuels remain abundant (Parks and Abatzoglou 2021). And larger, more frequent, and more severe wildfires accompanying a changing climate together may drive conversions in vegetation type from forest to shrub or grassland because of higher tree mortality, limited seed dispersal in larger burn patches, soil damage that reduces seedling establishment, and a changing climate that reduces seedling survival – all of which combine to inhibit forest regeneration (Keeley et al. 2019; Coop et al. 2020). No studies published in the scientific literature have specifically evaluated climate change impacts on Apache Trout distribution and abundance beyond lab studies of thermal tolerance, field studies of habitat selection of current temperatures, and how changes in riparian vegetation could influence stream temperatures (Recsetar 2011; Recsetar and Bonar 2013; Recsetar et al. 2014; Petre and Bonar 2017; Baker and Bonar 2019). Others have documented an increase in stream drying and intermittency with the loss of some populations but not in the context of future climates (Robinson et al. 2004).

Temperature

Air temperatures are projected to increase by 8.6°F (4.8°C; RCP8.5 model) in the Southwest, where some areas could see an increase of up to 45 more days of 90°F+ temperatures annually (Gonzales et al. 2018). Stream temperature models developed for Arizona suggest that streams will warm by 0.6°C for every 1.0°C increase in August air temperature (Isaak et al. 2017a). Climate studies for the Gila Trout suggest that thermally suitable habitat during the warm-season will decrease by 70% in the next 40-90 years when assessed using a climate-envelope approach (Kennedy et al. 2009), and some streams will no longer be suitable at all based on 1-km resolution stream temperature models (Dauwalter et al. 2017b).

Streamflows

Changes in climate have already altered precipitation patterns and reduced streamflows in the western U.S., and projections suggest these alterations will continue into the future (Barnett et al. 2008). Precipitation in the White Mountains primarily occurs as snow during winter and rain during summer monsoons (Mock 1996), and climate warming is expected to decrease winter and spring (snow) with a shift from snow to rain in cold seasons (Easterling et al. 2017). The total summer monsoon precipitation total is not expected to change in future climates, but the monsoon will begin later in the summer and extend later into the fall (Cook and Seager 2013). This will extend and exacerbate the low flow warm period in streams prior to the summer monsoon rains (Overpeck and Bonar 2021). And broad scale patterns of drought have already been documented, along with increased stream drying over the last decade (Robinson et al. 2004; Williams et al. 2020).

The flow regime is important to Apache Trout because the spring peak in snowmelt runoff serves as a cue to initiate spawning, and baseflows determine habitat volume and whether habitat decreases due to desiccation. Changes to climate pose a threat to flow regimes and are likely to result in increased stream drying, which has already been observed to extirpate some Apache Trout populations (Robinson et al. 2004; Williams and Carter 2009). Decreased precipitation in future climates, mostly as reduced snowpack, is expected to influence hydrology of Southwest streams, and the ecosystem effects of reduced snowpack are likely to be exacerbated by later monsoon seasons, which will lengthen the low flow hot period prior to the initiation of summer monsoons (Overpeck and Bonar 2021). Water withdrawals have not historically been a large threat to Apache Trout populations but may threaten flows in some situations as precipitation and drought patterns change and water demand increases.

Wildfire and Changing Forest Ecosystems

Wildfires have increased in frequency and severity in Arizona and New Mexico primarily due to changes in climate but also because of increased fuel loads (Mueller et al. 2020; Parks and Abatzoglou 2021), including within the historical ranges of Apache Trout and Gila Trout (Figure 10; Dauwalter et al. 2017b). Wildfires can result in ash flows that create unsuitable water quality conditions for salmonids, and high intensity fires in steep watersheds are likely to result in channel re-organizing debris flows (Gresswell 1999; Cannon et al. 2010). Parks et al. (2019) also projected that 30% of forests in the Southwest have an elevated risk conversion to shrubland and grassland because of increased fire severity due to climate change. Conifer reduction in the White Mountains could reduce stream shading that is important to keeping stream temperatures suitable for Apache Trout (Baker and Bonar 2019).

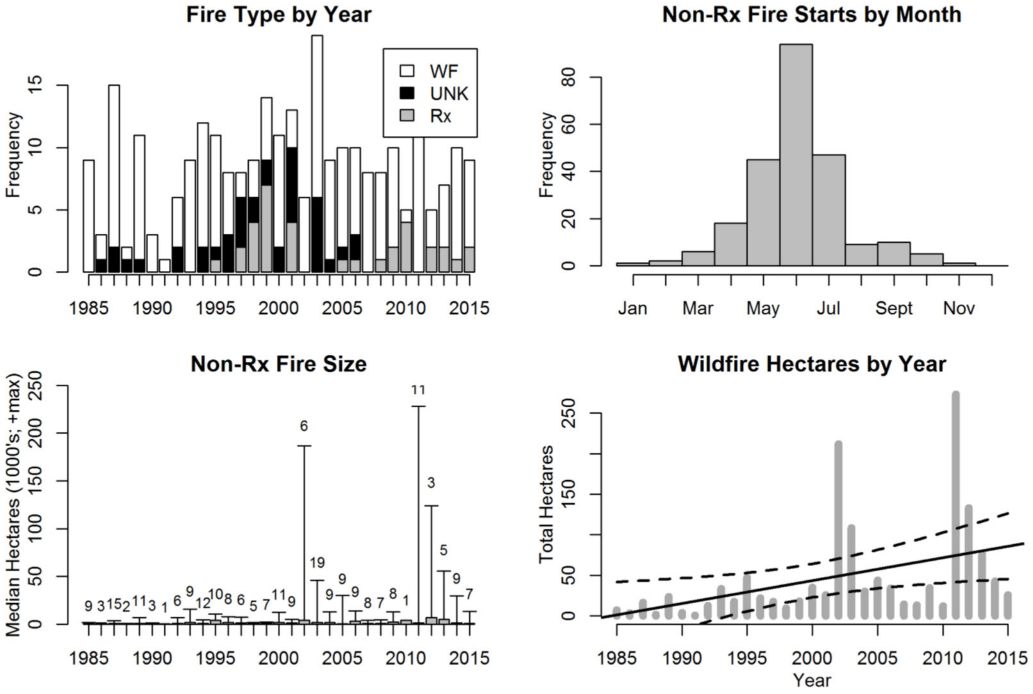

Figure 10. Frequency of wildfire (WF), prescription (Rx), and unknown (UNK) fire types by year (top left panel), frequency of wild- and unknown-fire starts by month (top right panel), median fire size (error bars = maximum; number of fires above bar) by year (bottom left), and total hectares burned by wildfire by year with trend line and 95% confidence intervals ($b_{Year} = 2.82$; $df = 29$; $P = 0.019$) in eastern Arizona and western New Mexico (core of Apache Trout and Gila Trout ranges). From Dauwalter et al. (2017b).

Climate Change Impacts on Apache Trout

In the absence of existing peer-reviewed science, the impact of climate change on Apache Trout was evaluated herein. Appendix B presents a coupled wildfire and temperature warming vulnerability analysis for Apache Trout populations using the vulnerability assessment approach applied to Gila Trout streams (Dauwalter et al. 2017b). The analysis suggests that streams like West Fork Little Colorado River have a high risk to crown fire and subsequent debris flows, whereas other streams in the 2011 Wallow Fire perimeter have a lower risk of future wildfires due to reduced fuel loads due to the Wallow Fire (Figure

11; Appendix B). All streams had a cold patch ≤16.5°C (mean July temperatures) in the 2080s (A1B emissions scenario), a conservative temperature threshold, and Big Bonito Creek, Fish Creek, and Boggy/Lofer creeks contained the largest amount of habitat with mean July temperatures below 16.5°C in the 2080s. The East Fork Little Colorado River, Snake Creek, Rock Creek, Rudd Creek, and South Fork Little Colorado River had the lowest percent of habitat with mean July temperatures ≤16.5°C in the 2080s, highlighting their vulnerability to future climates.

Appendix C presents our model on effects of climate change on Apache trout habitat availability and species distribution. This model suggests that most streams currently occupied by Apache Trout, or unoccupied but designated as recovery streams, are not temperature limited, and that suitability only improves when 2080s projections of temperature alone are considered, because some headwater reaches appear to be too cold, currently, for occupancy. That is, cold temperatures can be limiting Apache Trout populations in some streams, and any warming may benefit them in headwater reaches – at least up until the 2080s. It is only when future changes in precipitation are considered, as well, that habitat suitability decreases into the 2080s. Many habitat patches that are currently occupied by the species are projected to remain suitable into the 2080s, which suggests their resiliency is only limited by the size of the patch they currently occupy (Peterson et al. 2014; Isaak et al. 2015).

Nonnative Species

Nonnative species, especially nonnative salmonids, remain one of the largest threats to the Apache Trout (Rinne 1996). Over 61 million nonnative sport fishes have been stocked into lakes in the Little Colorado and Black river drainages since the 1930s (Rinne and Janisch 1995). Over 8 million nonnative sportfishes were introduced directly into the Little Colorado and Black rivers and their tributaries since the 1930s, and many of these were nonnative salmonids (Rinne and Janisch 1995). Recent stocking practices have been altered to reduce interactions with, and risks, to native species, such as using triploid (sterile) Rainbow Trout for stocking into open water systems (EcoPlan Associates 2011). But threats still remain due to naturalized populations from historical stockings.

As discussed below, hybridization with Rainbow Trout and Cutthroat Trout can lead to functional extirpation of populations. Competition and predation with Brown Trout and Brook Trout are also of high concern. While no published studies have documented competition and predation impacts on Apache Trout by nonnative salmonids such as Brown Trout and Brook Trout, it is generally believed that the negative interaction has led to reduction or extirpation of some populations (Mesick 1988; Rinne 1996). Appendix C shows the negative effect of nonnative trout presence on occupancy of juvenile (<125-mm TL) Apache Trout at the site scale (~100-m) in fish surveys.

Genetic Factors (Population)

There are three genetic factors that pose a risk to the viability of populations: hybridization, inbreeding, and low genetic variability. It is important to consider how each might affect Apache Trout. Inbreeding and low genetic variation were discussed above in the context of small population size and are only briefly mentioned here.

Hybridization

Hybridization can introduce traits that are maladaptive, disrupt adaptive gene complexes, or result in outbreeding depression (Hedrick 2000). Hybridization can also lead to the loss of species-specific alleles, and hybridization between Pacific trout species has long been recognized as a threat to native trout species (or subspecies) viability (Behnke 1992). This has resulted in arguments that only genetically pure populations should be considered a part of the species or subspecies (Allendorf et al. 2004).

A long history of nonnative trout stocking in Arizona has led to hybridization between Apache Trout and Rainbow Trout, even to the extent of genetic extirpation, and it is a main reason for the decline of Apache Trout (Rinne and Minckley 1985; Carmichael et al. 1993; Rinne 1996). The major threat of hybridization is why the 2009 Revised Recovery Plan lists as an objective: "Establish and/or maintain 30 self-sustaining, discrete populations of [genetically] pure Apache Trout within its historical range" (USFWS 2009), and largely the same objective has been in place since the first recovery plan was developed for the species (USFWS 1979). A comprehensive assessment of the genetic purity of naturally-reproducing Apache Trout populations showed only 11 of 31 streams lacked evidence of hybridization (Carmichael et al. 1993). At the time the 2009 Revised Recovery Plan was signed and published, 28 populations of genetically-pure Apache Trout were extant (USFWS 2009). However other populations have since been lost to wildfires, drought, or hybridization with Rainbow Trout (see "Species Current Condition" section).

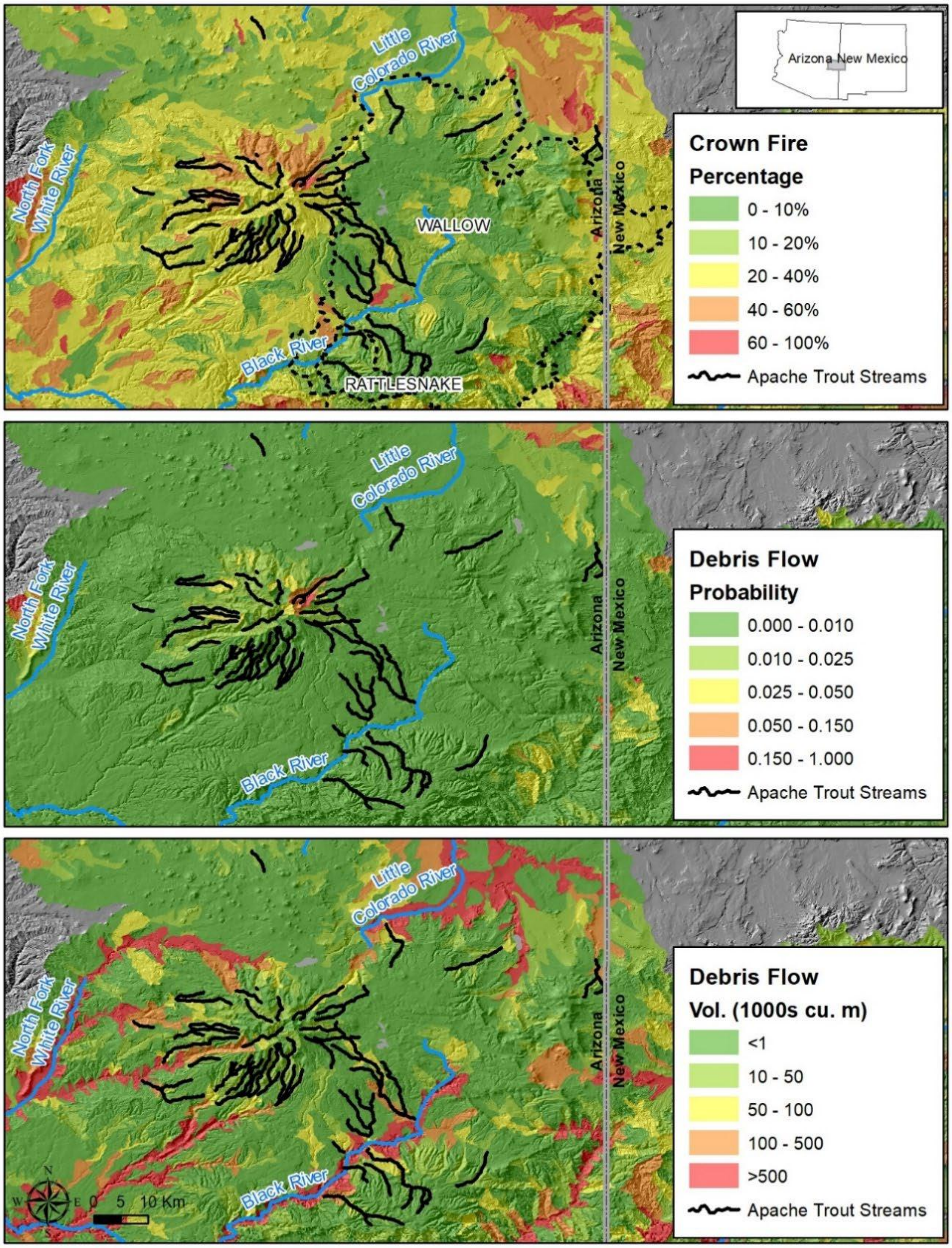

Figure 11. Percent watershed with high wildfire risk (active or passive crown fire) from FlamMap model (top panel), predicted debris flow probability given wildfire risk in watershed (middle panel), and predicted debris flow volume (bottom panel) for Apache Trout streams in Arizona. Wallow and Rattlesnake fire perimeters shown in top panel (black dashed line).

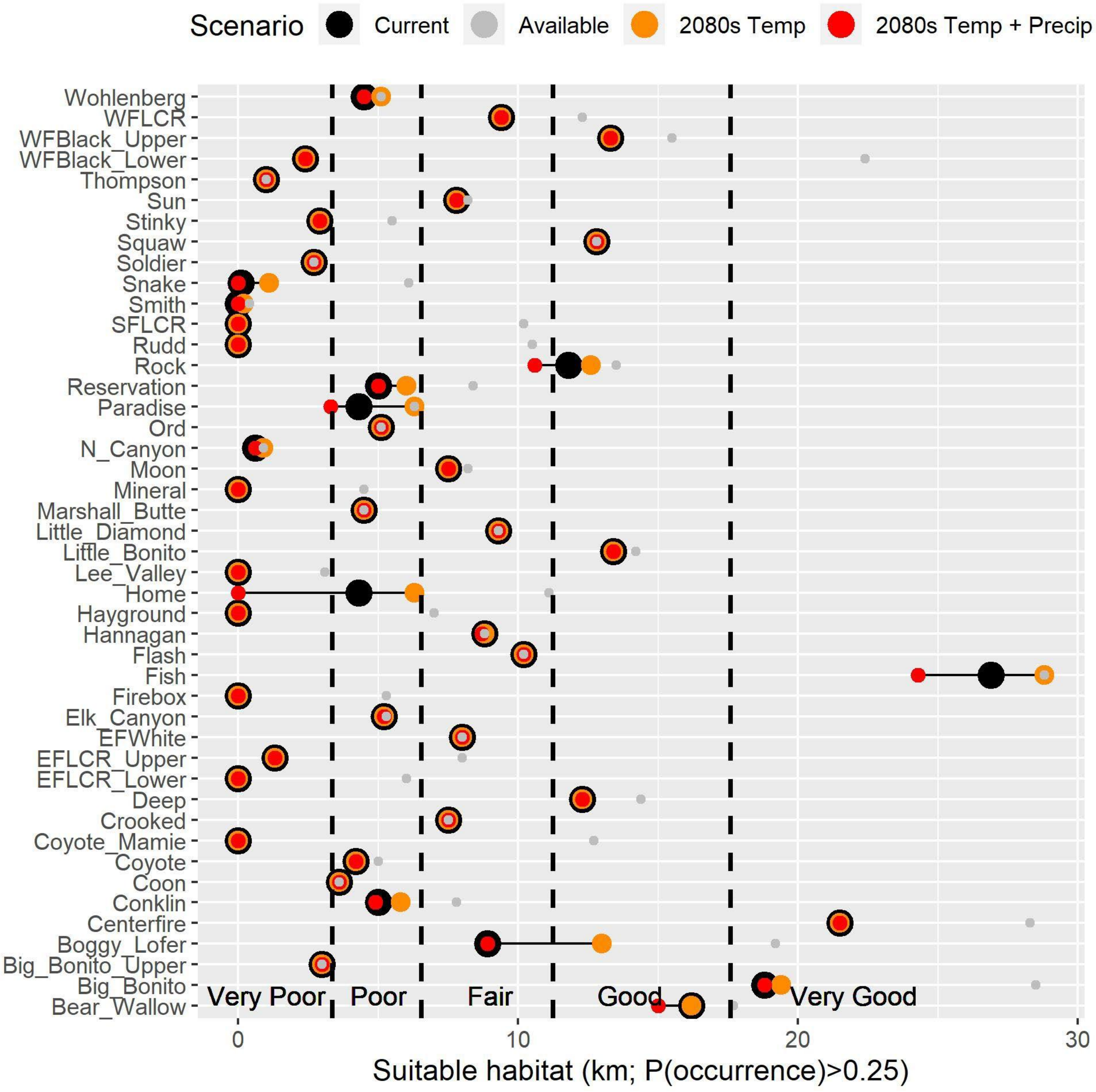

Figure 12. Kilometers in suitable habitat under current (present-day) conditions and in the 2080s with projected changes in July stream temperatures only and changes in temperature and precipitation. Suitable habitat was defined as juvenile Apache Trout (<125 mm TL) occurrence probability ≥0.25.

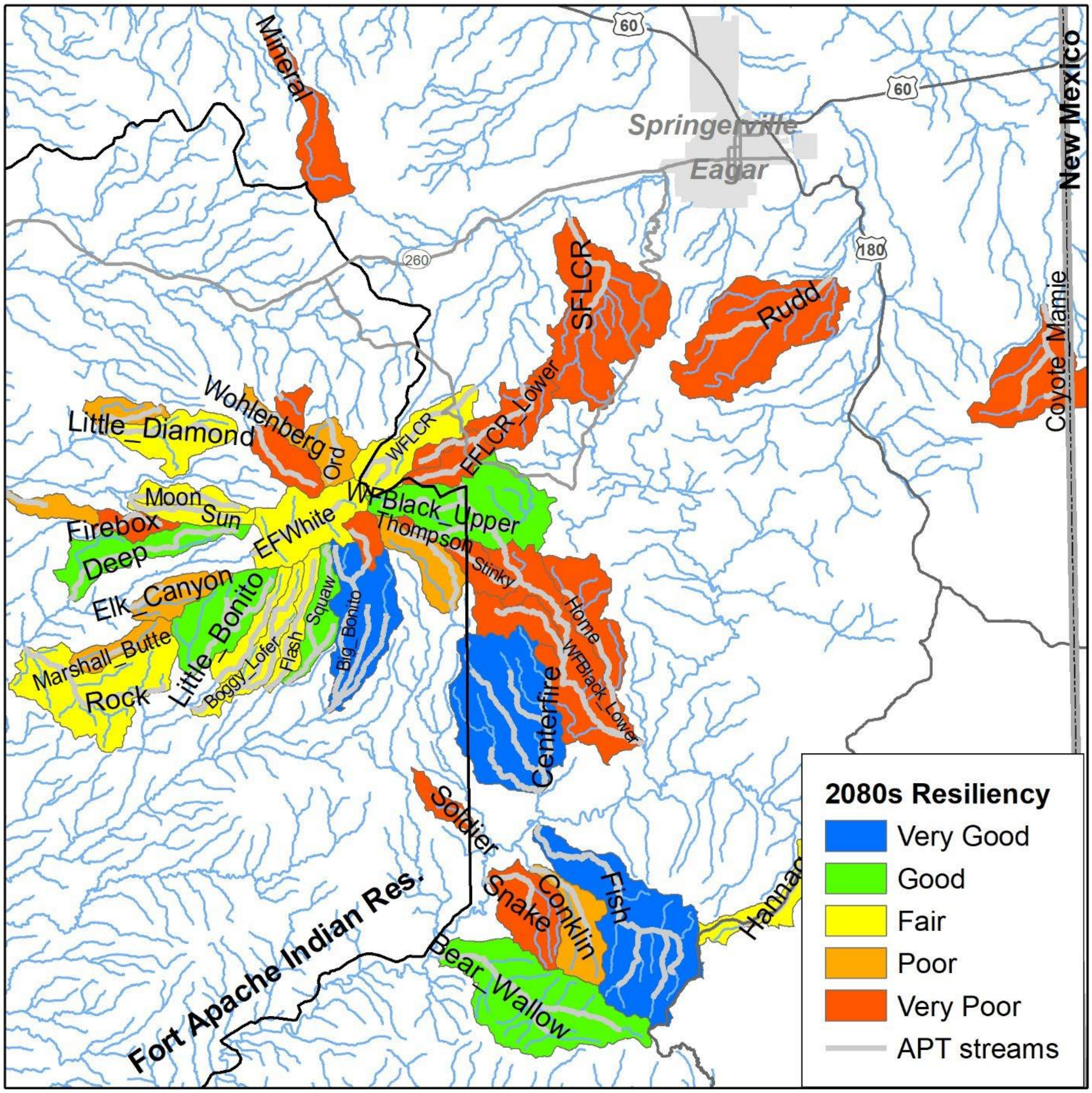

Figure 13. Resiliency of extant Apache Trout populations and unoccupied recovery streams to projected climate change in the 2080s based on amount of suitable habitat available as predicted from a species distribution model.

Some older studies have detected selection against hybridization in Apache Trout using older genetic techniques. In a morphometric study, Rinne and Minckley (1985) found that Apache Trout phenotypic characteristics predominated despite some evidence of past hybridization with Rainbow Trout. In a broad study, Carmichael et al. (1993) found only 11 of 31 populations to be genetically pure Apache Trout; only 5 of 19 hybridized populations had predominately pure Apache Trout whereas the remaining 14 hybridized populations were dominated by hybrid individuals and were considered hybrid swarms. In some hybrid swarms, the directionality of backcrosses to Apache Trout substantially outnumbered backcrosses to Rainbow Trout. Although Carmichael et al. (1993) suggested the lack of Rainbow Trout backcrosses was likely due to stocking practices leading to less successful Rainbow Trout reproduction, they also suggested that Rainbow Trout backcrosses may be much less viable. Rinne et al. (1985) also found reproductive incompatibility between Apache Trout (females) and Rainbow Trout (males) where fertilized eggs had low survival to fingerling stage in two trials (2 of 300 fertilized eggs, and five [three deformed] of 200 eggs survived), which suggested reproductive incompatibility; however, Behnke (1992) suggested the results of this study may be atypical and that a sterility barrier did not exist between the two species.

Inbreeding and Low Genetic Diversity

As discussed earlier, small populations are more likely to exhibit inbreeding and low genetic diversity. Inbreeding often results in inbreeding depression and expression of recessive and deleterious alleles (Wang et al. 2002). Cutthroat Trout are an example of inland trout in North America where inbreeding has been documented for some small, isolated populations (Metcalf et al. 2008; Carim et al. 2016). Low genetic diversity limits the ability of populations to adapt to changing and novel environments (Allendorf and Ryman 2002).

The only study of genetic diversity in Apache Trout showed strong distinction among three genetic lineages (Soldier, Ord, and East Fork White River lineages) represented by the nine populations studied, but genetic diversity was low within populations (Wares et al. 2004). Low genetic diversity within populations suggests that they were founded with a small number individuals. Replicate populations of Apache Trout have often been established with only a few hundred individuals, most likely with an unknown subset successfully reproducing. No studies have evaluated inbreeding in Apache Trout populations nor how genetic management (e.g., genetic rescue) may benefit Apache Trout populations but is a need given the small size of extant populations (Wang et al. 2002; Whiteley et al. 2015; Robinson et al. 2017).

Overutilization

Overharvest was not the main reason why Apache Trout were listed as Endangered in 1969, but it certainly contributed to the decline of some populations before AZGFD began regulating harvest around 1929 (USFWS 1983). Overutilization was also not considered to be a substantial threat at the time the species was downlisted to threatened in 1975 (USFWS 1975). Many recovery streams are closed to fishing, and other streams and lakes are managed for recreational fishing to alleviate fishing pressure on populations used for conservation or recovery of the species. Collection of Apache Trout for scientific and educational purposes is also currently regulated through permitting processes (USFWS 2009).

Parasites and Disease

Parasites and disease do not currently present a substantial threat to Apache Trout. In a study of Apache Trout parasites, 39 Apache Trout were collected from the East Fork White River, Big Bonito Creek, and Paradise Creek (129 to 276-mm TL). The trematode *Crepidostomum farionis* was recovered from intestines from 31 of 39 Apache Trout (mean 28.2 worms per fish), and it can cause intestinal inflammation in its hosts; the parasitic nematode *Metabronema salvelini* occurred in 31 of 39 fish at a mean of 3.81 worms per fish. These parasite loads were considered typical for small trout (Mpoame and Rinne 1984).

Whirling disease, an infection caused by the protozoan *Myxobolous cerebralis* that leads to head and spine deformities, has negatively impacted native trout populations in the western U.S (MacConnell and Vincent 2002). The whirling disease risk to Apache Trout was determined by its susceptibility to *M. cerebralis* infection in laboratory trials at doses of 25 to 2,000 triactinomyxons (TAMs) per fish at 66 to 201 days post hatch. Seventy-four percent of Apache Trout died by the end of the 90 d study period, and infection rates suggested that Apache Trout (as well as Gila Trout) are highly susceptible to *M. cerebralis* in laboratory trials (Thompson et al. 2010). Despite high susceptibility, there are no whirling-disease positive waters in close proximity to Apache Trout populations, and current management poses little risk. Therefore, the risk of whirling disease to Apache Trout is considered low, but introduction of *M.*

cerebralis into Apache Trout habitats would increase the risk to populations substantially. Despite minimal threat, disease monitoring is conducted when Apache Trout are moved among streams or into a hatchery.

Pollutants

Apache Trout streams are generally considered to not be impaired by water quality, and many of them are classified as Unique Waters by the State of Arizona. The Unique Water designation indicates that a surface water is an outstanding resource water due to exceptional ecological or recreational significance based on geology, flora, fauna, water quality, aesthetic values, or wilderness characteristics, or that threatened or endangered species are associated with the surface water, and existing water quality is essential to the maintenance and propagation of the species (USFWS 2009).

Conservation Actions

Several conservation actions are routinely undertaken to protect, restore, and re-establish Apache Trout populations across the species' historical range and in some cases outside of the historical range.

Barrier Management

Fish passage barriers have long been used as a conservation tool to protect Apache Trout populations from invading nonnative fishes that occur and are naturalized from historical stocking practices (Robinson et al. 2004; Avenetti et al. 2006). In fact, natural barriers (waterfalls) are what protected most relict populations before extensive recovery actions were initiated (USFWS 1979; USFWS 2009). Other physical barriers that are impassable to nonnative salmonids are constructed from various materials (gabion baskets, concrete, etc.) to create a physical barrier between Apache Trout populations upstream and nonnative fishes, typically salmonids, downstream (Table 9). Barrier locations are often chosen based on construction site suitability and access for materials while maintaining enough habitat upstream to maximize long-term persistence of the Apache Trout population (sensu Fausch et al. 2009). Avenetti et al. (2006) conducted a short-term evaluation of effectiveness of barriers protecting Apache Trout populations and found that only 1 of 1,436 salmonids marked downstream were collected upstream of the evaluated barriers over a three-year period. Despite short-term effectiveness, they suggested that long-term evaluation was needed. Maintenance on barriers is commonly conducted by managers when effectiveness is questionable due to physical integrity, flow patterns, when channel migration compromises structural integrity, or other reasons (Table 9). In addition, barrier design has sometimes been inadequate. Avenetti et al. (2006) observed large trout jumping step pools associated with a 1-m barrier on Fish Creek during high flows, suggesting passage was likely at high flows and that the design was inadequate. Recent barrier assessment included an engineer review and design modification suggestions that have informed barrier modification and maintenance, and recent barriers have been designed to withstand higher flows (AZGFD and USFWS 2015).

Nonnative Trout Removal

Removal of nonnative salmonids often occurs after barriers are constructed and before Apache Trout are reintroduced, or removals are done when barriers are ineffective and nonnative salmonids invade upstream into an extant Apache Trout population. Removal is commonly done using piscicides or electrofishing. A few studies have documented the high effectiveness of piscicides on removing nonnative trout from Apache Trout streams, including their effects on the invertebrate community, although more than one treatment may be required to remove all nonnative salmonids (Minckley and Mihalick 1981; Rinne et al. 1981; Kitcheyan 1999). These studies were based on Antimycin-A and not rotenone that is more commonly used today. Electrofishing is also used to remove nonnatives (often referred to as mechanical removal) where piscicides have not been approved for use, or where populations of Apache Trout are sympatric with nonnative trout and it is not desirable to eliminate Apache Trout simultaneously with nonnative trout. For example, from 2013 to 2021 electrofishing was used to remove over 20,000 Brook Trout and 2,500 Brown Trout from eight Apache Trout streams, with eradication suspected in some streams that will be confirmed with future electrofishing or environmental DNA (eDNA) surveys. Piscicides are typically more effective at ensuring all fish are removed, which is important because nonnative populations can become reestablished if only a few individuals survive (Thompson and Rahel 1996; Finlayson et al. 2005; Meyer et al. 2006); electrofishing removal is most effective in small stream systems with simple habitat (Meyer et al. 2006). Environmental DNA can be used to help locate remaining nonnative fish and target electrofishing or secondary applications of piscicides (Carim et al. 2020).

Reintroduction

Apache Trout are typically reintroduced after the habitat is protected by a barrier and nonnative salmonids have been removed. As outlined in the section "Species Current Condition", Apache Trout populations are usually established using fish from another population. The donor stream is selected, in part, based on the number of fish in that population so that removing them does not jeopardize donor population viability (Porath et al. 2010), but it is also based on interest in replicating relict populations to enhance redundancy of those lineages. Historically, 100–200 fish have been used to establish a population, but there is evidence that this low number of founding individuals has resulted in the low genetic diversity observed in some populations (Wares et al. 2004). See section "Species Current Condition" below.

Habitat Management and Restoration

Past habitat surveys and anecdotal observations have identified stream segments in poor condition and in need of protection and restoration (Carmichael et al. 1995; Robinson et al. 2004). The habitat of Apache Trout is managed, and land use impacts on them are reduced, through environmental review of proposed projects. For example, the ASNF Land Management Plan incorporates desired conditions for aquatic habitats to contribute to the recovery of federally listed species and provide self-sustaining populations of native species (ASNF 2015). The White Mountain Apache Tribe also has land management plans that help protect Apache Trout populations. Alteration of logging practices, road closure and removal, and ungulate exclusion through fencing or retiring allotments, have all been used to manage Apache Trout habitat on the ANSFs and FAIR (Robinson et al. 2004; USFWS 2009). While these actions have reduced management impacts, some legacy impacts still remain, and further emphasis should be given towards restoration of riparian and aquatic habitats (ASNF 2018). The Southwest Region (Region 3) of the U.S. Forest Service has the Riparian and Aquatic Ecosystem Strategy (USFS 2019), and restoration of aquatic habitat is identified through site-specific land management actions, such as the Black River Restoration Project (BRRP; currently ongoing). Working with partners on such actions is outlined in the Strategy (USFS 2019).

Hatcheries

Hatcheries have been used for Apache Trout conservation. Apache Trout from Williams Creek National Fish Hatchery have been used to establish some Apache Trout populations, such as in the West Fork Little Colorado River. However, use of this broodstock is currently being reconsidered for use in establishing recovery populations, and a genetics management plan is being implemented for this broodstock. Hatchery fish are commonly used to establish Apache Trout sport fishing opportunities in lakes and streams. For example, progeny from the Williams Creek broodstock are regularly raised in the Silver Creek and Tonto Creek hatcheries and stocked for recreation (e.g., West Fork Little Colorado River).

Angling and Harvest Regulation

Apache Trout streams are largely protected with fishing closures when populations are small and vulnerable or catch and release regulations in larger populations where harvest could negatively impact the population. Arizona Game and Fish Department does provide put-and-take opportunities for Apache Trout in Silver Creek, East Fork Black River, and West Fork Little Colorado River to generate public support for recovery of the species, as does the White Mountain Apache Tribe in the North Fork White River, lower East Fork White River, and lower Diamond Creek. Apache Trout fisheries are established in some lakes to afford the public opportunities to harvest Apache Trout, which also has the benefit of raising public awareness for the species. See section "Species Current Condition" below.

SPECIES CURRENT CONDITION

The Apache Trout was known as a unique salmonid species well before it was formally described by Miller (1972). By 1976, the species was estimated to be comprised of 14 genetically pure populations occupying less than 48 km (30 mi; USFWS 1983). The number of populations and amount of occupied habitat has varied since then due to replication of populations in new streams while losing others to hybridization, wildfire, and other factors (USFWS 2009).

The current distribution of Apache Trout is predominately comprised of 30 populations that are genetically pure based on genetic testing (n = 29) or suspected to be genetically pure (n = 1) in 282 km (175 mi) of stream (Table 8; Figure 14). These genetically pure populations comprise 17 relict populations in 161 km of habitat and 13 replicate populations in 120 km of habitat. Twenty-six of the genetically pure populations are protected by a natural or artificial barrier in 231 km of habitat, 19 populations occupy 147 km of habitat absent of nonnative trout, and 18 populations are protected in 141 km of habitat upstream of a protective barrier and absent of nonnative trout. There are also eight hybridized populations in 121 km of habitat, and six unoccupied recovery streams representing 61 km of habitat (Table 8). Apache Trout propagated at the Williams Creek National Fish Hatchery (WCNFH) and AZGFD Silver Creek Fish Hatchery (using eggs from WCNFH) and Tonto Creek Fish Hatchery are produced to stock streams and lakes on Tribal, State, and Federal lands for put-and-take and put-grow-take fisheries (section "Recreational Streams and Lakes").

Apache Trout populations and waters are commonly referenced by their purpose and role in recovery per the various recovery plans and documents, including the most recent 2009 Revised Recovery Plan for Apache Trout (USFWS 2009). The first distinction is whether a population or water's purpose, typically designated informally, is for ESA recovery or whether its purpose is mainly for recreation.

Table 8. Number of genetically pure relict, replicate, and hybridized Apache Trout populations and unoccupied recovery streams, and amount of habitat available for each. Habitat km taken from high resolution (1:24,000) National Hydrography Dataset.

Type	Number of populations	Available habitat (km)
Genetically pure populations	30	281.5
Relict	17	161.4
Replicate	13	120.1
Genetically pure + protective barrier	26	231.2
Genetically pure + no nonnative trout	19	146.7
Genetically pure + barrier + no nonnative trout	18	141.2
Hybrid populations	8	120.7
Unoccupied recovery streams	6	60.6

Recovery Population (Purpose): Many populations and streams are managed to meet Recovery Plan (USFWS 2009) criteria of genetic purity and to replicate populations on the landscape. In some cases, an unoccupied stream may be recognized as a recovery stream, with a future goal of protecting it above an intentional fish barrier, removing nonnative species from habitat above the barrier, and restoring an Apache Trout population in the reclaimed stream.

Recreational Population (Purpose): Some populations or waters may have, for example, hybridized Apache Trout that void them from meeting recovery criteria (genetic purity) but rather are managed for recreation. Many lakes and some streams in the White Mountains are also stocked with Apache Trout for recreational purposes; but because they are not self-sustaining populations they could not be used to meet recovery criteria (USFWS 2009). Instead, these fisheries are developed as angling opportunities for the public and to garner support for recovery of the species.

Beyond having a defined **Purpose** as recovery or recreational, Apache Trout populations and waters have been defined by **Type** based on origin and current and past presence of nonnative alleles from hybridizing species (current or past hybridization). These population types are: relict, replicate, and hybridized.

Relict Population (Type): A relict population of Apache Trout is one that was originally discovered in a stream within the historical range of the species that remains of original genetic stock. This includes populations with past evidence of introgression with Rainbow Trout, Cutthroat Trout, or another nonnative trout but is considered genetically pure due to recent genetic testing.

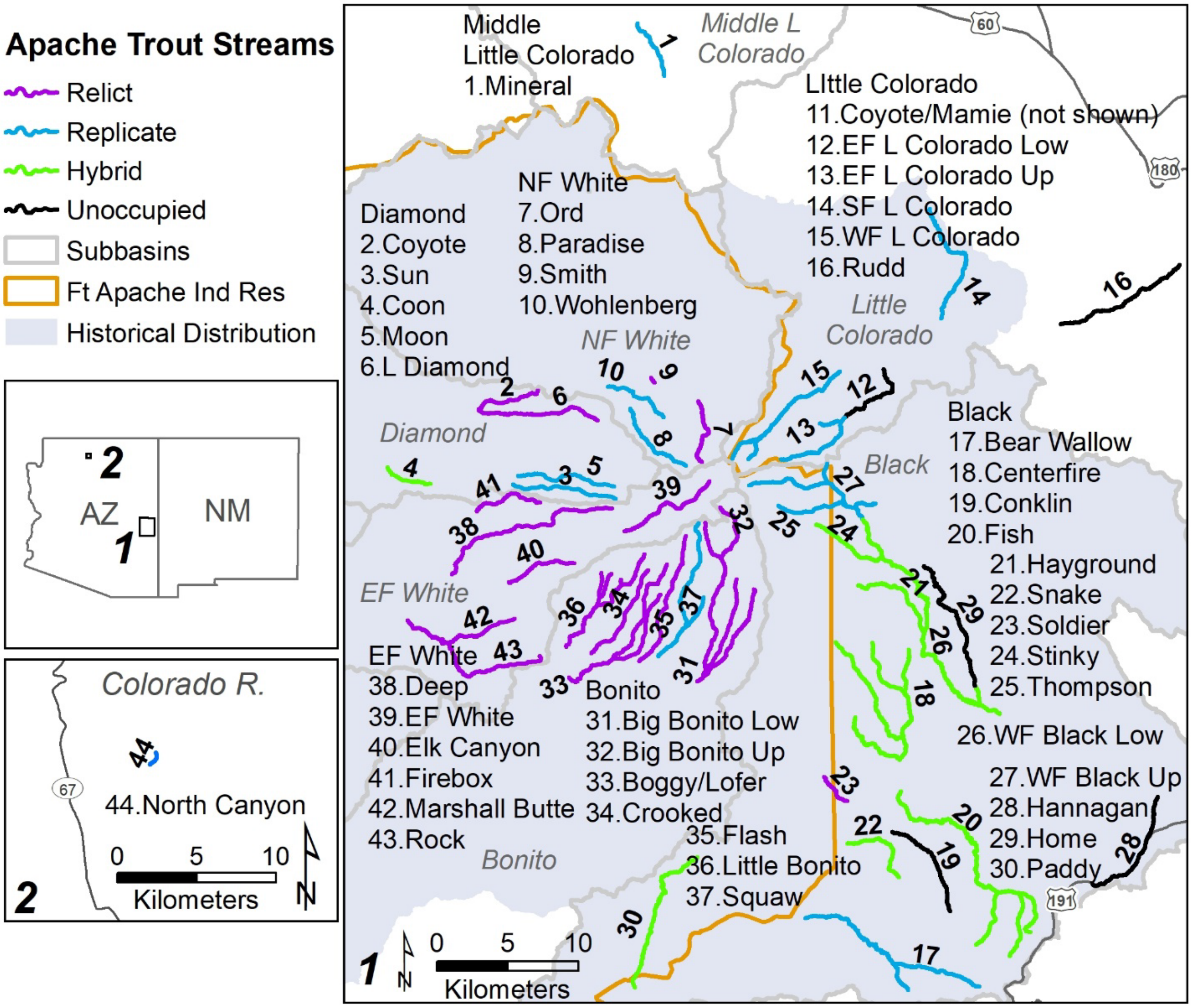

Figure 14. Relict, replicate, and hybrid Apache Trout populations and unoccupied recovery streams in east-central Arizona. Generalized historical distribution denoted in grey, and subbasins outlined in black with grey label.

Replicate Population (Type): A replicate population of Apache Trout is one that was established using individuals from a relict or replicate population (but a replicate that represents a relict genetic lineage). Replicate populations are usually established within the historical range of the species, including streams that were originally unoccupied by Apache Trout and where Apache Trout have been extirpated. Replicate populations do not show evidence of introgression with nonnative trout alleles and remain genetically pure. A replicate population effectively represents a replication of a relict lineage in a stream within the historical range of the species (within one exception: North Canyon Creek).

Hybridized Population (Type): An Apache Trout population that is known or suspected to have hybrid individuals. Hybridization may be documented by way of genetic testing for nonnative trout alleles as diagnostic loci (Carmichael et al. 1993; Wares et al. 2004). Hybridization may also be presumed by the presence of hybrid phenotypes visually identified by experienced biologists, although the accuracy of visual identification may be problematic (Weathers and Mussmann 2020). In some cases, populations are suspected to be hybridized because protective barriers are known to be non-functional (e.g., due to post wildfire debris flows) and nonnative trout are known to be nearby and are assumed to have invaded and hybridized with Apache Trout (e.g., several WFBR tributaries, see below).

Population Description and History

Salt River Watershed: Black River and White River Drainage

Relict Populations

Several populations have persisted since they were first discovered and are considered relict populations. Upper Big Bonito Creek above a natural waterfall, lower Big Bonito Creek below the waterfall, Boggy and Lofer creeks, Coyote Creek, Crooked Creek, Deep Creek, East Fork White River, Elk Canyon Creek, Firebox Creek, Flash Creek, Little Bonito Creek, Marshall Butte Creek (referred to as DP Creek in the past), Ord Creek, and Smith Creek on the FAIR and Soldier Springs Creek (on both FAIR and ASNF) all contain relict populations of genetically pure Apache Trout. Most relict populations are protected by natural (waterfalls) or constructed barriers unless noted below (Table 9). Coyote, Little Bonito, lower Big Bonito, Little Diamond, Rock, and Smith relict populations have been invaded by Brown Trout. AZGFD and USFWS (2015) detail the history of genetic testing and other management in these populations, and much of that information is also detailed below.

The lower Big Bonito Creek system (FAIR; including Big Bonito below the natural barrier, Hurricane, Hughey, and Peasoup creeks) historically contained Apache Trout, but no Apache Trout were observed during Brown Trout removal efforts (via electrofishing) in 2019 in Big Bonito Creek. The other tributaries (and headwaters) were not sampled in 2019, but it is assumed Apache Trout remain in the system because they were sampled from Pea Soup (n=26), Hughey (n=30), and Hurricane (n=26) creeks in the mid-late 1990's for genetic analysis where they were determined to be genetically pure (Ruiz and Ensman 2001). The current gabion barrier is non-functional, and a new barrier is scheduled for construction in 2022. Once a new barrier is in place the lower Big Bonito system will represent an interconnected system that could function as a metapopulation for Apache Trout; however, Brown Trout are in the system and would need to be suppressed if not eradicated for long-term Apache Trout persistence.

Ord Creek is considered a relict population protected above a timber and a gabion barrier, although it was re-established using Ord stock from another replicate stream. In the 1960's, Ord Creek fish were replicated into Coyote/Mamie Creek (ASNF) and North Canyon Creek (KNF; refuge population), and fish from these two creeks were used to re-establish fish into Ord Creek after renovation to remove Brook Trout in 1977–78 (Rinne et al. 1981). Apache Trout were collected from Coyote Creek (Coyote/Mamie; ASNF), which was rapidly dewatering due to drought conditions and were repatriated into Ord Creek in 1996 (AZGFD and USFWS 2015). Apache Trout were also collected from North Canyon Creek (KNF) and repatriated into Ord Creek in 1996. Additional fish were collected from North Canyon Creek and repatriated into Ord Creek in 1998 (AZGFD and USFWS 2015). Ord Creek stock were also placed into KP Creek (ASNF), Mineral Creek (ASNF), Ash Creek (CNF), Grant Creek (CNF), and Marijilda Creek (CNF). All of these but Mineral Creek are now considered historical Gila Trout habitat.

The Marshall Butte Creek, also known as DP Creek or unnamed tributary to Rock Creek (White River drainage), population of Apache Trout was discovered in 2007. Genetic testing showed no nonnative alleles, and the population was determined to be genetically pure (Carlson and Culver 2009). The population is protected above a natural barrier and contains no nonnatives despite Brown Trout occurring immediately below the barrier.

Little Diamond and Rock creeks (FAIR) are relict populations that had contained predominately pure individuals of Apache Trout but with some evidence of hybridization in the late 1980's (Carmichael et al. 1993). Additional samples were collected again in 2007 to reexamine the levels of hybridization in these populations, as Carmichael et al. (1993) noted that they were back-crossing towards pure Apache Trout. These populations are now considered to be genetically pure based on the 2007 tissue samples (Carlson and Culver 2009), although each stream has been confirmed to have Brown Trout present. Little Diamond has a barrier below its confluence with Coyote Creek.

Replicated Populations

Bear Wallow Creek (ASNF) was renovated in 1981 and 2003 to remove Brown Trout and hybrid Apache Trout from above the rock-masonry barrier constructed in 1979 (repaired in 1984 and 2003–2005). In 1981 and 1983 pure Apache Trout were stocked (Soldier Springs lineage). After the 2003 piscicide application (restocked with Soldier Springs lineage from Coleman Creek), hybrid Apache × Rainbow Trout were found, triggering the need for another piscicide treatment that occurred in 2005. Follow-up surveys in 2005 found no fish and Apache Trout of Soldier Springs lineage were stocked in October 2005 from Coleman Creek (n = 155) and Soldier Springs Creek (n = 147). A new cyclopean concrete barrier was constructed in 2007 on lower Bear Wallow Creek on the San Carlos Apache Indian Reservation (SCAIR) that extended habitat by approximately two miles; it was almost immediately found to be insufficient. Fish surveys evaluating barrier effectiveness found nonnative Brown Trout and hybrid Apache Trout upstream from the upper barrier in 2008, and genetic analysis showed a high degree of hybridization near the barrier and extending upstream (AZGFD and USFWS 2015). The upper barrier was repaired again in 2008. Fish surveys completed in 2009 and 2010 indicated that the lower barrier had failed on several occasions and allowed passage of numerous large fish. Fish surveys following the 2011 Wallow Fire showed no fish upstream of the upper barrier (AZGFD and USFWS 2015). The lower barrier was modified in 2018 and is now considered effective at streamflows up to a 25-year flood. Bear Wallow Creek was surveyed in 2020 to collect fish for genetic analysis. Apache Trout were collected in the North Fork, South Fork, and mainstem, and the 58 individuals analyzed showed no nonnative trout alleles and therefore no evidence of hybridization (Weathers and Mussmann 2021a). Further testing of 74 samples collected during 2021 all tested as genetically pure as well (Weathers and Mussmann 2021c). Environmental DNA sampling conducted during 2021 did not detect Brown Trout in Bear Wallow Creek indicating that the only salmonids inhabiting this stream are pure Apache Trout.

Paradise Creek (FAIR) contained a hybrid population of Apache × Rainbow Trout in 1988 (Carmichael et al. 1993). In 1994 and 1995, Paradise Creek was renovated to remove hybrid trout, Brown Trout, and Brook Trout above a gabion barrier constructed in the mid-1980s. In 2000, the gabion barrier was repaired and capped with shotcrete and the stream was renovated again in 2001. In 2003, 30 Apache Trout from Smith Creek were stocked into Paradise Creek. In 2007, only 27 Apache Trout were collected during monitoring, and these fish were moved back to Smith Creek to augment the small natural population there. Then, 124 Apache Trout from Deep Creek were stocked (above 3rd road crossing) in upper Paradise Creek in October 2007, and an additional 111 Deep Creek fish were stocked in 2009 (USFWS 2009; AZGFD and USFWS 2015). One Brown Trout was found above the barrier in 2012, and two were found in 2014. Nearly 2,200 Brown Trout were removed (using electrofishing) from this system during 2016–21 and the species has been eradicated from this recovery population.

Squaw Creek (FAIR) was renovated in 1996 to remove Brown Trout above a gabion barrier constructed in 1994. Following renovation, 118 Apache Trout from Flash Creek were stocked in 1996. The results of this project are detailed in Kitcheyan (1999). Since then, a substantial population of Apache Trout has been observed in Squaw Creek, which has been the focus of Brown Trout removal efforts in recent years. Brown Trout had colonized due to a non-functional gabion barrier at the lower extent of Squaw Creek (AZGFD and USFWS 2015). Barrier maintenance completed during 2020 returned this barrier to a functional status.

The upper portion of Thompson Creek, a tributary to the WFBR, above a culvert barrier on the FAIR contains a replicated population of Apache Trout from Firebox Creek introduced in 1996 (USFWS 2009).

Sun and Moon creeks are connected through Christmas Tree Lake. Both streams were renovated during construction of Christmas Tree Lake, which filled in 1967 and was then stocked with fish from Ord, Firebox, and Deep creeks (a mixed lineage). Apache Trout are found mostly in the headwaters of Sun and Moon creeks, but both streams can be intermittent in their lower reaches. It is unclear whether there is demographic exchange between the two creeks. There was some evidence of hybridization in Sun and Moon creeks in the late 1980's but also evidence of back-crossing to Apache Trout (Carmichael et al. 1993). Testing of genetic material from 2007 showed them to be genetically pure (Carlson and Culver 2009). Each stream has Brown Trout present, and Christmas Tree Lake is stocked with Apache Trout from Williams Creek National Fish Hatchery (East Fork White River lineage) and managed as a recreational fishery.

The lower portions of Thompson Creek below the barrier, as well as the upper WFBR above the upper constructed barrier, including Burro Creek [ASNF]), were renovated in 1996 to remove Brown Trout and Brook Trout; together these systems are referred to as the upper WFBR population. There are two barriers isolating the upper WFBR population from downstream species. Two gabion-basket (capped with concrete) barriers were constructed in 1996; the second downstream barrier, often referred to as the middle barrier, is considered non-functional (AZGFD and USFWS 2015). In 2015, a third barrier was constructed further downstream below the confluence with Home Creek; this barrier is often referred to as the lower barrier on the WFBR, but it currently bounds the lower end of what is considered to be the lower WFBR population in this SSA document (see Recovery Steams section below). The WFBR, lower Thompson Creek, and Burro Creek (believed to be unoccupied due to poor habitat conditions) contain Apache Trout from East Fork White River stock and are managed as part of the upper West Fork Black River metapopulation on ASNF due to its connected habitat; however Brook Trout have been found in sections of WFBR and Thompson Creek, and removal efforts are ongoing. Over 20,000 Brook Trout have been removed by electrofishing from the upper WFBR and Thompson Creek on FAIR during 2015–2021 eradication efforts.

Wohlenberg Creek (FAIR; also known as Wohlenberg Draw Creek) is considered to be historical Apache Trout habitat, although no Apache Trout were ever historically documented from the creek. The stream was renovated in 1999 to remove Brown Trout and Brook Trout above a timber barrier originally constructed in the early 1980s and rebuilt in 1999 (USFWS 2009). Fifty-one Apache Trout from Coyote Creek (FAIR) were stocked into Wohlenberg Creek in 2003. In 2007, 26 fish were collected in the reach from the barrier to just upstream of Stake Creek, and 24 fish from multiple age classes were captured during a survey in 2010 (AZGFD and USFWS 2015). Subsequent surveys have documented an increasing population of Apache Trout and the absence of nonnative trout as recently as 2019.

Hybrid Populations

The Centerfire Creek system (ASNF; including Boggy and Wildcat creeks) contained an Apache Trout population with evidence of hybridization with Rainbow Trout (Carmichael et al. 1995). Surveys in the mid-2000s found very few trout due to severe drought conditions (USFWS 2009), but it is believed to still have hybrid fish present.

The Conklin Creek system contained Brown Trout and hybrid Apache Trout, which were removed using piscicides in 2006 and 2007. However, fish were found upstream of the barrier after it was thought the piscicides were successful, and nonnative trout were found upstream of the barrier again in fall of 2008 after which a steel grate was added to the barrier. Electrofishing surveys found hybrid Apache Trout upstream of the barrier again in 2010, and fish were thought to be moving through the gabion baskets during high flow events; hybrid Apache Trout were again collected in 2011 prior to the Wallow Fire. Following the Wallow Fire, the stream was presumed fishless. Subsequent electrofishing surveys found no fish; however, 2019 eDNA samples showed one site with salmonid DNA. Follow up electrofishing and eDNA surveys were completed during 2020 with no fish or salmonid DNA detected (Z. Beard, Arizona Game and Fish Department, pers. comm.)

Coon Creek (FAIR) was shown to have low levels of hybridization in the late 1980's (Carmichael et al. 1993), and it is assumed to have hybrid Apache Trout. Coon Creek is also suspected to be occupied by Brown Trout. No recent information exists for this population.

The Fish Creek system (ASNF; including Corduroy, Double Cienega, and Fish creeks) was renovated in 2004 and 2005 to remove nonnative trout and Apache Trout hybrids from above the gabion barrier constructed in 1986 (gabions added in 1998, repaired 2003–2004). The stream was stocked with pure Apache Trout (Ord Creek lineage from North Canyon Creek) in 2005. It was stocked again with pure Apache Trout in 2006 (n=185) and 2007 (n=82) from the upper West Fork Black River population. After initial visual surveys in 2007 suggested some survival, electrofishing surveys in 2007, 2008, and 2009 found no Apache Trout. Extensive electrofishing surveys were conducted during 2010 and Apache Trout were found further upstream than during prior surveys (with evidence of recruitment), and Brown Trout were also found to have invaded the stream. The barrier was washed out after the Wallow Fire in 2011 and is now gone. It is suspected that the Apache Trout population has hybridized with Rainbow Trout that now occur in the system along with Brown Trout. Genetic testing to evaluate hybridization is planned for the near future along with identifying a new barrier site.

Hayground Creek (ASNF) was renovated in 1989, 2004, and 2005 above the gabion barrier constructed in 1985 (repaired in 2004 and 2005). After the 2005 treatment with Antimycin-A, 127 fish from North Canyon Creek (Ord Creek lineage) were stocked. Subsequent snorkeling surveys found only two Apache Trout in 2006, and electrofishing surveys found only three Apache Trout in 2007 when one Brown Trout was also found (above the barrier; AZGFD and USFWS 2015). The barrier was considered non-functional after Brown Trout were documented and needs maintenance following the Wallow Fire. The population is suspected to be hybridized.

Paddy Creek (FAIR) is a tributary to the Black River without a protective barrier. It was reported as having approximately 50% hybridized individuals from limited (n=5) genetic testing in the early 1990s (Carmichael et al. 1993). It was suggested by Carmichael et al. (1995) that Paddy Creek be evaluated further for hybridization with a larger sample size of tested individuals. It was also suggested that it be evaluated for a protective barrier and potential renovation to remove hybrids. Apache Trout were collected from Paddy Creek in the late fall of 2020, and genetic analysis of tissue samples from 3 of 38 fish showed evidence of a hybridization event three or more generations ago (Weathers and Mussmann 2021b). Rainbow Trout and Brown Trout are also present in the stream.

The Snake Creek system (ASNF) was treated in 2003 to remove Brown Trout and Apache Trout hybrids, and the barrier was washed out after the Wallow Fire. Given the lack of barrier, it is assumed that any Apache Trout are hybridized, although no recent surveys have been conducted.

Stinky Creek (ASNF) was renovated in 1994 and 2007 above the gabion barrier constructed in 1991 (maintained 2004). The stream was subsequently stocked with pure Apache Trout salvaged prior to the renovation in 2007 (originally stocked in 1995 from hatchery-reared East Fork White River Apache Trout); however, Brown Trout were found in the stream in late 2007 due to a barrier ineffectiveness, and the Apache Trout population is now suspected to be hybridized with Rainbow Trout.

The lower WFBR population (ASNF) is defined as between the downstream-most gabion barrier on the upper WFBR (often referred to as the middle barrier; see above) and a barrier constructed in 2015 below the Home Creek confluence with WFBR (commonly referred to as the lower barrier). Lower WFBR contains a hybridized population of Apache Trout (EFWR stock) and a substantial population of Brown Trout. This section of WFBR is awaiting chemical renovation. Renovation, and reconnecting access to tributaries through barrier removal (n=4), would potentially reconnect Home, Hayground, and Stinky creeks as a metapopulation (AZGFD and USFWS 2015).

Unoccupied (Potential) Recovery streams

Hannagan Creek (ASNF) used to be occupied by a hybridized population of Apache Trout and more recently by Brown Trout (USFWS 2009). However, the creek was severely impacted by the Wallow Fire in 2011 and was believed to be fishless; it has no protective barrier. An electrofishing survey of Hannagan Creek was completed during 2021 which resulted in the capture of 103 Brown Trout, 1 Apache Trout, and 15 Speckled Dace *Rhinicthys osculus*.

Home Creek was renovated after being isolated by a gabion barrier in 1987 (reconstructed in 1988), and 1,005 Apache Trout were stocked in 1988 (from East Fork White River lineage from Williams Creek National Fish Hatchery), 2,488 stocked in 1992 (EFWR lineage from Pinetop Hatchery), and 312 stocked in 1997 (EFWR lineage from Pinetop Hatchery). The population persisted into the 2000's until drought reduced flows and the population was extirpated (AZGFD and USFWS 2015). Home Creek is currently isolated from the lower WFBR by the lower barrier (constructed in 1994–1995), as the upper barrier (1987) is subject to high flows routing around it due to aggradation of sediment from the 2011 Wallow Fire.

Little Colorado River (LCR) Drainage

Relict Populations

There are no relict populations of Apache Trout in the Little Colorado River drainage.

Replicated Populations

The upper East Fork LCR (ASNF) was renovated in 2004 and 2005 and was stocked with pure Apache Trout in 2006 and 2007 from Soldier Springs Creek. Additional Apache Trout from Coleman Creek (Soldier Springs lineage) were translocated to the East Fork LCR in 2006 (16 fish), 2007 (10 fish), and 2009 (20 fish). In 2011, 72 Apache Trout from Soldier Springs Creek were translocated to East Fork LCR also. The East Fork was opened to catch-and-release angling and other protective regulations in 2015. Colter Dam, with a metal grate over a jump pool (installed 1998), protects this population from invasion by nonnative trout downstream.

Mineral Creek (ASNF) is in a closed basin within the Little Colorado River basin. The stream was renovated in 1967 and 1968 and subsequently stocked with genetically pure Apache Trout (Ord Creek lineage); it currently supports a small population of genetically pure Apache Trout. A gabion barrier was built in 1982 to protect this population.

The South Fork LCR (ASNF) contains two concrete barriers. The lower barrier constructed in 2004 is 1.5 km above the confluence with the LCR, and the upper barrier constructed in 2005 is 2.8 km above the lower barrier. The stream was renovated in 2007 and 2008, and it was stocked with pure Apache Trout from Big Bonito Creek (FAIR) in 2008 (n=121). Very few fish were collected during post-Wallow Fire surveys from 2012 to 2014 (AZGFD and USFWS 2015), and very few fish (n=3) were found during population monitoring in 2017. However, additional monitoring in 2021 suggested a population size of over 500 adult Apache Trout.

The West Fork LCR (ASNF and FAIR) was renovated in 2006 above two gabion barriers constructed in 2004. The stream was stocked with pure Apache Trout from Thompson Creek and WFBR (n = 202; East Fork White River lineage) in 2007. In 2009 and 2014, a substantial effort was made to remove Brown

Trout between the barriers, as the lower gabion barrier is ineffective. In 2018, putative hybrid Apache × Rainbow Trout were thought to have been collected above the upper gabion barrier and confirmed with preliminary genetic testing. However, a recent genetic analysis showed the genetics from putative Apache Trout × Rainbow Trout hybrids collected 2018 (tested positive for hybrid alleles at that time), and those collected in 2019, showed no recent introgression with Rainbow Trout alleles and that those fish reflected the genetic signature of East Fork White River lineage. The middle reaches of the creek near Sheep Crossing have been, and may continue to be, regularly stocked with hatchery Apache Trout by AZGFD to maintain a popular sport fishery at this location (AZGFD and USFWS 2015).

Hybrid Populations

There are no hybrid populations of Apache Trout in the Little Colorado River drainage.

Unoccupied (Potential) Recovery streams

Coyote and Mamie creeks (ASNF) had contained pure Apache Trout (Ord Creek lineage) that were stocked into Mamie Creek in 1965. A rock-masonry/gabion barrier was constructed in 1994 to protect the population. However, the population has since been extirpated; Apache Trout have not been documented since droughts in 2007 and 2008 (ASNF 2016).

East Fork Little Colorado (lower; ASNF), below Colter Dam downstream to about 1 mile above the West Fork LCR confluence, is considered a potential recovery stream. Two gabion barriers were constructed in 2004 but are considered non-functional and Rainbow Trout and Brown Trout would need to be removed in order for Apache Trout to be restored to the stream. The lower East Fork LCR was also impacted following the 2011 Wallow Fire (USFWS 2009; AZGFD and USFWS 2015).

Rudd Creek (ASNF) had supported a Rainbow Trout population upstream of Sipe Wildlife Area and that was extirpated from drought in 2002. A small Brook Trout population remained that was removed with electrofishing over several years (M. Lopez, ret. AZGFD, pers. comm.). Despite being considered recovery habitat, Rudd Creek streamflows remain very low and habitat suitability for Apache Trout is questionable; it was also impacted by the 2011 Wallow Fire.

Recreational Streams and Lakes

Some streams and lakes are managed for recreation. They may contain hybrid populations of Apache Trout or genetically pure Apache Trout stocked from hatchery sources.

Hatchery-reared Apache Trout have been stocked in Lee Valley Reservoir (ASNF) to support a sport fishery since 1968, and Lee Valley Creek above the reservoir once contained a recovery population of Apache Trout. A barrier was constructed on lower Lee Valley Creek, a tributary feeding Lee Valley Reservoir, in 1979. Lee Valley Creek was renovated in 1982 and stocked with Apache Trout (unknown origin), but Brook Trout recolonized from the reservoir and another renovation was conducted in 1987. The stream was renovated in 2003 and then stocked with pure Apache Trout (East Fork White River [EFWR] hatchery stock) in 2004 and augmented in 2007. As of the early 2010's, Lee Valley Creek has been considered unoccupied. The stream had eroded around the barrier sometime in the 2000's. In 2014 the barrier isolating Lee Valley Creek from Lee Valley Reservoir was removed and replaced with a cross-vane rock weir to control a head cut. Lee Valley Creek is no longer considered a recovery stream, and the reservoir is managed for sport fishing.

Reservation Creek contains a hybrid population of Apache Trout, flows into Reservation Lake (reservoir), and is managed for recreational fishing (nonnative trout). The following streams and rivers are also stocked with Apache Trout on the FAIR for recreation: Cibecue Creek, Diamond Creek, East Fork White River (lower), North Fork White River, and Paradise Creek (lower).

The following streams and rivers are stocked with Apache Trout on the ASNF for recreation: East Fork Black River, WFBR (below barriers), West Fork Little Colorado River above barriers, Little Colorado River (in Greer, AZ), and in Silver Creek.

Apache Trout are also stocked into lakes for recreational purposes. Lakes that have been stocked in the past, are currently stocked, or are scheduled for stocking in the near future are: A1 Lake, Aker Lake, Becker Lake, Big Bear Lake, Big Lake, Christmas Tree Lake, Cyclone Lake, Earl Park Lake, Hurricane Lake, Lee Valley Lake, Little Bear Lake, Long Lake, Pacheta Lake, Show Low Lake, Silver Lake, and Tunnel Reservoir.

Populations Outside Historical Range

Ash, Grant, Big, and Marijilda creeks in the Pinaleño Mountains (CNF) had or currently contain hybridized populations of Apache Trout (Porath et al. 2010). Ash and Marijilda creeks are tributaries to the Gila River and now considered within historical range of Gila Trout (USFWS 2003); Grant and Big creeks drain into the Willcox Playa, which is a closed basin (Minckley 1973). Ash Creek was treated with piscicides in 2012 and restocked with Gila Trout, which were extirpated due to the Frye Fire in 2017. Grant Creek in the Pinaleño Mountains (CNF) is fishless due to the Frye Fire in 2017. The status of Big Creek is unknown. Marijilda Creek was confirmed to be fishless in 2020 using environmental DNA (eDNA) after mechanical removal of Apache Trout, and it was stocked with Gila Trout in 2020. Deadman Creek (CNF) was stocked with Apache Trout in 1968 and 1969, and it is uncertain if hybridized trout persist; Deadman Creek is now considered within the historical range of Gila Trout.

Coleman Creek (ASNF) is a tributary to Campbell Blue Creek, which flows into the Blue River. At one point, Coleman Creek was considered historical Apache Trout habitat and was stocked with Soldier Springs stock in 1981 and 1983; however, the population was extirpated due to the Wallow Fire (2011), and it was stocked with Gila Trout in 2020. Apache Trout from Coleman Creek had been stocked into Bear Wallow Creek and the upper East Fork Little Colorado River.

KP and Grant creeks (ASNF), also tributaries to the Blue River, had contained hybridized populations of Apache Trout and are now considered within historical range of Gila Trout (USFWS 2003). KP was confirmed to be absent of salmonids above the barrier in 2020 using eDNA and was stocked with Gila Trout in 2021.

Horton Creek (Tonto National Forest) was stocked with hatchery Apache Trout in 1971; however, at the time the stream also had Rainbow, Brook, and Brown Trout populations. It is likely that any remaining Apache Trout would be hybridized and would not contribute to recovery; recent surveys have only shown the presence of Brown Trout (AZGFD, unpublished data).

North Canyon Creek (Kaibab National Forest) is a tributary to the Colorado River and supports a pure Apache Trout population (Ord Creek lineage). Apache Trout from North Canyon Creek were used to reintroduce trout back into Ord Creek in 1996 and into Hayground Creek in 2005. North Canyon Creek will be maintained as a refuge population of Apache Trout and a source of fish for population establishment or augmentation.

Table 9. Current and potential Apache Trout recovery streams, habitat, lineage, and barrier information on the Fort Apache Indian Reservation (F), Apache-Sitgreaves National Forests (A), Kaibab National Forest (K), and San Carlos Apache Reservation (S). EF=East Fork, SF=South Fork, and WF=West Fork.

Population Type	Population	Habitat (km^1)	Lineage stocked & years	Barrier Type and Material	Year Barrier Built and Maintenance
Relict	Big Bonito: up (F)	3.4	Relict	Natural	N/A
Relict	Big Bonito: low (F)	29.4	Relict	Artificial, gabion	1994, maintenance 1999, 2000, Shot-Crete 2001, nonfunctional–planning replacement
Relict	Boggy/Lofer (F)	19.7	Relict	Natural	N/A
Relict	Coyote (F)	5.1	Relict	Artificial, gabion	2002, functional-suspected, planning replacement
Relict	Crooked (F)	7.8	Relict	1) Natural; 2) Artificial, gabion	1) N/A; 2) 1995, maintenance (fill and cloth) 1998, functional–planning replacement
Relict	Deep (F)	14.6	Relict	Natural	N/A
Relict	EF White (F)	8.2	Relict	Natural	N/A
Relict	Elk Canyon (F)	5.4	Relict	Natural	N/A
Relict	Firebox (F)	5.4	Relict	Dewatered	N/A
Relict	Flash (F)	10.4	Relict	1) Natural; 2) Artificial, gabion	1) NA; 2) 1994, 1997, reinforced with gabions and Shot-Crete 2001, repaired 2020, functional–planning replacement
Relict	Little Bonito (F)	14.8	Relict	Artificial (2), gabions	1995, 1996, 1998, 2010, low non-functional, planning replacement
Relict	Little Diamond (F)	9.6	Relict	Artificial, gabion	2002, functional-suspected, planning replacement
Relict	Marshall Butte (F)	5.5	Relict	Natural	N/A
Relict	Ord (F)	5.6	Relict	Artificial (2), timber, gabion	1964; 1977, repaired 1998, reinforced with Shot-Crete 2000, functional–planning replacement
Relict	Rock Creek (F)	13.2	Relict	Natural	N/A
Relict	Smith (F)	0.7	Relict	Natural (n=2)	N/A
Relict	Soldier Springs (F/A)	2.7	Relict	Natural	N/A
Replicate	Bear Wallow (S/A)	18.6	Soldier 1981 (from Coleman 1983, 2005)	Artificial (2); 1) Rock-Masonry & Gabion; 2) Concrete & Masonry	1) 1979, repaired 1984, relined and splash pad 2003–2005, nonfunctional; 2) 2007; repaired in 2018, functional
Replicate	EF Little Colorado: up (A)	9.7	Soldier 2006, 2007	Artificial, grate over Colter Dam	1998
Replicate	Mineral (A)	4.7	Ord 1967, 1968	Artificial, gabion	1982

Population Type	Population	Habitat (km^1)	Lineage stocked & years	Barrier Type and Material	Year Barrier Built and Maintenance
Replicate	Moon (F)	7.7	Ord, Firebox, Deep 1967	Artificial, Christmas Tree Lake Dam	Christmas Tree Lake filled in 1967
Replicate	Paradise (F)	6.5	Deep 2007	Artificial, gabion	1985, concrete 2000, functional–planning replacement
Replicate	SF Little Colorado (A)	10.6	Big Bonito 2008	Artificial (2), concrete	low: 2004, 2014; up: 2005
Replicate	Squaw (F)	13.7	Flash 1996	Artificial, gabion	1994, repaired 1997–1999, sprayed with Shot-Crete 2001, repaired 2020, functional–planning replacement
Replicate	Sun (F)	7.8	Ord, Firebox, Deep 1967	Artificial, Christmas Tree Lake Dam	Christmas Tree Lake filled in 1967
Replicate	Thompson: up (F)	1.9	Firebox 1996	Artificial, culvert	Functional
Replicate	WF Black: up (incl Burrow, low Thompson; F/A)	18.6	EFWR (from hatchery) 1997, 1998	Artificial (2), gabions	1) 1996, 2002–2004; 2) 1993, 1996, 2002–2004, non-functional
Replicate	West Fk Little Colorado (F/A)	14.3	EFWR (from EFWR) 2007, EFWR (from WFBR)	Artificial (2), gabions	2004, low barrier non-functional
Replicate	Wohlenberg (F)	5.1	Coyote 2003	Artificial, timber	1982, reconstructed 1999 functional–planning replacement
Replicate	North Canyon Creek (K)	1	Ord 1963, 1967	N/A	N/A
Hybrid	Centerfire (A)	29.5	Unknown	Artificial, gabion	1984, reconstructed 2004, nonfunctional needs maintenance
Hybrid	Coon (F)	3.6	Coon	N/A	N/A
Hybrid	Fish (Ackre Lake, Fish, Corduroy, Double Cienega; A)	30.1	EFWR (from WFBR) 2006, 2007	Artificial, gabion	1986, additional gabions 1998, concrete & plastic liner 2003–2004, wing-walls 2005; washed out after Wallow Fire
Hybrid	Hayground (A)	7.5	Ord (from North Canyon) 2005	Artificial, gabion	1985, repaired 2004–2007, nonfunctional, removal planned
Hybrid	Paddy (F)	12.5	Paddy	None	N/A
Hybrid	Snake (A)	6.2	Unknown	Artificial	1987, grate and gabions installed 1998. Nonfunctional, washed out after Wallow Fire
Hybrid	Stinky (A)	5.6	EFWR (from hatchery) 1995	Artificial, gabion	1991, maintenance 2004, removal planned
Hybrid	WF Black: low (A)	25.7	EFWR	Artificial, concrete	2015

Population Type	Population	Habitat (km^1)	Lineage stocked & years	Barrier Type and Material	Year Barrier Built and Maintenance
Unoccupied	Conklin (A)	8.2	N/A	Artificial, culvert & gabion	1988, grate over culvert 2006
Unoccupied	Coyote/Mamie (A)	13.4	N/A	Artificial, rock masonry & gabion	1994
Unoccupied	East Fk Little Colorado: low (A)	6.9	N/A	Artificial (2), gabions	2004 (considered nonfunctional)
Unoccupied	Hannagan (A)	9.1	N/A	N/A	N/A
Unoccupied	Home (A)	11.4	N/A	Artificial (2), gabions	1980, up barrier nonfunctional, removal planned
Unoccupied	Rudd (A)	11.6	N/A	Artificial, culvert	N/A

Current Conditions

The current condition of the Apache Trout was assessed using the *representation* of and *redundancy* of relict populations by basin and subbasin, as well as a set of demographic and habitat factors that reflect population *resiliency*. Together, these 3 Rs reflect the current condition, viability, and health of the species.

Representation and Redundancy

Representation and redundancy for Apache Trout were evaluated by quantifying the presence of relict populations, and their replication on the landscape, as putative genetic lineages at the subbasin level (Figure 15). Representation was based on presence of genetically pure relict populations from each subbasin (~hydrologic unit code 8). Redundancy was measured as the replication of relict lineages into new streams by subbasin; replication of relict populations, and thus redundancy of purported relict subbasin lineages, was measured both within and outside of the native subbasin for each subbasin genetic lineage. The subbasins were: Black River, Bonito Creek, East Fork White River, North Fork White River, Diamond Creek, Little Colorado River, and Colorado River (outside of historical range but contains a refuge population that is replicated using Ord creek fish [North Fork White subbasin]). Tracking the representation and redundancy of relict populations by subbasin, as subbasin lineages, is a surrogate for the assumed unique genetic diversity, and presumed unique adaptation potential, that is often found to be structured around the hierarchical nature of drainage basins (Vrijenhoek et al. 1985; Wares et al. 2004). While such genetic structuring is evident in Apache Trout for the nine populations (and three genetic lineages) that have been studied (Wares et al. 2004), no comprehensive range wide study of genetic diversity has been conducted across all relict and replicate populations. Accounting for relict Apache Trout populations in this way assumedly reflects the representation and redundancy of genetic diversity, and thus adaptive potential, of the species associated with each subbasin for which it is native.

When quantified in this way, extant relict populations exist for 5 of 6 subbasins within the historical range of the Apache Trout; only the Little Colorado River subbasin is no longer represented within an extant relict lineage (Table 10; Figure 15; Figure 17). The East Fork White River subbasin has the highest level of redundancy with six relict populations still extant within the subbasin and four replicated populations in other subbasins that were founded with individuals from relict populations native to the East Fork White River subbasin (Table 10; Figure 17). After the Little Colorado River subbasin that contains no relict populations, the Black River and Diamond subbasins contained the lowest level of redundancy, with three populations each occurring on the landscape (Black River: 1 relict and 2 replicates; Diamond: 2 relicts and 1 replicate).

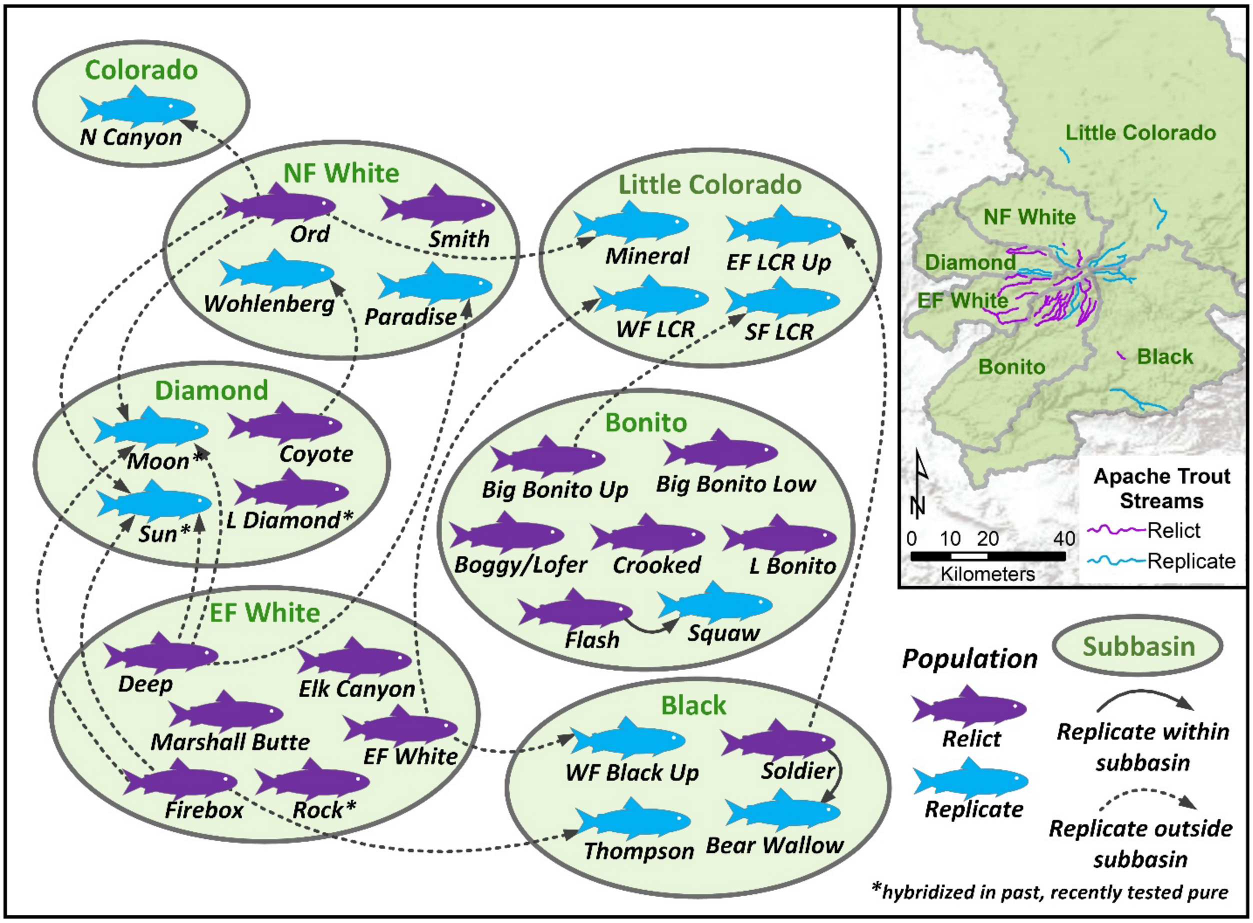

Figure 15. Conceptual representation of relict and replicate Apache Trout populations by subbasin and the population(s) with which replicates were founded. Solid arrows indicate replicate populations founded with a lineage within the native (same) subbasin, and dashed arrows indicate replicate populations founded with a lineage from outside of the native subbasin. Sun and Moon populations (Diamond subbasin) were founded with individuals from multiple populations (mixed lineage).

Resiliency – Demographic and Habitat Factors

Three demographic and six habitat factors were used to describe the current condition (status) and overall resiliency of Apache Trout populations. These factors are commonly used to describe the health and integrity of native trout populations in the western U.S. (Williams et al. 2007; USFWS 2009; Dauwalter et al. 2017a). Each factor is defined below by whether it is a numeric or class variable, the value ranges or categories are defined, and the use of the factor is rationalized. The value associated with each population was computed from field data, modeled data, or estimated using best professional (expert) judgement.

*Table 10. Representation of relict populations (genetically pure), replicates of relict populations (genetically pure) within and outside of their native subbasins, genetically pure populations by subbasin, and redundancy of subbasin relict and replicate populations by subbasin (both within and outside of native subbasin). Counts of relict and replicate populations does not include hybridized populations. Mixed lineages are not represented as replicated or in redundancy counts, but are considered as a genetically pure population within the subbasin. *indicates evidence of past hybridization but has tested genetically pure recently (Little Diamond, Sun, Moon, and Rock creeks); ^a indicates population outside of Apache Trout historical range.*

	Populations				
Subbasin	Relicts	Subbasin replicates within subbasin	Subbasin replicates outside subbasin	Subbasin redundancy (relicts + replicates)	Genetically pure within subbasin
Black	1	1	1	3	4
Bonito	6	1	1	8	7
EF White	6	0	4	10	6
NF White	2	0	2	4	4
Diamond	2*	0	1	3*	4*
Little Colorado	0	0	0	0	4
Colorado[a]	0	0	0	0	1
Rangewide	17*	2	9	28*	30*

Demographic Factors

Genetic Purity – Definition: The absence of hybrid individuals based on genetic testing for nonnative alleles, observed phenotype, or professional judgement (Class: Pure – tested; Pure – suspected; Hybrid – tested; Hybrid – suspected; None). Hybridization can introduce traits that are maladaptive or result in outbreeding depression and is why it has been considered a threat to native salmonid population and species viability (Behnke 1992; Hedrick 2000). Thus, only genetically pure populations are often considered to be part of a species for conservation purposes (Allendorf et al. 2004). Apache Trout recovery plans have also stated that only genetically-pure populations can count towards recovery goals and objectives (USFWS 1979; USFWS 1983; USFWS 2009). Apache Trout populations were classified using the results of the most recent genetic testing for the presence of nonnative trout alleles (Rainbow Trout and Cutthroat Trout) when available (Carmichael et al. 1993; Carlson and Culver 2009; Weathers and Mussmann 2020). Genetic material (e.g., fin clips) is often collected during population monitoring, or it is collected during surveys targeting fish for genetic testing if there is evidence that protective barriers are compromised or other evidence suggest that hybridizing species (Rainbow Trout and Cutthroat Trout) or hybrid individuals may be present (e.g., from visual assessment). In the absence of genetic testing, the presence of hybridizing species, presence of hybrid phenotypes or professional judgement based on putative barrier effectiveness were used to classify populations as being genetically pure or hybridized.

Adult Population Size (N) – Definition: The estimated number of adult Apache Trout (≥130-mm TL) in a population in the most recent year of population monitoring (Continuous: 0 to ∞). Population size is the estimated number of individuals in a defined population, and the number of adults reflects the potential breeding population, although not all adults may breed each year. Apache Trout reach maturity by ages 2 or 3 (Harper 1976; Harper 1978). The smallest mature female observed with eggs in Big Bonito Creek and East Fork White River was 130-mm TL, and the smallest male visibly spilling milt was 145-mm TL (Harper 1976; Harper 1978). Estimates of streamwide adult abundance were made from monitoring data collected under the Basinwide Visual Estimation Technique (BVET; Dolloff et al. 1993) protocol before 2016, based on a systematic sampling design from 2016 to present (Dauwalter et al. 2017a), and in a few cases from information collected during General Aquatic Wildlife surveys (e.g., Robinson et al. 2004) or electrofishing data (catch per 1 electrofishing pass) when collecting tissues for genetic analysis (e.g., Carlson and Culver 2009).

Recruitment Variability – Definition: Number of size classes present (Integer: 0 to 5). Length frequency data from population monitoring surveys were used to determine the number of size classes present as a proxy for the number of age classes. The presence of individuals in more size (and age) classes is indicative of more stable recruitment from year to year, which indicates that populations are more able to withstand year-to-year environmental variability (stochasticity; Maceina and Pereira 2007). The size classes were based on mean length at age data from the East Fork White River (Quist et al., in press), and were: <56-mm TL (Age-0), 56–105-mm TL (Age-1), 105–133-mm TL (Age-2), 133–155 (Age-3), and >155-mm TL (Age-4 and older). Length frequency data from monitoring surveys were used to determine the number of size classes present. These data were collected under the Basinwide Visual Estimation Technique (BVET; Dolloff et al. 1993) protocol before 2016 or based on a systematic sampling design from 2016 to present (Dauwalter et al. 2017a), and in a few cases from information collected during General Aquatic Wildlife surveys (e.g., Robinson et al. 2004) or electrofishing data when collecting tissues for genetic analysis (e.g., Carlson and Culver 2009).

Habitat Factors

Stream Length Occupied (km) – Definition: The occupied habitat extent (km) is the length of stream accessible to and occupied by a population (Continuous: 0 to ∞). The extent of stream habitat occupied by a population, often referred to as patch size, was measured in kilometers using National Hydrography Dataset (1:24,000 scale), and upstream and downstream extents were typically defined by experts as the extent of occupancy from fish survey data, suitable habitat, or barriers to fish passage (protective barriers). Extent of occupied habitat has been shown to be positively associated with the probability of population persistence (e.g., viability, extinction probability) for western native trout (Harig et al. 2000; Hilderbrand and Kershner 2000), and it has been used as an indicator of persistence in indices of population health and as an indicator of translocation success (Harig and Fausch 2002; Williams et al. 2007; Cook et al. 2010). Hilderbrand and Kershner (2000) estimated that at least 8-km were needed to support Colorado River Cutthroat Trout populations with an N_e of 500 or greater. Yellowstone Cutthroat Trout *O. c. bouvieri* occupying habitats longer than 6.5-km have been considered resilient (Al-Chokhachy et al. 2018). Larger habitats typically have more space to facilitate larger population sizes. They are also more likely to have all of the critical resources (e.g., food, space, habitat) needed for trout to meet all of their life history requirements and, thus, persist (Hilderbrand and Kershner 2000); larger interconnected habitats are also more likely to facilitate persistence during stochastic disturbances such as drought and wildfire (Dunham et al. 1997). However, some native trout populations have persisted for long periods of time in very small habitats, including Apache Trout populations above natural waterfalls that restricted the invasion of nonnative trout (USFWS 1983). Hilderbrand and Kershner (2000) did note that despite their results mentioned above, insufficient space to maintain 2,500 individuals (and N_e >500) does not mean that populations will not persist, as there are many examples of trout populations above waterfalls or in terminal streams in desert basins that have persisted for centuries and may have adapted to restricted space. Thus, stream length is an indicator of the likelihood of long-term viability (and resiliency) and not an absolute determinant of viability.

July Temperature (°C) – Definition: The maximum average July temperature predicted within the occupied habitat extent of a population (Continuous: 0 to ∞). The maximum July temperature is the warmest 1-km patch within habitat occupied by each population. Apache Trout, like other salmonids, is a cold-water stenotherm (a species that can survive only within a narrow range of temperature). The Life History section above highlights the thermal tolerance and habitat suitability values derived from several laboratory and field studies of Apache Trout (e.g., Table 4), and Appendix C explains an empirical modeling approach used to describe the average July thermal niche of Apache Trout using field data (see also Figure 16). The maximum mean July temperature in habitat extent occupied by each Apache Trout population is based on modeled average July temperatures predicted for each 1-km stream segment in Arizona from the NorWeST dataset (Isaak et al. 2017a). The NorWeST dataset predicts mean August temperatures (average of mean daily temperatures for the month of August) for each 1-km stream segment in the National Hydrography Dataset (1:100,000 scale). These predictions were adjusted based on an empirical relationship between mean August and mean July (monthly mean of mean daily temperatures) temperatures in Apache Trout streams from data collected by the ASNF. These *in situ* data were collected from 2012 to 2018 whereby thermographs were placed on Apache Trout streams on the ASNF and represent 49 site-years (number of sites × number of years) of data (Figure 6). These data show Apache Trout streams to typically be warmest in July before monsoon rains begin (mid-summer). There is a strong relationship between mean August and mean July temperatures in these streams that was used to predict mean July temperatures from the mean August temperature predictions available in the NorWeST dataset (mean July °C = 2.84 + 0.84[mean August °C]; $R^2 = 0.76$; Figure 6).

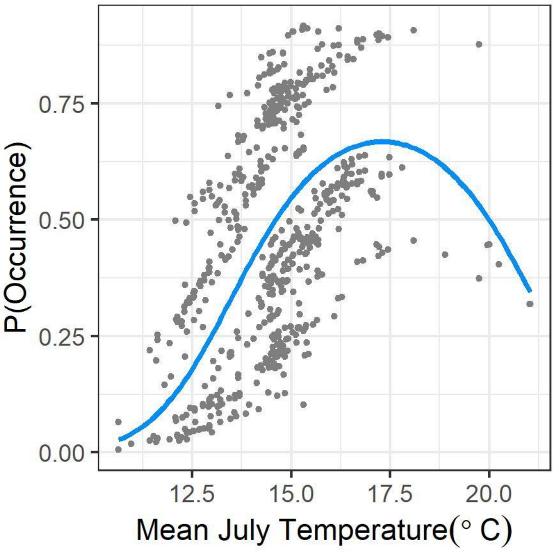

Figure 16. The probability of Apache Trout being present during electrofishing surveys as a function of mean July temperature as predicted from a NorWeST model. See Appendix C.

Intermittency (%) - Definition: The percent of occupied habitat extent estimated to become intermittent during severe drought years (Continuous: 0 to 100%). The percent of stream length occupied (see above) that becomes intermittent (dry) during severe drought years due to low natural flows, decreasing flow trends in recent years, anthropogenic impacts to flow, or other factors. The percentage was based on professional judgement and knowledge of the habitat. The southwest U.S. is a naturally warm and dry environment with reduced surface water resources that may subside due to low annual precipitation (snowpack and rainfall) and interactions with local geology (Long et al. 2006). The region is thought to be entering a megadrought that has large consequences for streamflows (Williams et al. 2020), and other researchers highlighted 2000–2003 as a severe drought period (Hoerling and Eischeid 2007). As an example of stream intermittency, Flash Creek (FAIR) was observed to have a 375-m section that was intermittent in 1995 through 1997 during low flow periods (e.g., summer; Kitcheyan 1999). Surveys of other streams (Conklin, Corduroy, and Double Cienega creeks) also showed certain sections to be dry during 2002–2003, which were severe drought years (Robinson et al. 2004; Hoerling and Eischeid 2007).

Habitat Quality (rank) – Definition: The condition of riparian and instream habitat quality throughout the occupied habitat extent (integer: 1 to 5). Stream habitat quality was classified based on professional judgement at the whole stream scale or by segment and then computed as a weighted average (weighted by length). Habitat quality was classified as follows: very poor =1, poor=2, fair=3, good=4, and very good=5. Habitat quality for Apache Trout has been measured and described in numerous ways. It has been described based on natural stream potential (flows, temperature, physical habitat; Clarkson and Wilson 1995; Cantrell et al. 2005; Long and Medina 2006) and impacts from stochastic events such as wildfire (Price 2013; Dauwalter et al. 2017b), but it also reflects anthropogenic factors such as improper livestock grazing, roads, and other uses within that natural potential (Clarkson and Wilson 1995; Long et al. 2006; ASNF 2015). Experts classified and ranked the predominant current habitat conditions within the occupied habitat extent of each Apache Trout stream using the following descriptive guidance:

1. **Very poor condition**: Heavy impacts from road crossings, developed floodplains, logging, or animal use. Heavy utilization of herbaceous vegetation and little to no woody riparian vegetation. No riparian canopy cover. Numerous eroding streambanks. No large wood. Poorly defined riffle-pool structure in meadow reaches / no habitat complexity. Excessive sedimentation. Heavily incised.
2. **Poor condition**: Moderate impacts from road crossings, developed floodplains, logging, or animal use; heavy in some areas. Herbaceous riparian vegetation heavily utilized in some areas. Woody riparian vegetation present, but some areas absent or with lack of plant recruitment. Canopy moderately closed in only a few areas. Eroding streambanks not uncommon. Fine sediments frequent. Large wood infrequent. Complex habitat found in few areas. Moderate to heavy channel incision.
3. **Fair condition**: Light to moderate impacts from road crossings, logging, or animal use. Herbaceous vegetation heavily utilized in some areas. Woody riparian vegetation present, but some areas without or with lack of recruitment. Riparian canopy moderately closed in some areas, open in others. Eroding streambanks not uncommon. Occasional areas of fine sediments. Occasional large wood. Complex habitat found in some areas. Moderate channel incision.
4. **Good condition**: Light impacts from road crossings, logging, or animal use. Herbaceous vegetation lightly used; moderate use in some areas. Woody riparian vegetation present, but with some evidence of use. Riparian canopy moderately to fully closed; open in some areas. Eroding streambanks infrequent. Occasional areas of fine sediments. Occasional to frequent large wood. Complex habitat found in some areas. Light channel incision if present.
5. **Very good condition**: Near pristine condition. Tall herbaceous and abundant woody riparian vegetation. Riparian canopy moderately to fully closed. Vegetated and undercut banks. Large wood present. Well defined riffle-pool structure in meadows / high habitat complexity. No channel incision.

Nonnative Trout Presence – Definition: The presence of Rainbow Trout, Brown Trout, Brook Trout, or Cutthroat Trout within the habitat accessible to the Apache Trout population (or defined habitat extent; Class: Confirmed; Suspected; None). Rainbow Trout and Cutthroat Trout have been documented to hybridize with Apache Trout (Carmichael et al. 1993), and Brown Trout and Brook Trout compete with and prey upon Apache Trout, thus reducing the carrying capacity of habitat to support Apache Trout (Carmichael et al. 1995). Presence of each species is attributed based on survey data, angler reports, anecdotal information, and, in some cases, barrier effectiveness and proximity of nonnative species and likelihood of invasion upstream of ineffective barriers.

Barrier Effectiveness – Definition: Presence and functionality of one or more natural or artificial barriers used to intentionally isolate, and therefore protect, Apache Trout habitat from nonnative trout downstream (Class: Functional; Functional–Suspected; Nonfunctional; None). Presence of barriers is based on knowledge of natural features (e.g., waterfalls) or unintentionally (e.g., dams, culverts) or intentionally (e.g., gabion barriers) constructed fish passage barriers used to protect Apache Trout populations from nonnative trout downstream (Avenetti et al. 2006). Thus, despite the fact that barriers restrict space, failure to isolate populations may lead to extinction from hybridization, competition, and predation such that barriers are viewed as a temporary solution to jeopardized populations (Hilderbrand and Kershner 2000). Barrier function was classified as functional or nonfunctional, and functionality was classified as known or suspected. Functionality was classified based on documented presence of nonnative trout above a barrier, documented movement of marked fish from below to above a barrier, known streamflow paths around or through barriers, poor structural integrity, or other factors influencing perceived functionality based on professional judgement. On some streams, more than one barrier has been constructed to provide functional redundancy and security due to possible failure, as well as to allow management flexibility for controlling nonnative trout invasions or conducting nonnative trout removals (mechanical or chemical).

Population Resiliency

Demographic and habitat factor data showed relict and hybridized Apache Trout populations to occur in two major river basins (Black and White), replicate populations occur in all major basins, and unoccupied recovery streams occur in the Little Colorado and Black River basins (Figure 17A). Relict populations occur in 5 of 6 subbasins to which they are native, and also the Colorado River subbasin which contains a replicate refuge population (North Canyon); hybridized populations occur in the Black and Diamond subbasins (Figure 17B). Thirty of 38 extant populations were genetically pure (81.1%), and only 1 of those has not been confirmed by genetic testing (Figure 17C); 1 of 6 (18.9%) populations have been confirmed as hybridized through genetic testing, whereas 5 have been assumed to be hybridized because of known barrier failure and invasion of Rainbow Trout (Figure 17C).

The 17 relict and 13 replicate populations comprise 16 relict population lineages (Figure 17D); the Big Bonito lineage is represented twice in the upper and lower Big Bonito populations (isolated by a natural waterfall). Two lineages represent populations that have had past evidence of hybridization, but recent testing has shown them to be genetically pure (Rock and Little Diamond). Two populations represent mixed lineages as they were founded with fish from multiple relict populations (Sun and Moon); Sun and Moon also were hybridized in the past but have since tested genetically pure (Table 11).

A summary of demographic factors showed a majority of Apache Trout populations to have adult (≥130-mm TL) populations sizes that are less than 500 individuals; one population, East Fork White River, was estimated to have over 2,000 adults (Figure 17B; Table 11). Despite low abundances, most populations showed consistent recruitment, with 4 or 5 size classes (and presumably year classes) present, which suggests they are stable and self-sustaining populations (Figure 17C; Table 11).

Habitat factors for Apache Trout populations showed a wide range of current conditions (Table 12). The extent of stream occupied by Apache Trout populations ranged from 0.4 to 30.1 km; most were less than 14 km (Figure 18D). Maximum mean July temperatures in occupied habitat were 15.5°C or less for relict and replicate populations, whereas unoccupied streams and hybrid populations had warmer maximum mean July temperatures up to 17.5°C (Figure 18E). Most populations or unoccupied streams exhibited little intermittency during severe drought, but two hybridized populations and one unoccupied stream were estimated to be over 50% intermittent (up to 95%; Figure 18F). Unoccupied streams and streams occupied by hybrid populations had the lowest habitat quality (in part due to 2011 Wallow Fire), whereas a majority of relict and replicate populations inhabited high quality habitat (Figure 18G). Nineteen Apache Trout populations were sympatric with Brown Trout, seven with Rainbow Trout, and two with Brook Trout (Figure 18H; Table 12). Thirty-six populations or unoccupied recovery streams currently have protective barriers to isolate them from nonnative fishes downstream, but only 31 populations are protected by barriers (35) known or suspected to be functional (Figure 19A); 10 populations had a second barrier downstream for added protection across all population types (relict, replicate, hybrid, unoccupied; Figure 19B; Table 12).

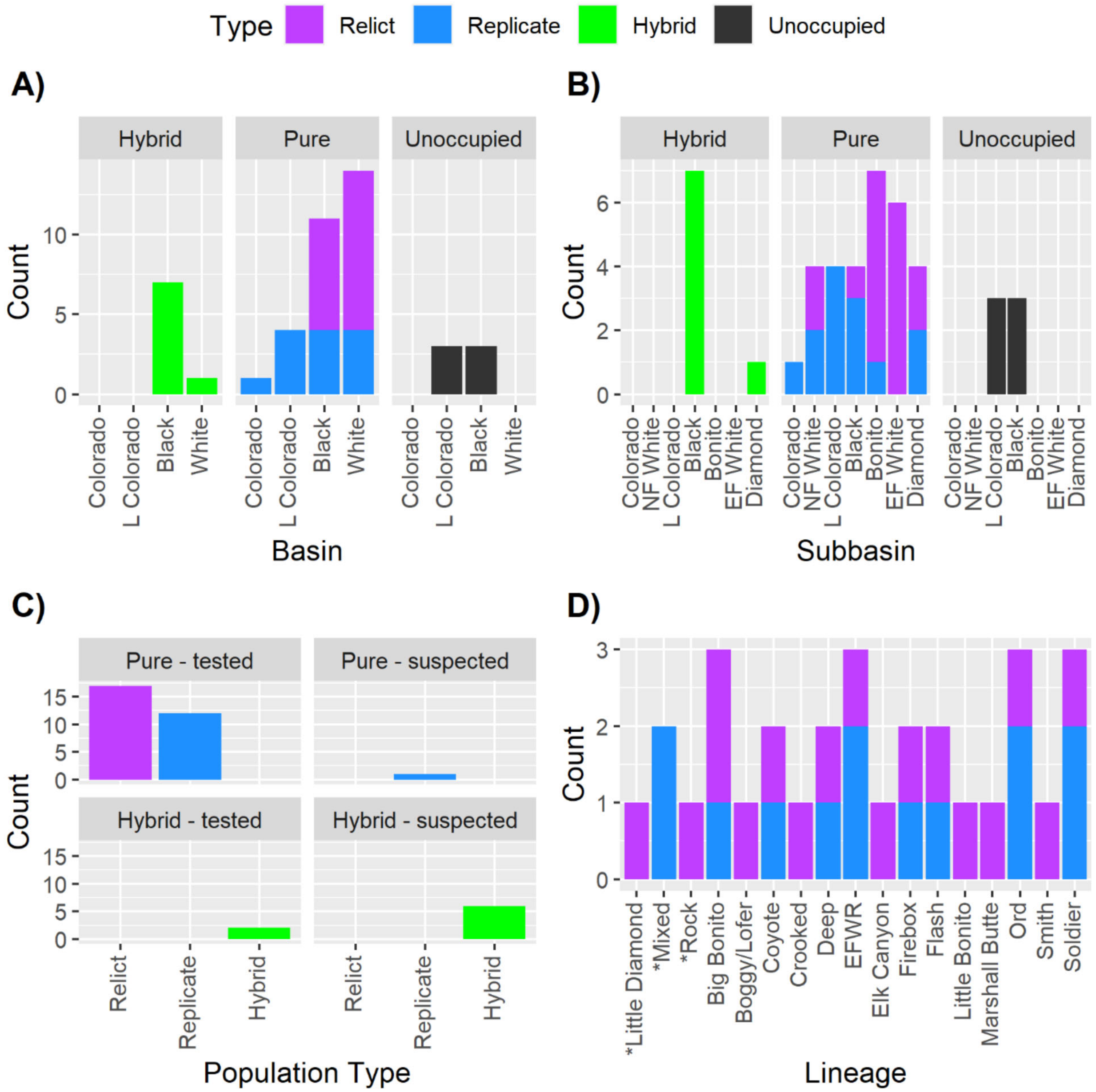

*Figure 17. Frequency of Apache Trout streams rangewide by A) basin and genetic purity, B) subbasin and genetic purity, C) rangewide and genetic purity, and D) population lineage (genetically pure populations only) by population type (Relict, Replicate, Hybrid or Unoccupied). *indicates currently genetically pure lineages with past evidence of introgression.*

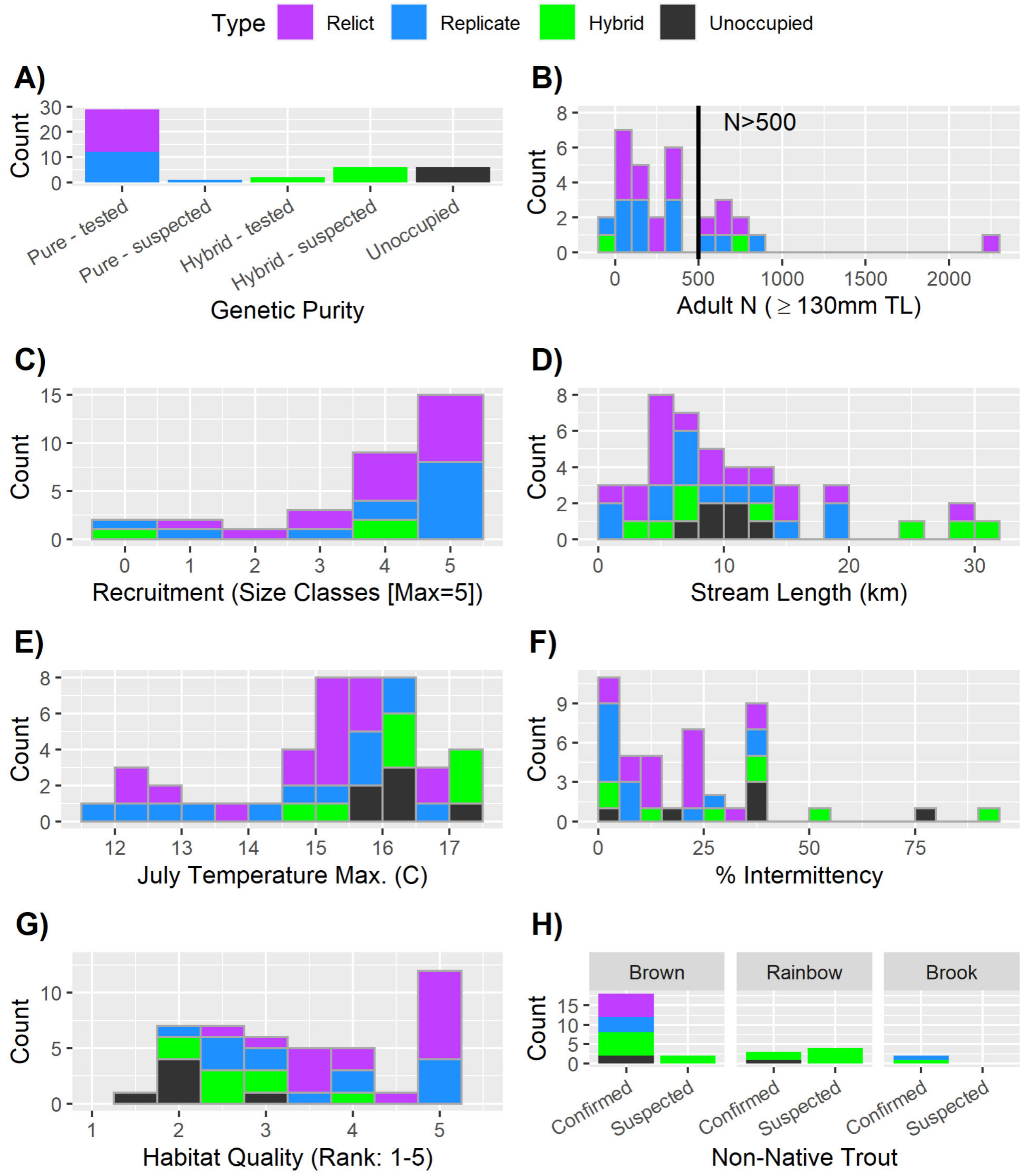

Figure 18. Frequency of Apache Trout populations, by type (Relict, Replicate, Natural, Unoccupied), for demographic factors A) genetic purity, B) adult abundance (N ≥130-mm TL), and C) recruitment variability (number of size classes), and habitat factors D) stream length occupied (patch size; km), E) maximum July temperature (°C), F) percent intermittency during severe drought, G) habitat quality (rank: 1=low, 5=high), and H) the confirmed or suspected presence of nonnative trout.

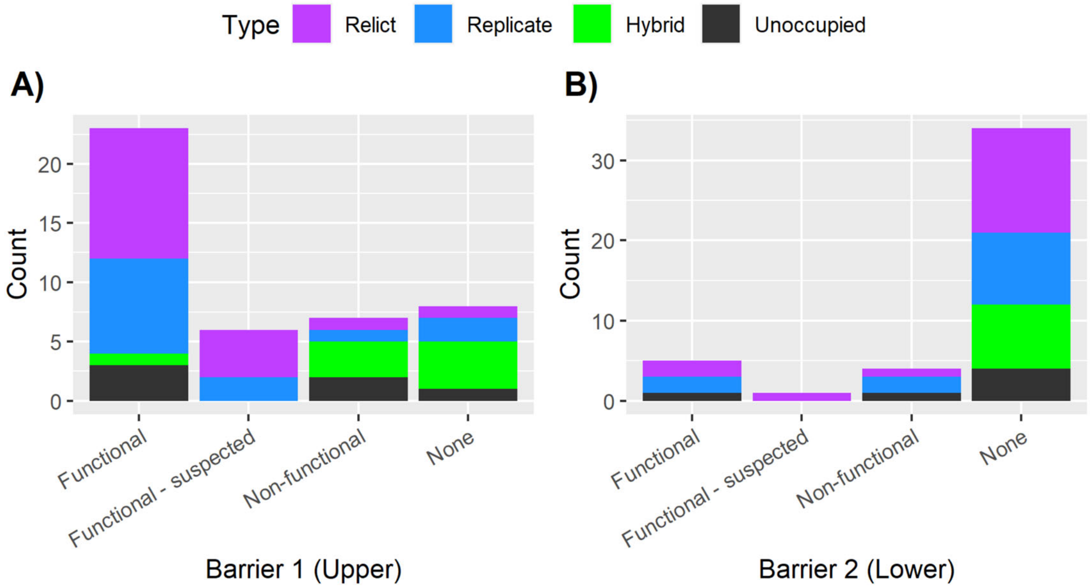

Figure 19. Frequency of Apache Trout populations by A) upstream barrier function, and B) downstream barrier function (if present) by population type (Relict, Replicate, Hybrid, Unoccupied).

Population Resiliency: A Grading Scale

A 4.0 grading scale was used to evaluate Apache Trout population resiliency for each individual factor, the demographic factors combined, the habitat factors combined, and both demographic and habitat factors combined (overall resiliency). The values or categories of each factor for each Apache Trout population were assigned a condition class (Very Poor, Poor, Fair, Good, Very Good) that was informed by expert elicitation via the Delphi method (see Appendix A), and the condition classes were used to assign grades and grade point equivalents on a 4.0 scale. Experts participating in the Delphi method represented the following agencies: White Mountain Apache Tribe, Arizona Game and Fish Department, USFWS (Ecological Services and the Arizona Fish and Wildlife Conservation Office), U.S. Forest Service, and a non-governmental organization (Trout Unlimited).

The Grading Scale

The resiliency of Apache Trout populations (and habitats) was assessed using a 4.0 grading scale and grade-point-average framework. Using this framework, each Apache Trout population received a grade and grade point equivalents based on the current condition of the three demographic and six habitat factors (Table 13). The condition of each factor was graded based on the results of expert elicitation from Survey #2 of the Delphi method described above (see Appendix A). A grade point average (GPA) was then used to assess the overall demographic and habitat condition of each population; the overall demographic GPA was based on the average of the three demographic factor grade-point-equivalents, and the overall habitat GPA was based on the average of the six habitat factor grade-point-equivalents. The overall current condition (GPA) for each population was based on the average GPAs for overall demographic and habitat factors (a mean of the means); the overall GPA for unoccupied streams was set to zero for demographic factors because there is no Apache Trout population occupying that stream, and thus it was set to zero overall as well. Populations with no abundance or recruitment data from recent and relevant fish surveys received a demographic score based solely on Genetic Purity (Table 14).

Table 11. Hydrographic basin, subbasin, population/stream, type, and lineage of Apache Trout population, and the current condition of demographic factors of Genetic Purity, Adult Abundance (N; ≥130-mm TL with 80% confidence interval), Recruitment Variability (number of size classes [max=5]), and year and type of recent survey for each Apache Trout recovery population and stream.

Basin	Subbasin	Population/stream	Type	Lineage	Genetic Purity	Adult N (±80CI)	Recruitment (# size classes)	Year (survey type)
Colorado	Colorado	North Canyon	Replicate	Ord	Pure–tested	320 (NA)	3	2019^{e}
L Colorado	L Colorado	Coyote/Mamie	Unoccupied	Unoccupied	Unoccupied	not applicable	not applicable	not applicable
L Colorado	L Colorado	EF Little Colo. (lower)	Unoccupied	Unoccupied	Unoccupied	not applicable	not applicable	not applicable
L Colorado	L Colorado	EF Little Colo. (upper)	Replicate	Soldier	Pure–tested	162 (78–245)	5	2020^{a}
L Colorado	L Colorado	Rudd	Unoccupied	Unoccupied	Unoccupied	not applicable	not applicable	not applicable
L Colorado	L Colorado	SF Little Colorado	Replicate	Big Bonito	Pure–suspected	527 (320–734)	5	2021^{a}
L Colorado	L Colorado	WF Little Colorado	Replicate	EFWR	Pure–tested	338 (220–455)	4	2018^{a}
L Colorado	L Colorado	Mineral	Replicate	Ord	Pure–tested	6 (1–13)	1	2017^{a}
Black	Black	Paddy	Hybrid	Paddy	Hybrid–tested	not applicable	4	2020^{d}
Black	Black	Bear Wallow	Replicate	Soldier	Pure–tested	384 (93–676)	5	2020^{d}
Black	Black	Centerfire	Hybrid	Unknown	Hybrid–suspected	not applicable	not applicable	not applicable
Black	Black	Conklin	Unoccupied	Unoccupied	Unoccupied	not applicable	not applicable	not applicable
Black	Black	Fish	Hybrid	EFWR	Hybrid–suspected	798 (119–1,476)	4	2018^{e}
Black	Black	Hannagan	Unoccupied	Unoccupied	Unoccupied	not applicable	not applicable	not applicable
Black	Black	Hayground	Hybrid	Ord	Hybrid–suspected	not applicable	not applicable	not applicable
Black	Black	Home	Unoccupied	Unoccupied	Unoccupied	not applicable	not applicable	not applicable
Black	Black	Snake	Hybrid	Unknown	Hybrid–suspected	not applicable	not applicable	not applicable
Black	Black	Soldier	Relict	Soldier	Pure–tested	504 (374–634)	5	2021^{a}
Black	Black	Stinky	Hybrid	EFWR	Hybrid–suspected	not applicable	not applicable	not applicable
Black	Black	Thompson (upper)	Replicate	Firebox	Pure–tested	0 (0–0)	0	2019^{a}
Black	Black	WFBR (lower)	Hybrid	EFWR	Hybrid–suspected	not applicable	not applicable	not applicable
Black	Black	WFBR (upper)	Replicate	EFWR	Pure–tested	635 (416–853)	2	2005^{c}
Black	Bonito	Big Bonito (lower)	Relict	Big Bonito	Pure–tested	not applicable	not applicable	not applicable
Black	Bonito	Big Bonito (upper)	Relict	Big Bonito	Pure–tested	624 (473–775)	5	2017^{a}
Black	Bonito	Boggy/Lofer	Relict	Boggy/Lofer	Pure–tested	323 (244–402)	5	2013^{b}
Black	Bonito	Crooked	Relict	Crooked	Pure–tested	301 (178–424)	5	2016^{a}
Black	Bonito	Flash	Relict	Flash	Pure–tested	177 (119–236)	4	2019^{a}
Black	Bonito	Little Bonito	Relict	Little Bonito	Pure–tested	369 (267–471)	5	2019^{a}
Black	Bonito	Squaw	Replicate	Flash	Pure–tested	848 (676–1,020)	5	2019^{a}
White	Diamond	Coon	Hybrid	Coon	Hybrid–tested	0 (0–0)	0	2007^{d}
White	Diamond	Coyote	Relict	Coyote	Pure–tested	26 (2–64)	2	2018^{a}
White	Diamond	Little Diamond	Relict	L. Diamond	Pure–tested	238 (NA)	4	2007^{d}

White	Diamond	Moon	Replicate	Mixed	Pure–tested	168 (NA)	5	2007[d]
White	Diamond	Sun	Replicate	Mixed	Pure–tested	162 (NA)	5	2007[d]
White	EF White	Deep	Relict	Deep	Pure–tested	665 (561–769)	4	2021[a]
White	EF White	EFWR	Relict	EFWR	Pure–tested	2,270 (2,042–2,498)	5	2021[a]
White	EF White	Elk Canyon	Relict	Elk Canyon	Pure–tested	30 (12–48)	4	2018[a]
White	EF White	Firebox	Relict	Firebox	Pure–tested	16 (1–39)	1	2018[a]
White	EF White	Marshall Butte (DP)	Relict	Marshall Butte	Pure–tested	113 (16–229)	4	2017[a]
White	EF White	Rock	Relict	Rock	Pure–tested	253 (42–464)	3	2007[d]
White	NF White	Ord	Relict	Ord	Pure–tested	707 (533–880)	5	2019[a]
White	NF White	Paradise	Replicate	Deep	Pure–tested	11 (3–21)	5	2018[a]
White	NF White	Smith	Relict	Smith	Pure–tested	3 (3–3)	3	2018[a]
White	NF White	Wohlenberg	Replicate	Coyote	Pure–tested	88 (67–109)	4	2013[b]

[a] 2017 Plan survey; [b] BVET survey; [c] GAWS survey; [d] Genetics survey; [e] Other

Table 12. Current condition habitat factors for each Apache Trout population: number of stream network branches (tributaries), stream length occupied (km), intermittency (%) during drought, maximum July temperature (C), habitat quality (rank: 1–5), the suspected or confirmed presence of Brown Trout, Rainbow Trout, and Brook Trout, and the status of protective barriers. Susp = suspected.

Population/stream	Stream km	Intermittency (%)	Max July (°C)	Habitat Quality (Rank)	Brown	Rainbow	Brook	Barrier (upper)	Barrier (lower)
North Canyon	0.9	0	14.3	5	None	None	None	Functional	None
Coyote/Mamie	13.4	38	15.8	2	None	None	None	Functional	None
EF Little Colo. (lower)	6.9	0	16.3	3	Confirmed	Confirmed	None	Nonfunctional	Nonfunctional
EF Little Colo. (upper)	9.7	0	16.3	3	None	None	None	Functional	None
Rudd	11.6	19	17.2	1.5	None	None	None	Functional	None
SF Little Colorado	10.6	0	16.5	2.5	None	None	None	Functional–susp	Functional
WF Little Colorado	14.3	0	13.3	4	Confirmed	None	None	Functional–susp	Nonfunctional
Mineral	4.7	0	15.6	2	None	None	None	Functional	None
Paddy	12.5	0	17.3	4	Confirmed	Confirmed	None	None	None
Bear Wallow	18.6	1	17	3	None	None	None	Nonfunctional	Functional
Centerfire	29.5	95	17.5	2	Confirmed	Suspected	None	Nonfunctional	None
Conklin	8.2	36	15.9	2	None	None	None	Functional	None
Fish	30.1	29	16.4	2.5	Confirmed	Confirmed	None	None	None
Hannagan	9.1	38	16.5	2	Confirmed	None	None	None	None
Hayground	7.5	0	16.3	2	Confirmed	Suspected	None	Nonfunctional	None
Home	11.4	76	16.5	2	None	None	None	Nonfunctional	Functional
Snake	6.2	55	16.3	2.5	Confirmed	None	None	None	None
Soldier	2.7	0	15.9	3	None	None	None	Functional	None
Stinky	5.6	39	14.7	3	Suspected	Suspected	None	Nonfunctional	None
Thompson (upper)	1.9	10	11.6	5	None	None	None	Functional	None
WF Black (lower)	25.7	13	17.5	3	Confirmed	Suspected	Confirmed	Functional	None
WF Black (upper)	18.6	25	15.9	3.5	None	None	Confirmed	Functional	Nonfunctional
Big Bonito (lower)	29.4	15	15.8	5	Confirmed	None	None	Nonfunctional	None
Big Bonito (upper)	3.4	15	12.3	4.5	None	None	None	Functional	None
Boggy/Lofer	19.7	25	15.5	4	None	None	None	Functional	None
Crooked	7.8	25	15.2	4	None	None	None	Functional	Functional
Flash	10.4	35	14.8	5	None	None	None	Functional	Functional
Little Bonito	14.8	25	15.5	5	Confirmed	None	None	Functional	Nonfunctional
Squaw	13.7	28	15.3	5	Confirmed	None	None	Functional	None

Coon	3.6	40	15.2	2.5	Suspected	None	None	None	None
Coyote	5.1	10	15.4	3.5	Confirmed	None	None	Functional–susp	None
Little Diamond	9.6	40	15.3	2.5	Confirmed	None	None	Functional–susp	None
Moon	7.7	40	14.9	2.5	Confirmed	None	None	None	None
Sun	7.8	40	15.9	2.5	Confirmed	None	None	None	None
Deep	14.6	15	16.6	5	None	None	None	Functional	None
EF White	8.2	15	13.8	5	None	None	None	Functional	None
Elk Canyon	5.4	25	14.6	5	None	None	None	Functional	None
Firebox	5.4	25	15.6	3.5	None	None	None	None	None
Marshall Butte (DP)	5.5	25	15.3	5	None	None	None	Functional	None
Rock	13.2	40	16.9	3.5	Confirmed	None	None	Functional–susp	None
Ord	5.6	10	12.7	5	None	None	None	Functional	None
Paradise	6.5	10	12.9	4	None	None	None	Functional	None
Smith	0.7	0	12.1	3.5	Confirmed	None	None	Functional–susp	Functional–susp
Wohlenberg	5.1	10	12.2	5	None	None	None	Functional	None

Table 13. Relationship between condition class, grade, grade points equivalents, GPA, and final grade describing the current condition of Apache Trout populations using demographic and habitat factors.

Condition	Grade	Grade Point Equivalents	Grade Point Average	Final Grade
Very Good	A	4.0	3.84–4.00	A
Very Good	A	4.0	3.50–3.83	A-
Very Good	A	4.0	3.17–3.49	B+
Good	B	3.0	2.84–3.16	B
Good	B	3.0	2.50–2.83	B-
Good	B	3.0	2.17–2.49	C+
Fair	C	2.0	1.84–2.16	C
Fair	C	2.0	1.50–1.83	C-
Fair	C	2.0	1.17–1.49	D+
Poor	D	1.0	0.84–1.16	D
Poor	D	1.0	0.50–0.83	D-
Very Poor	F	0.0	0.00–0.49	F

The Report Card

The average demographic GPA across all 38 Apache Trout populations was 2.53 (B- average). This average GPA omits 6 streams that are unoccupied (GPA is 0.00 by default for these populations and streams; Table 15; Figure 20D). One population (Coon Creek) tested as hybridized but without other demographic information had a GPA = 0.0 (Figure 20D). Relict Apache Trout populations tended to have high GPAs for demographic factors (average GPA = 2.98), as did replicate populations (average GPA = 2.82). Hybridized populations had low demographic GPAs (average GPA = 1.10), but there was variation among population types (Figure 20D). Hybridized Apache Trout populations (suspected and tested) graded low for genetic purity as expected (Figure 20A), whereas relict populations graded well for recruitment by having more year classes, which indicated stable year-to-year recruitment (Figure 20C).

Apache Trout populations and unoccupied streams had an average GPA of 2.62 (B- average) for the habitat factors. Most populations graded well for maximum mean July temperatures, having protective barriers, and having no nonnative trout present, but populations showed a wide range of grades for stream length occupied (patch size), percent intermittency during severe drought, and habitat quality (Table 15; Figure 21). Relict and replicate populations (average GPA = 2.87) tended to grade higher for overall habitat conditions than hybridized populations (average GPA = 1.85), but there was still a wide range of habitat conditions, and thus grades, across population types (Figure 21G).

Overall, the average GPA for all Apache Trout populations across demographic and habitat factors, excluding unoccupied streams, was 2.60 (B- average; Table 15; Figure 22). The average GPA for the 30 genetically pure Apache Trout populations that would count towards recovery (USFWS 2009) is 2.91 for demographic factors (B average), 2.87 for habitat factors (B average), and 2.89 overall (B average). Demographic GPAs for genetically pure populations were highest, on average, for the Bonito Creek and Black River subbasins, habitat GPAs for genetically pure populations were highest for the Black River, Bonito Creek, Colorado River, and Little Colorado River subbasins, and overall GPAs for genetically pure populations were highest for the Bonito Creek subbasin (Table 16).

Table 14. Apache Trout demographic and habitat factor classifications and grade point equivalents.

Group	Factor	Value	Class	Grade Point Equivalents
Demographic	Genetics	Unoccupied	Very Poor	0
	Genetics	Hybrid–tested	Very Poor	0
	Genetics	Hybrid–suspected	Poor	1
	Genetics	Pure–suspected	Good	3
	Genetics	Pure–tested	Very Good	4
	Adult Abundance	<85	Very Poor	0
	Adult Abundance	85–229	Poor	1
	Adult Abundance	230–434	Fair	2
	Adult Abundance	435–894	Good	3
	Adult Abundance	>894	Very Good	4
	Recruitment Variability	0 and 1	Very Poor	0
	Recruitment Variability	2	Poor	1
	Recruitment Variability	3	Fair	2
	Recruitment Variability	4	Good	3
	Recruitment Variability	5	Very Good	4
Habitat	Stream Length Occupied	<3.35	Very Poor	0
	Stream Length Occupied	3.35–6.54	Poor	1
	Stream Length Occupied	6.55–11.24	Fair	2
	Stream Length Occupied	11.25–17.5	Good	3
	Stream Length Occupied	>17.5	Very Good	4
	Intermittency	>49.2	Very Poor	0
	Intermittency	31.5–49.2	Poor	1
	Intermittency	18.2–31.4	Fair	2
	Intermittency	7.7–18.1	Good	3
	Intermittency	<7.7	Very Good	4
	Max July Temperature	>19.9	Very Poor	0
	Max July Temperature	19.0–19.9	Poor	1
	Max July Temperature	18.0–18.9	Fair	2
	Max July Temperature	17.0–17.9	Good	3
	Max July Temperature	<17.0	Very Good	4
	Habitat Quality	0.0–1.4	Very Poor	0
	Habitat Quality	1.5–2.4	Poor	1
	Habitat Quality	2.5–3.4	Fair	2
	Habitat Quality	3.5–4.4	Good	3
	Habitat Quality	4.5–5.0	Very Good	4
	Nonnative Trout	Rainbow + Brook + Brown	Very Poor	0
	Nonnative Trout	Rainbow + Brook	Very Poor	0
	Nonnative Trout	Rainbow Trout	Very Poor	0
	Nonnative Trout	Rainbow + Brown	Very Poor	0
	Nonnative Trout	Brown Trout	Poor	1
	Nonnative Trout	Brook Trout	Fair	2
	Nonnative Trout	None	Very Good	4
	Barrier	2 Nonfunctional	Very Poor	0
	Barrier	1 Nonfunctional	Very Poor	0
	Barrier	None	Poor	1
	Barrier	1 Functional–suspected	Fair	2
	Barrier	2 Functional–suspected	Good	3
	Barrier	1 Functional	Good	3
	Barrier	1 Functional, 1 Funct.–susp.	Good	3
	Barrier	2 Functional	Very Good	4

Table 15. Grade point equivalents for the three demographic factors [genetics (GEN), adult abundance (N), and recruitment (REC)] and six habitat factors [habitat kilometers (HKM), percent intermittency (INT), maximum July temperature (MJT), habitat quality (HQ), nonnative trout (NNT), and barriers (BAR), grade-point-averages (GPA) for all demographic and habitat factors combined (third- and second-to-last columns), and overall GPA (last column) for Apache Trout populations and unoccupied recovery streams in east-central Arizona. Rows with NA (gray) for all three demographic factors are unoccupied streams. Subbasins (SUB) noted in far left column; Black River (BR), Bonito (Bo), Colorado (CO), Little Colorado (LC), Diamond (DIA), East Fork White River (EFWR), and North Fork White River (NFWR). Color gradient shows low grade point equivalents (dark orange) to high grade point equivalents (white). Grade point equivalents are: 0.0=F; 1.0=D; 2.0=C; 3.0=B; 4.0=A. See Table 13 for GPA translations to letter grades.

SUB	Stream	GEN	N	REC	HKM	INT	MJT	HQ	NNT	BAR	DGPA		HGPA	OGPA
BR	Bear Wallow	4	2	4	4	4	4	2	1	3	3.33		3.00	3.16
BR	Centerfire	1	NA	NA	4	0	3	1	0	0	1.00		1.33	1.17
BR	Conklin	NA	NA	NA	2	1	4	1	4	3	0.00		2.50	0.00
BR	Fish	1	3	3	4	2	4	2	0	1	2.33		2.17	2.25
BR	Hannagan	NA	NA	NA	2	1	4	1	1	1	0.00		1.67	0.00
BR	Hayground	1	NA	NA	2	4	4	1	0	0	1.00		1.83	1.42
BR	Home	NA	NA	NA	3	0	4	1	4	3	0.00		2.50	0.00
BR	Paddy	0	NA	3	3	4	4	3	0	1	1.50		2.50	2.00
BR	Snake	1	NA	NA	1	0	4	2	1	1	1.00		1.50	1.25
BR	Soldier	4	3	4	0	4	4	2	4	3	3.67		2.83	3.25
BR	Stinky	1	NA	NA	1	1	4	2	0	0	1.00		1.33	1.17
BR	Thompson-up	4	0	0	0	3	4	4	4	3	1.33		3.00	2.16
BR	WFBR-low	1	NA	NA	4	3	3	2	0	3	1.00		2.50	1.75
BR	WFBR-up	4	3	4	4	2	4	3	2	3	3.67		3.00	3.34
Bo	Big Bo-low	4	NA	NA	4	3	4	4	1	0	4.00		2.67	3.34
Bo	Big Bo-up	4	3	4	1	3	4	4	4	3	3.67		3.17	3.42
Bo	Boggy/Lofer	4	2	4	4	2	4	3	4	3	3.33		3.33	3.33
Bo	Crooked	4	2	4	2	2	4	3	4	4	3.33		3.17	3.25
Bo	Flash	4	1	3	2	1	4	4	4	4	2.67		3.17	2.92
Bo	Little Bo	4	2	4	3	2	4	4	1	3	3.33		2.83	3.08
Bo	Squaw	4	3	4	3	2	4	4	1	2	3.67		2.67	3.17
CO	North Canyon	4	2	2	0	4	4	4	4	3	2.67		3.17	2.92
LC	Coyote/Mamie	NA	NA	NA	3	1	4	1	4	3	0.00		2.67	0.00
LC	EFLC-low	NA	NA	NA	2	4	4	2	0	0	0.00		2.00	0.00
LC	EFLC-up	4	1	4	2	4	4	2	4	3	3.00		3.17	3.08
LC	Mineral	4	0	0	1	4	4	1	4	3	1.33		2.83	2.08
LC	Rudd	NA	NA	NA	3	2	4	1	4	3	0.00		2.83	0.00
LC	SFLC	3	3	4	2	4	4	2	4	3	3.33		3.17	3.25
LC	WFLC	4	2	3	3	4	4	3	0	3	3.00		2.83	2.92
DIA	Coon	0	0	0	1	1	4	2	1	1	0.00		1.67	0.84
DIA	Coyote	4	0	1	1	3	4	3	1	2	1.67		2.33	2.00
DIA	Little DIA	4	2	3	2	1	4	2	1	1	3.00		1.83	2.42
DIA	Moon	4	1	4	2	1	4	2	1	1	3.00		1.83	2.42
DIA	Sun	4	1	4	2	1	4	2	1	1	3.00		1.83	2.42
EFW	Deep	4	3	3	3	3	4	4	4	3	3.33		3.50	3.42
EFW	EF White	4	4	4	2	3	4	4	4	3	4.00		3.33	3.66
EFW	Elk Canyon	4	0	3	1	2	4	4	4	3	2.33		3.00	2.66

EFW	Firebox	4	0	0	1	2	4	3	4	1	1.33		2.50	1.92
EFW	Marshall Butte	4	1	3	1	2	4	4	4	3	2.67		3.00	2.84
EFW	Rock	4	2	2	3	1	4	3	1	2	2.67		2.33	2.50
NFW	Ord	4	3	4	1	3	4	4	4	3	3.67		3.17	3.42
NFW	Paradise	4	0	4	1	3	4	3	4	3	2.67		3.00	2.84
NFW	Smith	4	0	2	0	4	4	3	1	3	2.00		2.50	2.25
NFW	Wohlenberg	4	1	3	1	3	4	4	4	3	2.67		3.17	2.92

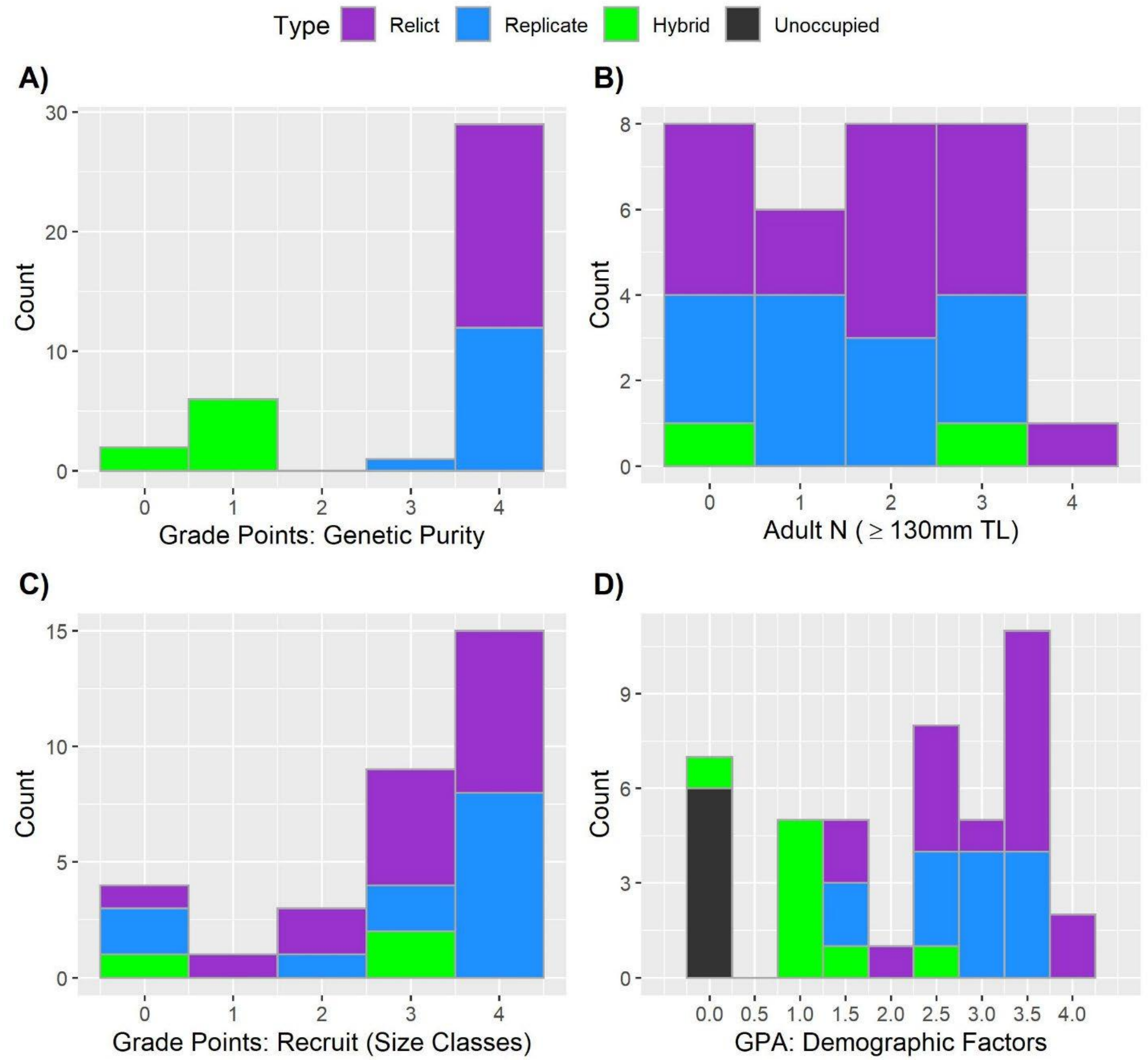

Figure 20. Grade frequency of Apache Trout populations, colored by type (Relict, Replicate, Hybridized, Unoccupied), for the demographic factors of A) genetic purity, B), adult abundance (≥130-mm TL), C) recruitment (number of size classes) that describe the current conditions of populations, and D) the composite grade point average (GPA) for all three demographic factors.

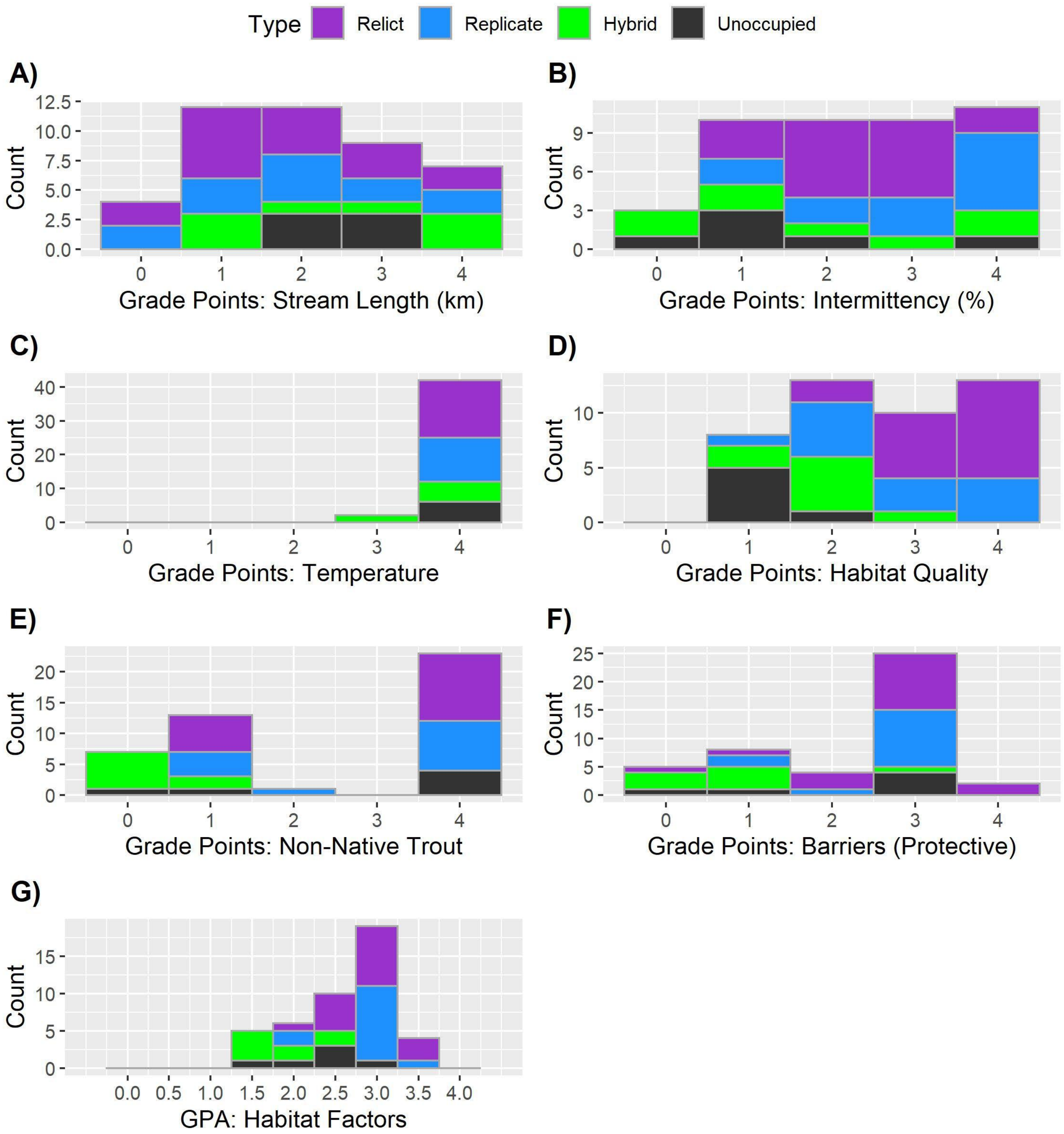

Figure 21. Grade point frequency of Apache Trout populations, colored by type, for the six habitat factors of A) stream length occupied, B) percent intermittency during severe drought, C) maximum July temperature, D) habitat quality, E) presence of nonnative trout, and F) protective barriers that describe the current conditions of populations and unoccupied habitats, as well as the composite grade point average (GPA) for all six habitat factors (G).

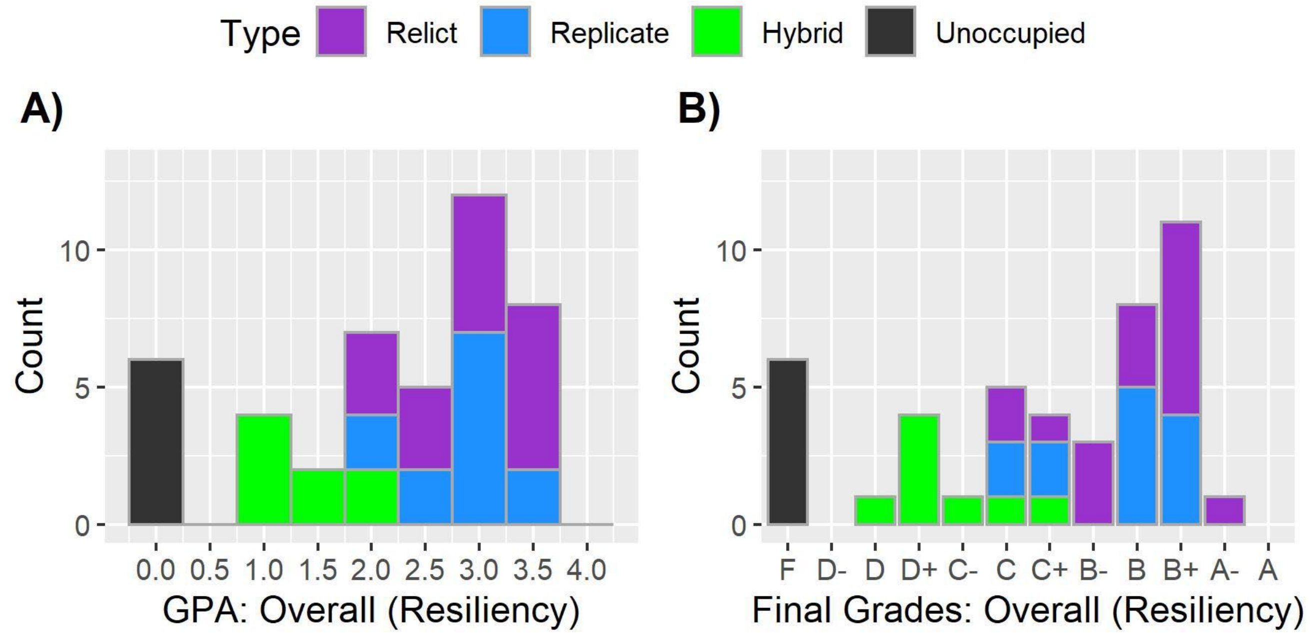

Figure 22. A) Frequency of overall grade-point-averages (GPAs) and B) final grades for Apache Trout populations and unoccupied streams, by type, in east-central Arizona. See Table 13.

Table 15. Mean demographic, habitat, and overall grade-point-averages (GPAs), and number of populations by final letter grade, for relict and replicate (genetically pure) Apache Trout populations (n=30) by subbasin and rangewide (see Table 13).

	Mean GPA			Number of Populations by Letter Grade			
Subbasin	Demographic	Habitat	Overall	A	B	C	D/F
Black River	3.00	3.08	3.04	0	3	1	0
Bonito Creek	3.43	3.02	3.23	0	7	0	0
Colorado River	2.67	3.17	2.92	0	1	0	0
Little Colorado River	2.67	3.00	2.83	0	3	1	0
Diamond Creek	2.67	2.00	2.33	0	1	3	0
East Fork White River	2.72	2.94	2.83	1	4	1	0
North Fork White River	2.75	2.96	2.86	0	3	1	0
Rangewide	2.91	2.87	2.89	1	22	7	0

SPECIES FUTURE CONDITION

A central element of the SSA Framework is an estimate of the species' future conditions based on probable future scenarios of environmental conditions and conservation actions (USFWS 2016). This involves a description and analysis of future conditions from environmental change and management actions and the projected influences on the species' ability to sustain populations in the wild over defined timeframes.

Future conditions of the Apache Trout were evaluated using a two-step process. The first step was understanding how future conservation actions and resource conditions influence all populations across the range – thus species viability – due to various threat factors. The second step was to evaluate the future condition of populations under five future scenarios. This was done using group elicitation, using a survey instrument, to understand the relative risks of threats and impacts of conservation actions on the status of Apache Trout populations and the species. The relevance of future threats and the five future scenarios were evaluated over a 30-year timeframe. A 30-year timeframe was chosen because it is biologically reasonable (6 generations for Apache Trout; $GT = AGE_{SM} + (1/d)$, where GT is average generation time in years (5 years), AGE_{SM} is average age at sexual maturity ($AGE_{SM} = 2.5$), and d is average annual death rate (0.40; see Table 3); $GT / 30 = 6$), and it is also a foreseeable management horizon.

Threat Factors

Each Apache Trout expert ranked the impact of various threat factors and conservation actions (see section: Risks Factors) on the impact to Apache Trout viability over the next 30 years. Factors were under these main groups: Climate; Habitat; Nonnatives; Demographic; and Conservation Action. Each factor was ranked from 1 to 10 (1= No Risk; 10=Extreme Risk).

The threat factors Apache Trout experts considered most important to Apache Trout viability over the next 30 years were conservation actions (signified with an 'A'): Funding, Protective Barrier Construction, and Chemical Removal of Nonnative Trout (Figure 23A). Increased Wildfire Frequency and Severity was the fourth highest threat factor overall and the highest ranked Climate factor. Experts thought low streamflows and increased stream temperatures also posed high risk to Apache Trout viability. Increased Chemical Pollution, More Intense Summer Monsoons, and Increased Water Use were the lowest ranking threat factors. Within the broad classes, experts thought that factors related to undertaking conservation actions were most important to the future viability of the Apache Trout. Some climate factors were through to post high risk (wildfire, low streamflows, and high temperature) where as others (rain-on-snow, monsoon intensity) posed low risk, leading to high variability among the climate factors as shown by the standard error bars for the climate threat factors (Figure 23A, B).

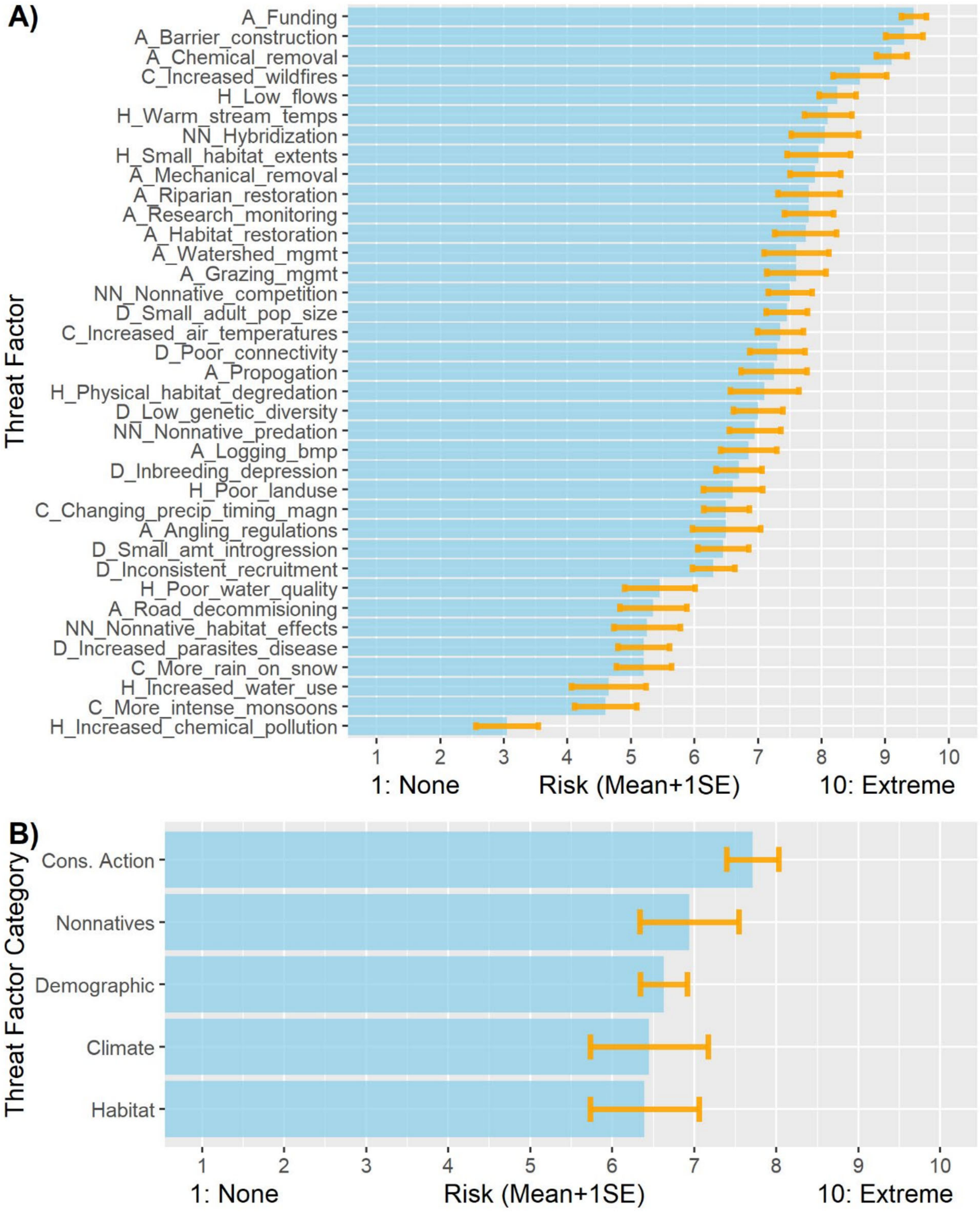

Figure 23. A) Mean (±1 SE) risk of various threat factors to Apache Trout species viability over the next 30-years based on survey of Apache Trout Core Team, and B) Mean (±1 SE) risk across threat categories. Each factor was ranked from 1 to 10 (1= No Risk; 10=Extreme Risk). N = 20.

Future Conditions of Apache Trout

Future Scenarios and Expert Elicitation

The future condition of Apache Trout was assessed through consideration of five future scenarios and what Apache Trout experts thought each scenario meant for the condition of individual populations, which were summarized to understand influence of each scenario on the species. The scenarios reflected both exogenous factors such as watershed condition and climactic changes, as well as management action feasibility and volume given funding and other programmatic constraints (funding and other resources) and policy. The scenarios ranged from reduced to increased levels of management, incorporated the delisting of Apache Trout under the Endangered Species Act, implementation of a multi-agency Cooperative Management Plan (CMP), and scientific and technological advancement. Each scenario was based on a 30-year timeframe and included climate change impacts and other factors threatening the Apache Trout (see "Risk Factors" section above).

For each scenario, the Apache Trout experts indicated in an online survey the overall impact of each scenario on populations across the species' range, or subsets of the range with which they are familiar, using their best professional judgement. Each Apache Trout expert responded to survey questions in terms of what the condition – described as a Grade Point Average (GPA) – of each Apache Trout population (or currently unoccupied stream) would be, based on the grading scale used to describe current conditions (see "Population Resiliency: A Grading Scale" section above), under each of the five future condition scenarios after a 30-year timeframe. GPAs were summarized across populations to assess the influence of each scenario on the rangewide status of Apache Trout. The Delphi method again was used whereby experts responded to Survey #1. They then participated in a discussion regarding Survey #1 responses in which they could ask questions, get clarifications, and observe their answers relative to a group summary. They then retook the survey (Survey #2) or elected to retain their responses to Survey #1. The scenarios were:

Scenario #1 (Reduced Management, No Delisting, No CMP): Recovery and management actions are reduced to minimal levels because of funding reductions and some program dissolution. Proactive, adaptive management, and voluntary actions are substantially reduced. Using the time period of 2000–2020 as a baseline, under this scenario there are reduced levels of barrier maintenance, nonnative trout eradications and suppressions, and watershed and stream restorations. Protections from new barriers, forest planning for ESA species, and restrictive angling regulations are reduced. USFWS assistance to the White Mountain Apache Tribe is also substantially reduced. Other funding sources, such as the National Fish and Wildlife Foundation (NFWF) Apache Trout Keystone Initiative sunset and their resources are no longer available.

- Barriers deteriorate and become non-functional, and nonnative trout populations expand. Some populations become introgressed with Rainbow Trout and others extirpated due to competition with and predation by Brook Trout and Brown Trout.
- Only populations above natural barriers (waterfalls) not invaded by nonnative trout persist.
- Across the range of Apache Trout, watershed functional conditions decline, riparian and instream habitat are reduced in quality, and stream temperatures become too warm to support Apache Trout in some streams due to riparian and instream habitat degradation.
- Effectiveness of land management policies for stream ecosystems and threatened species is reduced.
- Stream temperatures get warmer, there is less snowpack but more rain on snow events, droughts are more frequent and severe, and there are more intense summer monsoon rains due to climate change.

Scenario #2 (Sustained Management Until Delisting, but No CMP): Recovery and conservation actions continue at levels from 2000–2020 that are beneficial to the species for the first 10 years, at which time Apache Trout are delisted but without a CMP in place. After barrier construction, population expansion, and nonnative trout removals initially occur at levels required to meet recovery criteria (30 pure populations, or similar), but no de-listing CMP is in place to ensure commitment of resources to Apache Trout conservation at 2000–2020 levels. Thus, the last twenty years of the 30-year period see reduced levels of barrier maintenance, nonnative trout removals and suppressions, and watershed and stream restorations. Protections from new barriers, land management planning for ESA species, and restrictive angling regulations are also reduced. USFWS assistance to the White Mountain Apache Tribe is substantially reduced after delisting. Other funding sources, such as the NFWF Apache Trout Keystone Initiative disappear.

- After delisting, one half of populations become functionally extirpated due to hybridization with Rainbow Trout and competition and predation by Brook Trout and Brown Trout, other populations are suppressed in abundance and distribution due to deteriorating riparian and instream habitat conditions and climate change. Populations above natural barriers (waterfalls) remain un-invaded by nonnative trout and persist.
- Effectiveness of land management policies for stream ecosystems and threatened species is initially maintained, but then reduced after de-listing. In some portion of the Apache Trout range, watershed functional conditions decline, riparian and instream habitat are reduced in quality, and stream temperatures become too warm to support Apache Trout in some streams due to less stringent protections during land management planning and implementation.
- Stream temperatures get warmer, there is less snowpack but more rain on snow events, droughts are more frequent and severe, and there are more intense summer monsoon rains due to climate change.

Scenario #3 (Sustained Management, No Delisting or Delisting with CMP): Recovery and conservation efforts continue at levels from 2000–2020 that are beneficial to the species, at which time Apache Trout are either not delisted, or the species is delisted but management levels are maintained with a CMP in place. Thus, actions continue and are effective at reducing some threats. This includes legally required actions and those voluntarily agreed to in the CMP. Barrier construction, population expansion, and nonnative trout removals occur at levels required to meet recovery criteria (30 pure populations, or similar) and are maintained thereafter. USFWS assistance to the White Mountain Apache Tribe continues. Other funding sources, such as the NFWF Apache Trout Keystone Initiative disappear, but other funding sources emerge in its place (e.g., National Fish Habitat Act; Recovering America’s Wildlife Act). This scenario represented the status quo scenario with approximately the same amount of resources and management action as a 2000–2020 baseline.

- Barrier installation and maintenance continues at 2000–2020 levels. The number of viable Apache Trout populations and metapopulations increases to meeting recovery goals and is maintained after delisting.
- Effectiveness of land management policies for stream ecosystem and threatened species is initially maintained through de-listing due to the CMP agreement in place. Across the Apache Trout range, watershed functional conditions are maintained or improved, riparian and instream habitat are maintained or improved in quality, and stream temperatures are maintained or improved to support Apache Trout due to protections during land management planning and implementation.
- Stream temperatures get warmer, there is less snowpack but more rain on snow events, droughts are more frequent and severe, and there are more intense summer monsoon rains due to climate change.

Scenario #4 (Increased Management, Delisting, with CMP): Recovery and conservation efforts continue but at levels increased slightly from 2000–2020 that are beneficial to the species. Management actions continue and some become effective at reducing some threats. After barrier construction, population expansion, and nonnative trout removals initially occur at levels required to meet recovery criteria (30 pure populations, or similar) and Apache Trout are delisted, the level of actions is maintained due to the

CMP in place, but also increases due to emergence of new research and technology. USFWS assistance to the White Mountain Apache Tribe continues. New legislation emerges resulting in new funding for fish habitat projects (e.g., National Fish Habitat Act; Recovering America's Wildlife Act), and there is broad implementation of the Four Forest Restoration Initiative, Black River Restoration Environmental Assessment (EA), and FAIR Forest Management Plan (fuels management) that are beneficial to watershed functional conditions and reduced wildfire risk.

- Barrier installation and maintenance increases slightly from 2000–2020 levels due to new technology that increases effectiveness and reduces cost and maintenance. The number of viable Apache Trout populations increases, and one large metapopulation is realized (e.g., WFBR), to meet and exceed recovery goals.
- Effectiveness of land management policies for stream ecosystem and threatened species is initially maintained through de-listing due to the CMP in place. Across the Apache Trout range, watershed functional conditions are improved, riparian and instream habitat are improved in quality, and stream temperatures are improved (riparian restoration and recovery) to support Apache Trout due to protections during land management planning and implementation.
- Stream temperatures warm, there is less snowpack but more rain on snow events, droughts are more frequent and severe, and summer monsoon rains are more intense due to climate change.

Scenario #5 (Greatly Increased Management, Delisting, with CMP): Improved recovery actions result in many secured populations free of nonnative trout, including several metapopulations with high resilience and improved effectiveness of recovery and conservation actions before and after de-listing. Additional funding becomes available due to CMP in place and new legislation resulting in more funding for fish habitat projects (National Fish Habitat Act; Recovering America's Wildlife Act). Broad implementation of the Four Forest Restoration Initiative, Black River Restoration Environmental Assessment (EA), and FAIR Forest Management Plan (fuels management) are realized. Watershed conditions improve, and wildfire risk is reduced. Entities like the NFWF emerge with new large scale, long-term initiatives for Apache Trout.

- Barrier installation and maintenance increases slightly above 2000–2020 levels due to new technology that increases effectiveness and reduces cost and maintenance
- Nonnative trout suppression and eradications have been widely successful due to broad allowance of piscicide use and effectiveness of YY Brook Trout and YY Brown Trout programs.
- Populations with small levels of introgression are shown to purge nonnative alleles over time through continued genetic monitoring of populations.
- At least one large interconnected system in each subbasin (Big Bonito, White, Black, and LCR) have been established, substantially improving population and species resilience.
- Watershed, riparian, and instream habitat quality improve due to implementation of land management actions at levels surpassing those in the ASNF and WMAT Plans (e.g., annually, work with partners to reduce animal damage to native willows and other riparian species on an average of 5 miles of riparian habitat).
- Forest fuels management reduce wildfire risk and severity.
- However, stream temperature increases still impact some lower elevation populations and droughts are more frequent and severe, although the effects are dampened due to strategic riparian restoration to improve stream shading and habitat resiliency

Expert Responses to Future Condition Scenarios

Apache Trout experts, as revealed by Survey #2 responses per the Delphi method, think that the future condition of Apache Trout populations and streams should improve from Scenario #1 to #2, #2 to #3, #3 to #4 and so on through Scenario #5 (Figure 24; Figure 25). They showed strong agreement, as indicated by small error bars reflecting the range of responses, on what the scenarios mean for the future condition of individual Apache Trout populations. For example, responses showed low variability in responses for Deep Creek (FAIR) for each scenario (shown by error bars in Figure 24). In other cases, such as in currently unoccupied Hannagan Creek, there was strong agreement among experts that future condition Scenario #1 would maintain a low GPA signifying that a population was unlikely to be established in that stream or if one would become established it would remain in very poor condition; however, there was a large range in responses for whether a population might be established in Hannagan Creek and what its status might be under Scenarios #4 and #5. Responses for the Lower WFBR were highly variable across all five scenarios (lower right of Figure 24).

When survey responses of future condition were summarized (averaged) across populations for each scenario to infer a future rangewide condition of the Apache Trout under each scenario, the future condition of the species was expected to improve sequentially from Scenario #1 to Scenario #5, similar to that of individual populations (Figure 25; Table 17). The experts thought that the future condition of the Apache Trout would decrease under Scenario #1 and #2. Future Scenario #3, sustained management with no delisting or delisting with a CMP in place, would maintain the current condition of the species at a GPA just over 2.0 (C average). And Scenarios #4 and #5 would improve the status of the species to a 2.5 and a 2.9 GPA, respectively (Figure 25; Table 18). That Scenario #3 was thought by the experts the most likely to occur over the next 30 years (see Appendix A) suggests that people working on the species today expect management to continue into the future at a level similar to that of the recent past if the species remains listed on the List of Threatened and Endangered Species. It also portends that a CMP needs to be in place if delisting were to occur to maintain the future condition of the species close to what it is today.

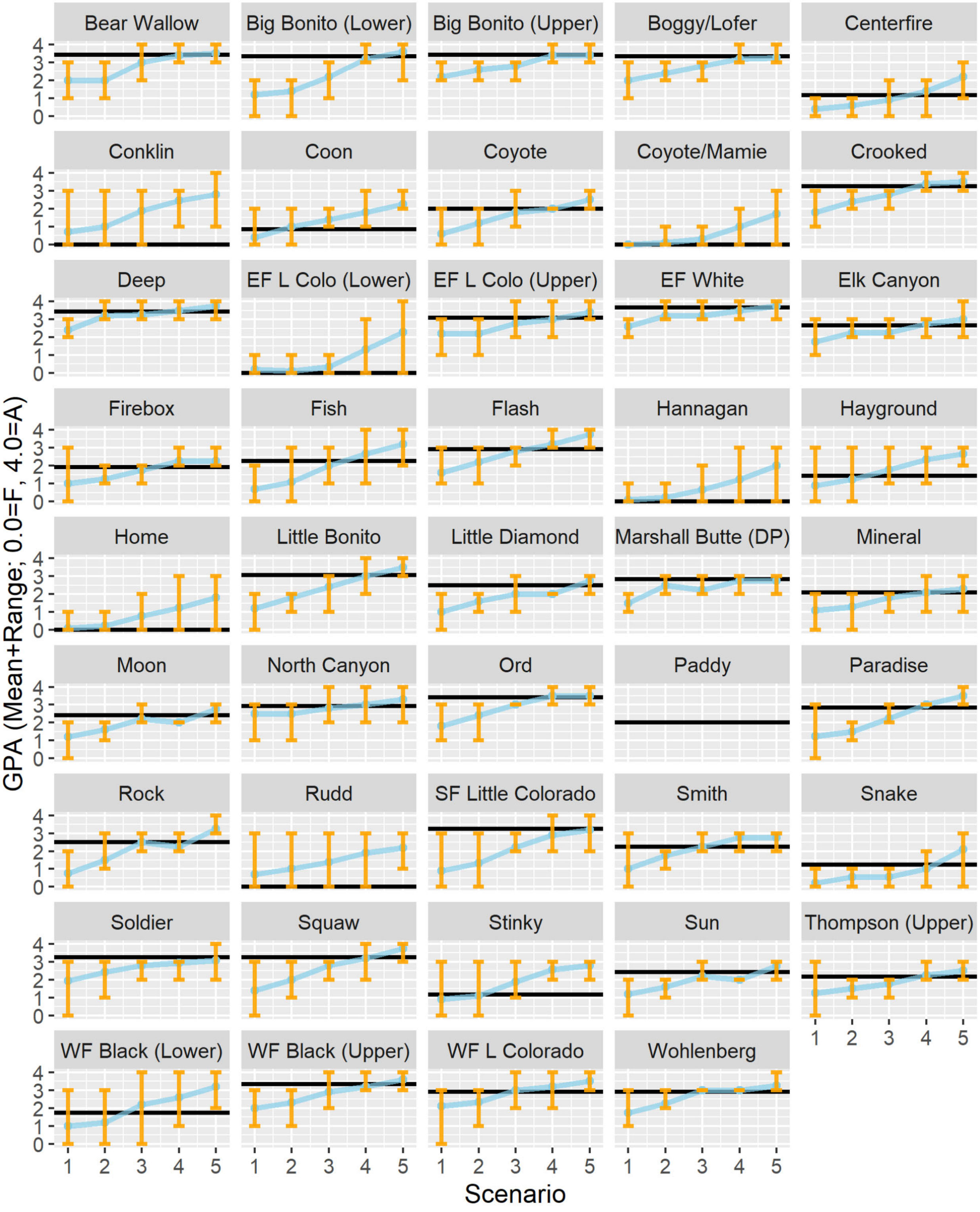

Figure 24. Mean Grade Point Average (GPA; ±range as orange error bars) from Apache Trout expert responses to Survey #2 regarding the influence of five Future Conditions scenarios on the GPA of Apache Trout. There were nine experts (N=9) for ASNF streams, and seven experts (N=7) for FAIR streams. Black line indicates GPA for current conditions for each population or unoccupied stream.

Table 16. Mean grade point averages (GPAs) for relict and replicate (genetically pure) Apache Trout populations by subbasin, and mean subbasin GPA (bold), from Apache Trout expert responses (N=9 for ASNF streams, and N=7 for FAIR streams) to Survey #2 regarding the influence of five Future Conditions scenarios on future condition of Apache Trout.

Subbasin	Stream	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Black	**All streams**	**1.79 (C-)**	**2.06 (C)**	**2.61 (B-)**	**2.95 (B)**	**3.17 (B+)**
Black	Bear Wallow	2.00 (C)	2.00 (C+)	3.00 (B)	3.40 (B+)	3.50 (A-)
Black	Soldier	1.93 (C)	2.43 (C+)	2.79 (B-)	2.93 (B)	3.07 (B)
Black	Thompson (Upper)	1.25 (D+)	1.50 (C-)	1.75 (C-)	2.25 (C+)	2.50 (B-)
Black	WF Black (Upper)	2.00 (C)	2.30 (C+)	2.90 (B)	3.20 (B+)	3.60 (A-)
Bonito	**All streams**	**1.63 (C-)**	**2.11 (C)**	**2.66 (B-)**	**3.23 (B+)**	**3.54 (A-)**
Bonito	Big Bonito (Lower)	1.20 (D+)	1.40 (D+)	2.20 (C+)	3.20 (B+)	3.60 (A-)
Bonito	Big Bonito (Upper)	2.20 (C+)	2.60 (B-)	2.80 (B-)	3.40 (B+)	3.40 (B+)
Bonito	Boggy/Lofer	2.00 (C)	2.40 (C+)	2.80 (B-)	3.20 (B+)	3.25 (B+)
Bonito	Crooked	1.80 (C-)	2.40 (C+)	2.80 (B-)	3.40 (B+)	3.50 (A-)
Bonito	Flash	1.60 (C-)	2.20 (C+)	2.80 (B-)	3.20 (B+)	3.75 (A-)
Bonito	Little Bonito	1.20 (D+)	1.80 (C-)	2.40 (C+)	3.00 (B)	3.50 (A-)
Bonito	Squaw	1.40 (D+)	2.00 (C)	2.80 (B-)	3.20 (B+)	3.75 (A-)
Colorado	**All streams**	**2.50 (B-)**	**2.50 (B-)**	**2.80 (B-)**	**3.00 (B)**	**3.30 (B+)**
Colorado	North Canyon	2.50 (B-)	2.50 (B-)0	2.80 (B-)	3.00 (B)	3.30 (B+)
L. Colorado	**All streams**	**1.58 (C-)**	**1.79 (C-)**	**2.45 (C+)**	**2.80 (B-)**	**3.10 (B)**
L. Colorado	EF Little Colorado (Upper)	2.20 (C+)	2.20 (C+)	2.78 (B-)	3.00 (B)	3.40 (B+)
L. Colorado	Mineral	1.10 (D)	1.30 (D+)	1.80 (C-)	2.10 (C)	2.30 (C+)
L. Colorado	SF Little Colorado	0.90 (D)	1.33 (D+)	2.22 (C+)	2.89 (B)	3.20 (B+)
L. Colorado	WF Little Colorado	2.10 (C)	2.33 (C+)	3.00 (B)	3.20 (B+)	3.50 (A-)
Diamond	**All streams**	**1.00 (D)**	**1.50 (C-)**	**2.05 (C)**	**2.00 (C)**	**2.72 (B-)**
Diamond	Coyote	0.60 (D-)	1.20 (D+)	1.80 (C-)	2.00 (C)	2.50 (B-)
Diamond	Little Diamond	1.00 (D)	1.60 (C-)	2.00 (C)	2.00 (C)	2.75 (B-)
Diamond	Moon	1.20 (D+)	1.60 (C-)	2.20 (C+)	2.00 (C)	2.75 (B-)
Diamond	Sun	1.20 (D+)	1.60 (C-)	2.20 (C+)	2.00 (C)	2.75 (B-)
EF White	**All streams**	**1.67 (C-)**	**2.32 (C+)**	**2.53 (B-)**	**2.83 (B-)**	**3.12 (B)**
EF White	Deep	2.40 (C+)	3.20 (B+)	3.25 (B+)	3.50 (A-)	3.75 (A-)
EF White	EF White	2.60 (B-)	3.20 (B+)	3.20 (B+)	3.50 (A-)	3.75 (A-)
EF White	Elk Canyon	1.75 (C-)	2.25 (C+)	2.25 (C+)	2.75 (B-)	3.00 (B)
EF White	Firebox	1.00 (D)	1.25 (D+)	1.75 (C-)	2.25 (C+)	2.25 (C+)
EF White	Marshall Butte (DP)	1.50 (C-)	2.50 (B-)	2.25 (C+)	2.75 (B-)	2.75 (B-)
EF White	Rock	0.75 (D-)	1.50 (C-)	2.50 (B-)	2.25 (C+)	3.25 (B+)
NF White	**All streams**	**1.45 (D+)**	**1.98 (C)**	**2.62 (B-)**	**3.06 (B)**	**3.25 (B+)**
NF White	Ord	1.80 (C-)	2.40 (C+)	3.00 (B)	3.50 (A-)	3.50 (A-)
NF White	Paradise	1.25 (D+)	1.50 (C-)	2.25 (C+)	3.00 (B)	3.50 (A-)
NF White	Smith	1.00 (D)	1.75 (C-)	2.25 (C+)	2.75 (B-)	2.75 (B-)
NF White	Wohlenberg	1.75 (C-)	2.25 (C+)	3.00 (B)	3.00 (B)	3.25 (B+)

Table 17. Number of Apache Trout populations by subbasin receiving final letter grades A, B, C, D. and F as translated from mean GPAs from Apache Trout expert responses to Survey #2 regarding the influence of five scenarios on Future Conditions of Apache Trout. See Table 13.

	Scenario 1				Scenario 2				Scenario 3			Scenario 4				Scenario 5			
Subbasin	A	B	C	D/F	A	B	C	D/F	B	C	D/F	A	B	C	D/F	A	B	C	D/F
Black	0	0	3	1	0	0	4	0	3	1	0	0	3	1	0	2	2	0	0
Bonito	0	0	4	3	0	1	5	1	5	2	0	0	7	0	0	5	2	0	0
Colorado	0	1	0	0	0	1	0	0	1	0	0	0	1	0	0	0	1	0	0
L Colorado	0	0	2	2	0	0	2	2	2	2	0	0	3	1	0	1	2	1	0
Diamond	0	0	0	4	0	0	3	1	0	4	0	0	0	4	0	0	4	0	0
EF White	0	1	3	2	0	3	2	1	3	3	0	2	2	2	0	2	3	1	0
NF White	0	0	2	2	0	0	4	0	2	2	0	1	3	0	0	2	2	0	0
Rangewide	0	2	14	14	0	5	20	5	16	14	0	3	19	8	0	12	16	2	0

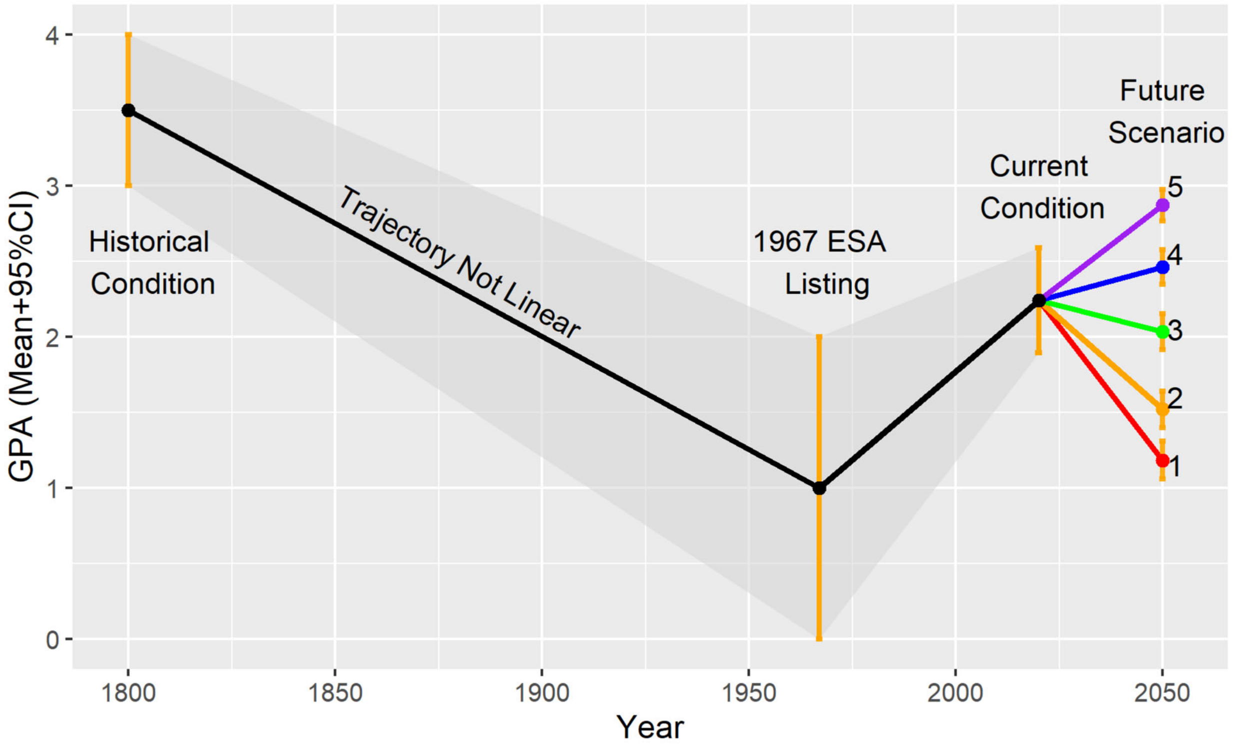

Figure 25 Overall mean (±95%CI and 95% confidence band) future Grade Point Average (GPA) for the Apache Trout, as elicited from Apache Trout experts (Survey #2), in response to five future conditions scenarios. There were nine experts (N=9) for ASNF streams and seven experts (N=7) for FAIR streams. Historical 1800 and 1967 GPAs (and error) were approximated using best professional judgement.

Looking Forward

The current condition of the Apache Trout is a result of populations protected by natural barriers that have not been invaded by nonnative trout, as well as management actions that have been focused on, but not limited to, protecting additional populations from the negative impacts of nonnative species. This especially includes hybridizing species such as Rainbow Trout, but also competition and predation from nonnative Brook Trout and Brown Trout. Protection efforts have focused on the joint actions of protecting populations above fish passage barriers and removal and suppression of nonnative species.

The 2011 Wallow Fire impacted some populations and recovery stream habitats, and set back some actions planned to meet Apache Trout recovery goals (USFWS 2009).

The future condition of the Apache Trout will be contingent upon continued management. Species are considered conservation reliant if both populations and threats require some form of continued management (Scott et al. 2005). In fact, 84% of species on the Federal List of Threatened and Endangered Wildlife under the Endangered Species Act are considered conservation reliant (Scott et al. 2010). Thus, once a species is recovered (de-listed), assurances for the sufficient management of populations and threats through a post-delisting management agreement may be needed to maintain a recovered status (Goble et al. 2012); section 4(g) of the ESA requires that monitoring occur for at least five years after recovery. Given the difficulty in widespread eradication of nonnative fishes throughout river networks, and ongoing protective barrier construction, maintenance, and repair because of material decay or other events (e.g., post-wildfire floods and debris flows), the future condition of the Apache Trout is contingent on continued management because many populations, but not all, are currently invaded or threatened with invasion by nonnative trout. The future scenarios most likely to play out in the next 30 years, as indicated by species experts, all require some level of management. Rising temperatures, declining precipitation, longer and more severe droughts, and increasing wildfire frequency and severity—all due to climate change—will change habitat conditions for Apache Trout and the backdrop on which conservation actions for the species are taken, thus creating uncertainty but highlighting the need for monitoring and active management to protect populations. And while the level of management will determine the species condition and viability into the future, the necessity of management highlights the fact that the Apache Trout is a conservation reliant species.

Protective gabion barrier on Paradise Creek, Arizona.

REFERENCES

Al-Chokhachy, R., B. B. Shepard, J. C. Burckhardt, D. Garren, S. Opitz, T. M. Koel, L. Nelson, and R. E. Gresswell. 2018. A portfolio framework for prioritizing conservation efforts for Yellowstone Cutthroat Trout populations. Fisheries 43:485–496.

Alcorn, S. R. 1976. Temperature tolerances and upper lethal limits of *Salmo apache*. Transactions of the American Fisheries Society 105:294–295.

Allendorf, F. W., R. F. Leary, N. P. Hitt, K. L. Knudsen, L. L. Lundquist, and P. Spruell. 2004. Intercrosses and the U.S. Endangered Species Act: should hybridized populations be included as Westslope Cutthroat Trout? Conservation Biology 18:1203–1213.

Allendorf, F. W., and N. Ryman. 2002. The role of genetics in population viability analysis. S. R. Beissinger, and D. R. McCullough, editors. Population viability analysis. University of Chicago, Chicago.

Angel, J., C. Swanston, B. M. Baustead, K. C. Conlon, K. R. Hall, J. L. Jorns, K. E. Kunkel, M. C. Lemos, B. Lofgren, T. A. Ontl, J. Posey, K. Stone, G. Takle, and D. Todey. 2018. Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II. D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, editors. Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program,, Washington, D.C.

Arend, K. K. 1999. Macrohabitat identification. Pages 75–93 *in* M. B. Bain, and N. J. Stevenson, editors. Aquatic habitat assessment: common methods. American Fisheries Society, Bethesda, Maryland.

ASNF. 2015. Land management plan for the Apache-Sitgreaves National Forests (revised). MB-R3-01-10. Apache-Sitgreaves National Forests, Forest Service, US Department of Agriculture.

ASNF. 2016. Apache-Sitgreaves National Forests Plan: monitoring and evaluation report fiscal year 2015. S. R. Apache-Sitgreaves National Forests, Forest Service, US Department of Agriculture, Springerville, Arizona. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd512794.pdf.

ASNF. 2018. Biennial monitoring evaluation report for the Apache-Sitgreaves National Forests. F. S. Apache-Sitgreaves National Forests, US Department of Agriculture, Springerville, Arizona.

Avenetti, L. D., A. T. Robinson, and C. J. Cantrell. 2006. Short-term effectiveness of constructed barriers at protecting Apache Trout. North American Journal of Fisheries Management 26:213–216.

AZGFD, and USFWS. 2015. (Draft) Apache Trout Keystone Initiative: summary of activities conducted on the Apache-Sitgreaves National Forests and Fort Apache Indian Reservation; 2008–2014. Unpublished report by Arizona Game and Fish Department and U.S. Fish and Wildlife Service to National Fish and Wildlife Foundation. Phoenix, Arizona.

Baker, J. P., and S. A. Bonar. 2019. Using a mechanistic model to develop management strategies to cool Apache Trout streams under the threat of climate change. North American Journal of Fisheries Management 39:849–867.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. Science 319:1080–1083.

Behnke, R. J. 1992. Native trout of western North America. American Fisheries Society Monograph 6, Bethesda, Maryland.

Behnke, R. J. 2002. Trout and salmon of North America. The Free Press, New York.

Behnke, R. J., and M. Zarn. 1976. Biology and managementt of threatened and endangered western trouts. Fort Collins, Colorado.

Bonar, S. A., and S. J. Petre. 2015. Ground-based thermal imaging of stream surface temperatures: technique and evaluation. North American Journal of Fisheries Management 35:1209–1218.

Brook, B. W., C. J. A. Bradshaw, L. W. Traill, and R. Frankham. 2011. Minimum viable population size: not magic, but necessary. Trends in Ecology & Evolution 26:619–620.

Brown, D. K., A. A. Echelle, D. L. Propst, J. E. Brooks, and W. L. Fisher. 2001. Catastrophic wildfire and number of populations as factors influencing risk of extinction for Gila Trout (*Oncorhynchus gilae*). Western North American Naturalist 61:139–148.

Brown, R. S., W. A. Hubert, and S. F. Daly. 2011. A primer on winter, ice, and fish: what fisheries biologists should know about winter ice processes and stream-dwelling fish. Fisheries 36:8–26.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach, Second edition. Springer-Verlag, New York.

Cannon, S. H., J. E. Gartner, M. G. Rupert, J. A. Michael, A. H. Rea, and C. Parrett. 2010. Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. GSA Bulletin 122:127–144.

Cantrell, C. J., A. T. Robinson, and L. D. Avenetti. 2005. Habitat selection by Apache Trout in six east-central Arizona streams. Transactions of the American Fisheries Society 134:1382–1388.

Carim, K. J., N. J. Bean, J. M. Connor, W. P. Baker, M. Jaeger, M. P. Ruggles, K. S. McKelvey, T. W. Franklin, M. K. Young, and M. K. Schwartz. 2020. Environmental DNA sampling informs fish eradication efforts: case studies and lessons learned. North American Journal of Fisheries Management 40:488–508.

Carim, K. J., L. A. Eby, C. A. Barfoot, and M. C. Boyer. 2016. Consistent loss of genetic diversity in isolated Cutthroat TSrout populations independent of habitat size and quality. Conservation Genetics 17:1363–1376.

Carlson, A., and M. Culver. 2009. Detection of hybridization in Apache Trout in Arizona through incorporation of both sequence and microsatellite data. Phoenix, Arizona.

Carlson, A. J., and F. J. Rahel. 2010. Annual intrabasin movement and mortality of adult Bonneville Cutthroat Trout among complementary riverine habitats. Transactions of the American Fisheries Society 139:1360–1371.

Carmichael, G. J., J. N. Hanson, J. R. Novy, K. J. Meyer, and D. C. Marizot. 1995. Apache Trout management: cultured fish, genetics, habitat improvements, and regulations. American Fisheries Society Symposium 15:112–121.

Carmichael, G. J., J. N. Hanson, M. E. Schmidt, and D. C. Morizot. 1993. Introgression among Apache, Cutthroat, and Rainbow Trout in Arizona. Transactions of the American Fisheries Society 122:121–130.

Caughley, G. 1994. Directions in conservation biololgy. Journal of Animal Ecology 63:215–244.

Ciuhandu, C. S., P. A. Wright, J. I. Goldberg, and E. D. Stevens. 2007. Parameters influencing the dissolved oxygen in the boundary layer of Rainbow Trout (*Oncorhynchus mykiss*) embryos and larvae. Journal of Experimental Biology 210:1435–1445.

Clarkson, R. W., and J. R. Wilson. 1995. Trout biomass and stream habitat relationships in the White Mountains area, east-central Arizona. Transactions of the American Fisheries Society 124:599–612.

Coleman, M. A., and K. D. Fausch. 2007. Cold summer temperature limits recruitment of age-0 Cutthroat Trout in high-elevation Colorado streams. Transactions of the American Fisheries Society 136:1231–1244.

Conroy, M. J., and J. T. Peterson. 2013. Decision making in natural resource management. John Wiley and Sons, Ltd, West Sussex, United Kingdom.

Cook, B. I., and R. Seager. 2013. The response of the North American Monsoon to increased greenhouse gas forcing. Journal of Geophysical Research: Atmospheres 118:1690–1699.

Cook, N., F. J. Rahel, and W. A. Hubert. 2010. Persistence of Colorado River Cutthroat Trout populations in isolated headwater streams of Wyoming. Transactions of the American Fisheries Society 129:1500–1510.

Coop, J. D., S. A. Parks, C. S. Stevens-Rumann, S. D. Crausbay, P. E. Higuera, M. D. Hurteau, A. Tepley, E. Whitman, T. Assal, B. M. Collins, K. T. Davis, S. Dobrowski, D. A. Falk, P. J. Fornwalt, P. Z. Fulé, B. J. Harvey, V. R. Kane, C. E. Littlefield, E. Q. Margolis, M. North, M. A. Parisien, S. Prichard, and K. C. Rodman. 2020. Wildfire-driven forest conversion in western North American landscapes. BioScience 70:659–673.

Cope, E. D., and H. C. Yarrow. 1875. Report upon the collections of fishes made in portions of Nevada, Utah, California, Colorado, New Mexico, and Arizona, during the years 1871, 1872, 1873, and 1874. Report Geography Geology Exploration Survey W. 100th Meridian (Wheeler Survey),, Washington, D.C.

Crausbay, S. D., J. Betancourt, J. Bradford, J. Cartwright, W. C. Dennison, J. Dunham, C. A. F. Enquist, A. G. Frazier, K. R. Hall, J. S. Littell, C. H. Luce, R. Palmer, A. R. Ramirez, I. Rangwala, L. Thompson, B. M. Walsh, and S. Carter. 2020. Unfamiliar territory: emerging themes for ecological drought research and management. One Earth 3:337–353.

Dauwalter, D., B. Giordano, Z. Jackson, J. Johnson, M. Lopez, and T. Stephens. 2017a. Apache Trout monitoring plan: a monitoring plan for small and isolated trout populations. Arlington, Virginia.

Dauwalter, D. C., J. E. Williams, J. McGurrin, J. E. Brooks, and D. L. Propst. 2017b. Vulnerability of Gila Trout streams to future wildfires and temperature warming. Pages 195–205 *in* R. F. Carline, editor. Proceedings of the Wild Trout Symposium XII—Science, politics, and wild trout management: who's driving and where are we going?, West Yellowstone, Montana.

Delbecq, A. L., A. H. Van de Ven, and D. H. Gustafson. 1975. Group techniques for program planning: a guide to nominal group and Delphi processes. Scott Foresman and Company, Glenview, Illinios.

Dolloff, C. A., D. G. Hankin, and G. H. Reeves. 1993. Basinwide estimation of habitat and fish populations in streams. General Technical Report SE-83. Asheville, North Carolina.

Dowling, T. E., and M. R. Childs. 1992. Impact of hybridization on a threatened trout of the southwestern United States. Conservation Biology 6:355–364.

Dunham, J. B., S. B. Adams, R. E. Schroeter, and D. C. Novinger. 2002a. Alien invasions in aquatic ecosystems: toward an understanding of Brook Trout invasions and potential impacts on inland Cutthroat Trout in western North America. Reviews in Fish Biology and Fisheries 12:373–391.

Dunham, J. B., and B. E. Rieman. 1999. Metapopulation structure of Bull Trout: influences of physical, biotic and geometrical landscape characteristics. Ecological Applications 9:642–655.

Dunham, J. B., B. E. Rieman, and J. T. Peterson. 2002b. Patch-based models of species occurence: lessons from salmonid fishes in streams. Pages 327–334 *in* J. M. Scott, P. J. Heglund, M. L. Morrison, M. G. Raphael, J. B. Haufler, and B. Wall, editors. Predicting species occurrences: issues of scale and accuracy. Island Press, Covelo, California.

Dunham, J. B., A. E. Rosenberger, R. F. Thurow, C. A. Dolloff, and P. J. Howell. 2009. Coldwater fish in wadeable streams. Pages 119–138 *in* S. A. Bonar, W. A. Hubert, and D. W. Willis, editors. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Dunham, J. B., G. L. Vinyard, and B. E. Rieman. 1997. Habitat fragmentation and extinction risk of Lahontan Cutthroat Trout. North American Journal of Fisheries Management 17:1126–1133.

Eaglin, G. S., and W. A. Hubert. 1993. Effects of logging and roads on substrate and trout in streams of the Medicine Bow National Forest, Wyoming. North American Journal of Fisheries Management 13:844–846.

Easterling, D. R., K. E. Kunkel, J. R. Arnold, T. Knutson, L. A. N, L. R. Leung, R. S. Vose, D. E. Waliser, and M. F. Wehner. 2017. Precipitation change in the United States. Pages 207–230 *in* D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. Climate science special report: fourth national climate assessment. U.S. Global Research Program, Washington, D.C.

EcoPlan Associates. 2011. Arizona Game and Fish Department Sport Fish Stocking Program. Final Environmental Assessment, Prepared by EcoPlan Associates for U.S. Fish and Wildlife Service and Arizona Game and Fish Department, Phoenix. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd488919.pdf.

Eidenshink, J., B. Schwind, K. Brewer, Z. L. Zhu, B. Quayle, and S. Howard. 2007. A project for monitoring trends in burn severity. Fire Ecology 3:3–21.

Fagan, W. F., and E. E. Holmes. 2006. Quantifying the extinction vortex. Ecology Letters.

Fausch, K. D., B. E. Rieman, J. B. Dunham, M. K. Young, and D. P. Peterson. 2009. Invasion versus isolation: trade-offs in managing native salmonids with barriers to upstream movement. Conservation Biology 23:859–870.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52:483–498.

Finlayson, B., W. Somer, D. Duffield, D. Propst, C. Mellison, T. Pettengill, H. Sexauer, T. Nesler, S. Gurtin, J. Elliot, F. Partridge, and D. Skaar. 2005. Native Inland Trout Restoration on National Forests in the Western United States. Fisheries 30:10–19.

Forthofer, J. M. 2007. Modeling wind in complex terrain for use in fire spread prediction. Fort Collins, Colorado.

Frissell, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199–214.

Gendaszek, A. S., J. B. Dunham, C. E. Torgersen, D. P. Hockman-Wert, M. P. Heck, J. Thorson, J. Mintz, and T. Allai. 2020. Land-cover and climatic controls on water temperature, flow permanence, and fragmentation of Great Basin stream networks. Water 12:1962.

Genetic Analysis, I. 1994. Unpublished data. S. Corporation, editor, Smithville, Texas.

Goble, D. D., J. A. Wiens, J. M. Scott, T. D. Male, and J. A. Hall. 2012. Conservation-reliant species. BioScience 62:869–873.

Gonzales, P., G. M. Garfin, D. D. Breshears, K. M. Brooks, H. E. Brown, E. H. Elias, A. Gunasekara, N. Huntly, J. K. Maldonado, N. J. Mantua, H. G. Margolis, S. McAfee, B. R. Middleton, and B. H. Udall. 2018. Southwest. Pages 1101–1184 *in* D. R. Reidmiller, C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, editors. Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Research Program, Washington, D.C.

Gresswell, R. E. 1999. Fire and aquatic ecosystems in forested biomes of North America. Transactions of the American Fisheries Society 128:193–221.

Gresswell, R. E. 2011. Biology, status, and management of the Yellowstone Cutthroat Trout. North American Journal of Fisheries Management 31:782–812.

Haak, A. L., and J. E. Williams. 2012. Spreading the risk: native trout management in an warmer and less-certain future. North American Journal of Fisheries Management 32:387–401.

Hamlet, A. F., M. M. Elsner, G. S. Mauger, S. Y. Lee, I. Tohver, and R. A. Norheim. 2013. An overview of the Columbia Basin Climate Change Scenarios Project: approach, methods, and summary of key results. Atmosphere-Ocean 51:392–415.

Hansen, M. J., C. S. Guy, P. Budy, and T. E. McMahon. 2019. Trout as native and nonnative species: a management paradox. Pages 645–684 *in* J. L. Kershner, J. E. Williams, R. E. Gresswell, and J. Lobon-Cervia, editors. Trout and char of the world. American Fisheries Society, Bethesda, Maryland.

Hanski, I. 1999. Metapopulation ecology. Oxford University Press, Oxford.

Harig, A. L., and K. D. Fausch. 2002. Minimum habitat requirements for establishing translocated Cutthroat Trout populations. Ecological Applications 12:535–551.

Harig, A. L., K. D. Fausch, and M. K. Young. 2000. Factors influencing success of Greenback Cutthroat Trout translocations. North American Journal of Fisheries Management 20:994–1004.

Harper, K. C. 1976. On the biology of *Salmo apache* and its management implications. MS Thesis. University of Arizona, Tuscon.

Harper, K. C. 1978. Biology of a southwestern salmonid, *Salmo apache* (Miller 1972). Pages 99–111 *in* J. R. Moring, editor. Proceedings of the wild trout - catchable trout symposium. Oregon Department of Fish and Wildlife, Research and Development Section, Eugene, Oregon.

Hawkins, C. P., J. L. Kershner, P. A. Bisson, M. D. Bryant, L. M. Decker, S. V. Gregory, D. A. McCullough, C. K. Overton, G. H. Reeves, R. J. Steedman, and M. K. Young. 1993. A hierarchical approach to classifying stream habitat features. Fisheries 18:3–12.

Hedrick, P. W. 2000. Genetics of populations. Jones and Bartlett Publishers, Sudbury, Massachusetts.

Hilderbrand, R. H. 2003. The roles of carrying capacity, immigration, and population synchrony on persistence of stream-resident Cutthroat Trout. Biological Conservation 110:257–266.

Hilderbrand, R. H., and J. L. Kershner. 2000. Conserving inland Cutthroat Trout in small streams: how much stream is enough? North American Journal of Fisheries Management 20:513–520.

Hilderbrand, R. H., and J. L. Kershner. 2004. Are there differences in growth and condition between mobile and resident Cutthroat Trout? Transactions of the American Fisheries Society 133:1042–1046.

Hoerling, M. P., and J. Eischeid. 2007. Past peak water in the Southwest. Southwest Hydrology 6:18–19,35.

Horan, D. L., J. L. Kershner, C. P. Hawkins, and T. A. Crowl. 2000. Effects of habitat area and complexity on Colorado River Cutthroat Trout density in the Uinta Mountain streams. Transactions of the American Fisheries Society 129:1250–1263.

Hosmer, D. W., and S. Lemeshow. 2000. Applied logistic regression, second edition. John Wiley & Sons, Inc., New York.

Hoxmeier, R. J. H., and D. J. Dieterman. 2013. Seasonal movement, growth and survival of Brook Trout in sympatry with Brown Trout in Midwestern US streams. Ecology of Freshwater Fish 22:530–542.

Hufbauer, R. A., M. Szűcs, E. Kasyon, C. Youngberg, M. J. Koontz, C. Richards, T. Tuff, and B. A. Melbourne. 2015. Three types of rescue can avert extinction in a changing environment. Proceedings of the National Academy of Sciences 112:10557–10562.

Huntington, J. L., and R. G. Niswonger. 2012. Role of surface-water and groundwater interactions on projected summertime streamflow in snow dominated regions: An integrated modeling approach. Water Resources Research 48.

Isaak, D. J., S. J. Wenger, E. E. Peterson, J. M. Ver Hoef, S. W. Hostetler, C. H. Luce, J. B. Dunham, J. L. Kershner, B. B. Roper, D. E. Nagel, G. L. Chandler, S. P. Wollrab, S. L. Parkes, and D. L. Horan. 2016. NorWeST modeled summer stream temperature scenarios for the western U.S., Fort Collins, Colorado.

Isaak, D. J., S. J. Wenger, E. E. Peterson, J. M. Ver Hoef, D. E. Nagel, C. H. Luce, S. W. Hostetler, J. B. Dunham, B. B. Roper, S. P. Wollrab, G. L. Chandler, D. L. Horan, and S. Parkes-Payne. 2017a. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user-community and predict broad climate warming of rivers and streams. Water Resources Research 53:9181–9205.

Isaak, D. J., S. J. Wenger, and M. K. Young. 2017b. Big biology meets microclimatology: defining thermal niches of ectotherms at landscape scales for conservation planning. Ecological Applications 27:977–990.

Isaak, D. J., M. K. Young, D. E. Nagel, D. L. Horan, and M. C. Groce. 2015. The cold-water climate shield: delineating refugia for preserving salmonid fishes through the 21st century. Global Change Biology 21:2540–2553.

Johnstone, H. C., and F. J. Rahel. 2003. Assessing temperature tolerance of Bonneville Cutthroat Trout based on constant and cycling thermal regimes. Transactions of the American Fisheries Society 132:92–99.

Jordan, D. S., and B. W. Evermann. 1896. The fishes of north and middle America. Bulletin of the United States Natural History Museum, Part 1 47:i–ix,1–1240.

Keeley, J. E., P. van Mantgem, and D. A. Falk. 2019. Fire, climate and changing forests. Nature Plants 5:774–775.

Kennedy, T. L., D. S. Gutzler, and R. L. Leung. 2009. Predicting future threats to the long-term survival of Gila Trout using a high-resolution simulation of climate change. Climatic Change 94:503–515.

Kitcheyan, D. C. 1999. Population structure of Apache Trout (*Oncorhynchus apache*) in Flash and Squaw creeks on the Fort Apache Indian Reservation, Arizona. Master's thesis. University of Arizona, Tuscon.

Knighton, D. 1998. Fluvial forms and processes: a new perspective. Oxford University Press, Inc., New York.

Kovach, R. P., C. C. Muhlfeld, R. Al-Chokhachy, J. B. Dunham, B. H. Letcher, and J. L. Kershner. 2016. Impacts of climatic variation on trout: a global synthesis and path forward. Reviews in Fish Biology and Fisheries 26:135.

Kynard, B. E. 1976. A study of the pollution sources and their effect on the aquatic habitat of Eagle Creek watershed. Tempe, Arizona.

Leasure, D. R., S. J. Wenger, N. D. Chelgren, H. M. Neville, D. C. Dauwalter, R. Bjork, K. A. Fesenmyer, J. B. Dunham, M. M. Peacock, C. H. Luce, A. C. Lute, and D. J. Isaak. 2019. Hierarchical multi-population viability analysis. Ecology 100:e02538.

Lee, R. M., and J. N. Rinne. 1980. Critical thermal maxima of five trout species in the southwestern United States. Transactions of the American Fisheries Society 109:632–635.

Long, J. W., and A. L. Medina. 2006. Consequences of ignoring geologic variation in evaluating grazing impacts. Rangeland Ecology and Management 59:373–382,.

Long, J. W., A. L. Medina, and A. Tecle. 2006. Geologic influences on Apache Trout habitat in the White Mountains of Arizona. Journal of the Arizona-Nevada Academy of Science 38:88–101.

Loudenslager, E. J., J. N. Rinne, G. A. E. Gall, and R. E. David. 1986. Biochemical genetic studies of native Arizona and New Mexico trout. The Southwestern Naturalist 31:221–234.

MacConnell, E., and E. R. Vincent. 2002. Review: the effects of *Myxobolus cerebralis* on the salmonid host. Pages 95–108 *in* J. L. Bartholomew, and J. C. Wilson, editors. Whirling disease: reviews and current topics. American Fisheries Society, Symposium 29, Bethesda, Maryland.

Maceina, M. J., and D. L. Pereira. 2007. Recruitment. C. S. Guy, and M. L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

McKay, L., T. Bondelid, T. Dewald, J. Johnston, R. Moore, and A. Rea. 2012. NHDPlus version 2: user guide. Prepared for: U.S. Environmental Protection Agency, Office of Water. https://nctc.fws.gov/courses/references/tutorials/geospatial/CSP7306/Readings/NHDPlusV2_User_Guide.pdf.

Mesick, C. F. 1988. Effects of food and cover on numbers of Apache and Brown Trout establishing residency in artificial stream channels. Transactions of the American Fisheries Society 117:421–431.

Metcalf, J. L., M. R. Siegle, and A. P. Martin. 2008. Hybridization dynamics between Colorado's native Cutthroat Trout and introduced Rainbow Trout. Journal of Heredity 99:149–156.

Meyer, K. A., and J. S. Griffith. 1997. First-winter survival of Rainbow Trout and Brook Trout in the Henrys Fork of the Snake River, Idaho. Canadian Journal of Zoology 75:59–63.

Meyer, K. A., J. A. Lamansky, and D. J. Schill. 2006. Evaluation of an unsuccessful Brook Trout electrofishing removal project in a small Rocky Mountain stream. North American Journal of Fisheries Management 26:849–860.

Miller, R. R. 1950. Notes on the Cutthroat and Rainbow Trouts with the description of a new species from the Gila River, New Mexico. Number 529. Ann Arbor.

Miller, R. R. 1961. Man and the changing fish fauna of the American Southwest. Papers of the Michigan Academy of Sciences, Arts and Letters 45:365–404.

Miller, R. R. 1972. Classification of the native trouts of Arizona with the description of a new species, *Salmo apache*. Copeia 1972:401–422.

Mills, L. S., and F. W. Allendorf. 1996. The one-migrant-per-generation rule in conservation and management. Conservation Biology 10:1509–1518.

Minckley, W. L. 1973. Fishes of Arizona. Sims Printing Company, Phoenix, Arizona.

Minckley, W. L., and P. Mihalick. 1981. Effects of chemical treatment for fish eradication on stream-dwelling invertebrates. Journal of the Arizona-Nevada Academy of Science 16:79–82.

Mock, C. J. 1996. Climate controls and spatial variations of precipitation in the western United States. Journal of Climate:1111–1125.

Mpoame, M., and J. N. Rinne. 1984. Helminths of Apache (*Salmo apache*), Gila (*S. gilae*), and Brown (*S. trutta*) trouts. The Southwestern Naturalist 29:505–506.

Mueller, S. E., A. E. Thode, E. Q. Margolis, L. L. Yocom, J. D. Young, and J. M. Iniguez. 2020. Climate relationships with increasing wildfire in the southwestern US from 1984 to 2015. Forest Ecology and Management 460:117861.

Muhlfeld, C. C., D. C. Dauwalter, V. S. D'Angelo, A. Ferguson, J. J. Giersch, N. D. Impson, I. Kiozumi, R. P. Kovach, P. McGinnity, J. Schoeffmann, L. A. Vollestad, and J. Epifanio. 2019. Global status of freshwater trout and char: conservation challenges in the 21st Century. Pages 717–760 *in* J. L. Kershner, J. E. Williams, R. E. Gresswell, and J. Lobon-Cervia, editors. Status and conservation of trout and char worldwide. American Fisheries Society, Bethesda, Maryland.

Murphy, D. D., and P. S. Weiland. 2016. Guidance on the use of best available science under the U.S. Endangered Species Act. Environmental Management 58:1–14.

Myers, B. J. E., A. J. Lynch, D. B. Bunnell, C. Chu, J. A. Falke, R. P. Kovach, T. J. Krabbenhoft, T. J. Kwak, and C. P. Paukert. 2017. Global synthesis of the documented and projected effects of climate change on inland fishes. Reviews in Fish Biology and Fisheries:1–23.

Mysterud, A., and R. A. Ims. 1998. Functional responses in habitat use: availability influences relative use in trade-off situations. Ecology 79:1435–1441.

Nelson, J. S., E. J. Crossman, H. Espinosa-Perez, L. T. Findley, C. R. Gilbert, R. N. Lea, and J. D. Williams. 2004. Common and scientific names of fishes from the United States, Canada, and Mexico: 6th Edition. Special Publication 29, American Fisheries Society, Bethesda, Maryland.

Neville, H., J. Dunham, A. Rosenberger, J. Umek, and B. Nelson. 2009. Influences of wildfire, habitat size, and connectivity on trout in headwater streams revealed by patterns of genetic diversity. Transactions of the American Fisheries Society 138:1314–1327.

Neville, H. M., D. R. Leasure, D. C. Dauwalter, J. B. Dunham, R. Bjork, K. A. Fesenmyer, N. D. Chelgren, M. M. Peacock, C. H. Luce, D. J. Isaak, L. A. Carranza, J. Sjoberg, and S. J. Wenger. 2020. Application of multiple-population viability analysis to evaluate species recovery alternatives. Conservation Biology 34:482–493.

Overpeck, J. T., and S. A. Bonar. 2021. Southwestern fish and aquatic systems: the climate challenge. Pages 137–152 *in* D. L. Propst, J. E. Williams, K. R. Bestgen, and C. W. Hoagstrom, editors. Standing between life and extinction. University of Chicago Press, Chicago, Illinios.

Page, L. M., H. Espinosa-Perez, L. Findley, C. R. Gilbert, R. N. Lea, N. E. Mandrak, R. L. Mayden, and J. S. Nelson. 2013. Common and scientific names of fishes from the United States, Canada, and Mexico: 7th Edition. Special Publication 34, American Fisheries Society, Bethesda, Maryland.

Parks, S. A., and J. T. Abatzoglou. 2021. Warmer and drier fire seasons contribute to increases in area burned at high severity in western US forests from 1985–2017. Geophysical Research Letters in press.

Parks, S. A., S. Z. Dobrowski, J. D. Shaw, and C. Miller. 2019. Living on the edge: trailing edge forests at risk of fire-facilitated conversion to non-forest. Ecosphere 10:e02651.

Peterson, D. P., B. E. Rieman, D. L. Horan, and M. K. Young. 2014. Patch size but not short-term isolation influences occurrence of Westslope Cutthroat Trout above human-made barriers. Ecology of Freshwater Fish 23:556–571.

Petre, S. J., and S. A. Bonar. 2017. Determination of habitat requirements for Apache trout. Transactions of the American Fisheries Society 146:1–15.

Porath, M. T., H. B. Blasius, J. A. Conn, K. L. Young, and L. S. Jacks. 2010. Evaluating translocation of the Apache Trout (Oncorhynchus apache) to nonhistorical renovated streams. Southwestern Naturalist 55:229–239.

Potter, K. W. 1991. Hydrological impacts of changing land management practices in a moderate-sized agricultural catchment. Water Resources Research 27:845–855.

Price, J. E. 2013. Potential methods to cool streams containing Apache Trout in the White Mountains of Arizona and implications for climate change. University of Arizona, Tuscon.

Propst, D. L. 2020. Ecology, politics and conservation of Gila Trout. Pages 295–315 *in* D. L. Propst, J. E. Williams, K. R. Bestgen, and C. W. Hoagstrom, editors. Standing between life and extinction: ethics and ecology of conserving aquatic species in the American Southwest.

Propst, D. L., and J. A. Stefferud. 1997. Population dynamics of Gila Trout in the Gila River drainage of the southwestern United States. Journal of Fish Biology 51:1137–1154.

Quist, M. C., M. E. Ulaski, K. M. Manuell, Z. J. Jackson, and T. Gatewood. In press. Precision of structures used to estimate age and growth of Apache Trout from the White Mountains of Arizona. Journal of Fish and Wildlife Management.

Recsetar, M. S. 2011. Thermal tolerance of Apache Trout at varoius life stages. M.S. Thesis. University of Arizona, Tuscon.

Recsetar, M. S., and S. A. Bonar. 2013. Survival of Apache Trout eggs and alevins under static and fluctuating temperature regimes. Transactions of the American Fisheries Society 142:373–379.

Recsetar, M. S., S. A. Bonar, and O. G. Feuerbacher. 2014. Growth and survival of Apache Trout under static and fluctuating temperature regimes. Transactions of the American Fisheries Society 143:1247–1254.

Recsetar, M. S., M. P. Zeigler, D. L. Ward, S. A. Bonar, and C. A. Caldwell. 2012. Relationship between fish size and upper thermal tolerance. Transactions of the American Fisheries Society 141:1433–1438.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin 191. Ottawa.

Rieman, B. E., and J. D. McIntyre. 1995. Occurrence of Bull Trout in naturally fragmented habitat patches of varied size. Transactions of the American Fisheries Society 124:285–296.

Rinne, J. 1985. Variation in Apache trout populations in the White Mountains, Arizona. North American Journal of Fisheries Management 5:146–158.

Rinne, J. N. 1988. Grazing effects on stream habitat and fishes: research design considerations. North American Journal of Fisheries Management 8:240–247.

Rinne, J. N. 1990. The utility of stream habitat and biota for identifying potential conflicting forest land uses: Montane riparian areas. Forest Ecology and Management 33–34:363–383.

Rinne, J. N. 1996. The effects of introduced fishes on native fishes: Arizona, southwestern United States. Pages 149–159 *in* D. P. Philipp, J. Epifanio, J. E. Marsden, J. E. Claussen, and R. J. Wolotira, editors. Protection of aquatic biodiversity: Proceedings of the World Fisheries Congress, Theme 3. Oxford & IBH Publishing, New Dehli.

Rinne, J. N. 2001. Effects of substrate composition on Apache Trout fry emergence. Journal of Freshwater Ecology 16:355–365.

Rinne, J. N., and J. Janisch. 1995. Coldwater fish stocking and native fishes in Arizona: past, present, and future. Pages 397–406 *in* H. L. J. Schramm, and R. G. Piper, editors. Uses and effects of cultured fishes in aquatic ecosystems, volume 15. American Fisheries Society, Bethesda, Maryland.

Rinne, J. N., and A. L. Medina. 1988. Factors influencing salmonid populations in six headwater streams, central Arizona, USA. Polskie Archiwum Hydrobiologii 34:515–532.

Rinne, J. N., and W. L. Minckley. 1985. Patterns of variation and distribution in Apache Trout (*Salmo apache*) relative to co-occurrence with introduced salmonids. Copeia 1985:285–292.

Rinne, J. N., W. L. Minckley, and J. N. Hanson. 1981. Chemical treatment of Ord Creek, Apache County, Arizona, to re-establish Arizona Trout. Journal of the Arizona-Nevada Academy of Science 16:74–78.

Rinne, J. N., R. Sorensen, and S. C. Belfit. 1985. An Analysis of F_1 Hybrids between Apache, (*Salmo apache*) and Rainbow Trout, (*Salmo gairdneri*). Journal of the Arizona-Nevada Academy of Science 20:63–69.

Robins, R. R., R. M. Bailey, C. E. Bond, J. R. Brooker, E. A. Lachner, R. N. Lea, and W. B. Scott. 1980. A list of common and scientific names of fishes from the United States and Canada, Fourth Edition. American Fisheries Society, Bethesda, Maryland.

Robinson, A. T., L. D. Avenetti, and C. J. Cantrell. 2004. Evaluation of Apache Trout protection actions. Arizona Game and Fish Department, Phoenix, Arizona.

Robinson, A. T., and J. C. Tash. 1979. Feeding by Arizona Trout (*Salmo apache*) and Brown Trout (*Salmo trutta*) at different light intensities. Environmental Biology of Fishes 4:363–368.

Robinson, Z. L., J. A. Coombs, M. Hudy, K. H. Nislow, B. H. Letcher, and A. R. Whiteley. 2017. Experimental test of genetic rescue in isolated populations of Brook Trout. Molecular Ecology 26:4418–4433.

Rombough, P. J. 1986. Mathematical model for predicting the dissolved oxygen requirements of steelhead (*Salmo gairdneri*) embryos and alevins in hatchery incubators. Aquaculture 59:119–137.

Rosenberger, A. E., J. B. Dunham, J. R. Neuswanger, and S. F. Railsback. 2015. Legacy effects of wildfire on stream thermal regimes and Rainbow Trout ecology: an integrated analysis of observation and individual-based models. Freshwater Science 34:1571–1584.

Ruiz, L., and T. Ensman. 2001. Apache Trout genetic analysis: summary of results from 1994–2001. Pinetop, Arizona.

Schultz, L. D., M. P. Heck, D. Hockman-Wert, T. Allai, S. Wenger, N. A. Cook, and J. B. Dunham. 2017. Spatial and temporal variability in the effects of wildfire and drought on thermal habitat for a desert trout. Journal of Arid Environments 145:60–68.

Scott, J. H., and R. E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model.

Scott, J. M., D. D. Goble, A. M. Haines, J. A. Wiens, and M. C. Neel. 2010. Conservation-reliant species and the future of conservation. Conservation Letters 3:91–97.

Scott, J. M., D. D. Goble, J. A. Wiens, D. S. Wilcove, M. Bean, and T. Male. 2005. Recovery of imperiled species under the Endangered Species Act: the need for a new approach. Frontiers in Ecology and the Environment 3:383–389.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. Science 316:1181–1184.

Smith, D. R., N. L. Allan, C. P. McGowan, J. A. Szymanski, S. R. Oetker, and H. M. Bell. 2018. Development of a Species Status Assessment Process for Decisions under the U.S. Endangered Species Act. Journal of Fish and Wildlife Management 9:302–320.

Smith, G. R., and R. F. Stearley. 1989. The classification and scientific names of Rainbow and Cutthroat trouts. Fisheries 14:4–10.

Stratton, R. D. 2009. Guidebook on LANDFIRE fuels data acquisition, critique, modification, maintanence, and model calibration. Fort Collins, Colorado.

Tesch, F. W. 1971. Age and growth. Pages 98–130 *in* W. E. Ricker, editor. Methods for assessment of fish production in freshwaters. Blackwell Scientific Publications, Oxford, England.

Thompson, J. B., K. R. Snekvik, and E. R. Vincent. 2010. The effects of *Myxobolus cerebralis* on Apache and Gila Trout in laboratory exposures. Journal of Aquatic Animal Health 22:87–91.

Thompson, P. D., and F. J. Rahel. 1996. Evaluation of depletion-removal electrofishing of Brook Trout in small Rocky Mountain streams. North American Journal of Fisheries Management 16:332–339.

Thurman, L. L., B. A. Stein, E. A. Beever, W. Foden, S. R. Geange, N. Green, J. E. Gross, D. J. Lawrence, O. LeDee, J. D. Olden, L. M. Thompson, and B. E. Young. 2020. Persist in place or shift in space? Evaluating the adaptive capacity of species to climate change. Frontiers in Ecology and the Environment 18:520–528.

Torgersen, C. E., J. L. Ebersole, and D. M. Keenan. 2012. Primer for identifying cold-water refuges to protect and restore thermal diversity in riverine landscapes. EPA 910-C-12-001. Seattle.

Traill, L. W., B. W. Brook, R. R. Frankham, and C. J. A. Bradshaw. 2010. Pragmatic population viability targets in a rapidly changing world. Biological Conservation 143:28–34.

Trotter, P., P. Bisson, L. Schultz, and B. Roper. 2018. Cutthroat Trout: evoluationary biology and taxonomy. Special Publication 36, American Fisheries Society, Bethesda, Maryland.

Udall, B., and J. Overpeck. 2017. The twenty-first century Colorado River hot drought and implications for the future. Water Resources Research 53:2404–2418.

USFS. 2019. Riparian and aquatic ecosystem strategy: Southwest Region of the Forest Service. MB-R3-16-13, F. S. U.S. Department of Agriculture, Southwest Region,. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd762374.pdf.

USFWS. 1967. Native fish and wildlife - endangered species. Federal Register 32 (48):4001.

USFWS. 1975. "Threatened" status for three species of trout. Federal Register 40 (137):29863–29864.

USFWS. 1979. Recovery plan for Arizona Trout, *Salmo apache*, Miller, 1972. Apache Trout Recovery Team & U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

USFWS. 1983. Recovery plan for Arizona Trout, *Salmo apache*, Miller, 1972. Apache Trout Recovery Team & U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

USFWS. 2003. Gila trout recovery plan (third revision). Albuquerque, New Mexico.

USFWS. 2009. Apache Trout recovery plan. U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

USFWS. 2010. Apache Trout (*Onchorhynchus apache*) 5 year review: summary and evaluation. Pinetop, Arizona.

USFWS. 2016. USFWS Species Status Assessment Framework: an integrated analytical framework for conservation. Version 3.4, August 2016.

USGCRP. 2017. Climate science special report: fourth national climate assessment, Volume 1. Washington, DC, USA.

Vose, R. S., D. R. Easterling, K. E. Kunkel, A. N. LeGrande, and M. F. Wehner. 2017. Temperature changes in the United States. D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. Climate science special report: fourth national climate assessment, volume I. U.S. Global Change Research Program, Washington, D.C.

Vrijenhoek, R. C., M. E. Douglas, and G. K. Meffe. 1985. Conservation genetics of endangered fish populations in Arizona. Science 229:400–402.

Wada, L. L. L. 1991. Summer habitat use by Apache Trout (*Oncorhynchus apache*) in five streams on the Fort Apache Indian Reservation. Master's thesis. University of Arizona, Tuscon.

Wada, L. L. L., O. E. Maughan, and S. C. Leon. 1995. Habitat use by Apacht Trout (*Oncorhynchus apache*) on the Fort Apache Indial Reservation, Arizona. R. Barnhart, B. Shake, and R. H. Harnes, editors. Symposium Proceedings of Wild Trout V: Wild Trout in the 21st Century, Bozeman, Montana.

Walrath, J. D., D. C. Dauwalter, and D. Reinke. 2016. Influence of stream condition on habitat diversity and fish assemblages in an impaired upper Snake River Basin watershed. Transactions of the American Fisheries Society 145:821–834.

Wang, S., J. J. Hard, and F. Utter. 2002. Salmonid inbreeding: a review. Reviews in Fish Biology and Fisheries 11:301–319.

Waples, R. S. 2002. Definition and estimation of effective population size in the conseration of endangered species. S. R. Beissinger, and D. R. McCullough, editors. Population viability analysis. University of Chicago Press, Chicago.

Wares, J. P., D. Alo, and T. F. Turner. 2004. A genetic perspective on management and recovery of federally endangered trout (*Oncorhynchus gilae*) in the American Southwest. Canadian Journal of Fisheries and Aquatic Sciences 61:1890–1899.

Weathers, T. C., and S. Mussmann. 2020. Determining Apache Trout (*Oncorhynchus apache*) x Rainbow Trout (*Oncorhynchus mykiss*) hybrid introgression within the West Fork of the Little Colorado River, AZ. Report to Arizona Game and Fish Department, Southwestern Native Aquatic Resources and Recovery Center, U.S. Fish and Wildlife Service, Dexter, New Mexico.

Weathers, T. C., and S. Mussmann. 2021a. Assessing Apache Trout (*Oncorhynchus apache*) x Rainbow Trout (*Oncorhynchus mykiss*) hybrid introgression within Bear Wallow Creek, AZ. Report to Arizona Game and Fish Department, Southwestern Native Aquatic Resources and Recovery Center, U.S. Fish and Wildlife Service, Dexter, New Mexico.

Weathers, T. C., and S. Mussmann. 2021b. Evidence of Apache Trout (*Oncorhynchus apache*) x Rainbow Trout (*Oncorhynchus mykiss*) hybridiation within Paddy Creek, Arizona. Final report for Arizona Fish and Wildlife Conservation Office and White Mountain Apache Tribe Game and Fish Department, Southwestern Native Aquatic Resources and Recovery Center, U.S. Fish and Wildlife Service, Dexter, New Mexico.

Weathers, T. C., and S. Mussmann. 2021c. Genetic monitoring of an Apache Trout (*Oncorhynchus apache*) population in Bear Wallow Creek, Arizona. Final report for the Arizona Game and Fish Department, Southwestern Native Aquatic Resources and Recovery Center, U.S. Fish and Wildlife Service, Dexter, New Mexico.

Weise, E. M., N. M. Sard, A. Nehfer, and K. T. Scribner. 2020. Adaptive genetic management: assessing the benefits of translocations. Conservation Genetics 21:277–287.

Wenger, S. J., D. J. Isaak, C. H. Luce, H. M. Neville, K. D. Fausch, J. B. Dunham, D. C. Dauwalter, M. K. Young, M. M. Elsner, B. E. Rieman, A. F. Hamlet, and J. E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences 108:14175–14180.

Whiteley, A. R., S. W. Fitzpatrick, W. C. Funk, and D. A. Tallmon. 2015. Genetic rescue to the rescue. Trends in Ecology & Evolution 30:42–49.

Whiteley, A. R., K. Hastings, J. K. Wenburg, C. A. Frissell, J. c. Martin, and F. W. Allendorf. 2010. Genetic variation and effective population size in isolated populations of Coastal Cutthroat Trout. Conservation Genetics 11:1929–1943.

Whiteley, A. R., B. E. Penaluna, E. B. Taylor, S. Weiss, A. Abadía-Cardoso, D. Gomez-Uchida, I. Kiozumi, and P. Trotter. 2019. Trout and char: taxonomy, systematics, and phylogeography. Pages 95–140 *in* J. L.

Kershner, J. E. Williams, R. E. Gresswell, and J. Lobon-Cervia, editors. Trout and char of the world. American Fisheries Society, Bethesda, Maryland.

Whitney, J. E., K. B. Gido, T. J. Pilger, D. L. Propst, and T. F. Turner. 2015. Consecutive wildfires affect stream biota in cold- and warmwater dryland river networks. Freshwater Science 34:1510–1526.

Whitney, J. E., K. B. Gido, T. J. Pilger, D. L. Propst, and T. F. Turner. 2016. Metapopulation analysis indicates native and nonnative fishes respond differently to effects of wildfire on desert streams. Ecology of Freshwater Fish 25:376–392.

Williams, A. P., E. R. Cook, J. E. Smerdon, B. I. Cook, J. T. Abatzoglou, K. Bolles, S. H. Baek, A. M. Badger, and B. Livneh. 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. Science 368:314–318.

Williams, J. E., and J. M. Carter. 2009. Managing native trout past peak water. Southwest Hydrology 8:26–27, 34.

Williams, J. E., A. L. Haak, N. G. Gillespie, and W. T. Colyer. 2007. The Conservation Success Index: synthesizing and communicating salmonid condition and management needs. Fisheries 32:477–492.

Williams, J. E., A. L. Haak, H. M. Neville, and W. T. Colyer. 2009. Potential consequences of climate change to persistence of Cutthroat Trout populations. North American Journal of Fisheries Management 29:533–548.

Williams, J. E., H. M. Neville, A. L. Haak, W. T. Colyer, S. J. Wenger, and S. Bradshaw. 2015. Climate change adaptation and restoration of western trout streams: opportunities and strategies. Fisheries 40:304–317.

Williams, T., and B. C. Bedford. 1974. The use of otoliths for age determination. Pages 114–123 *in* T. B. Bagenal, editor. Ageing of fish. The Gresham Press, Old Working, Surrey, England.

Wilson, W. D., and T. F. Turner. 2009. Phylogenetic analysis of the Pacific Cutthroat Trout (*Oncorhynchus clarki ssp.*: Salmonidae) based on partial mtDNA ND4 sequences: A closer look at the highly fragmented inland species. Molecular Phylogenetics and Evolution 52:406–415.

Zeigler, M. P., K. B. Rogers, J. J. Roberts, A. S. Todd, and K. D. Fausch. 2019. Predicting persistence of Rio Grande Cutthroat Trout populations in an uncertain future. North American Journal of Fisheries Management 39:819–848.

APPENDIX A. EXPERT ELICITATION TO DEFINE APACHE TROUT CONDITION AND THE LIKELIHOOD OF FUTURE SCENARIOS

Expert Elicitation and the Delphi Method

The Delphi method is a technique widely used for group elicitation in natural resource management to understand ecological relationships and demographic parameters (Conroy and Peterson 2013). The Delphi method generally uses the following process: experts are provided with a background and description of the ecological system, experts provide their expert judgement independent of the group, the expert's judgements are summarized and anonymously provided back to individuals in the group to inform a group discussion around the problem at hand, and then the experts are given an opportunity to revise their judgement (Delbecq et al. 1975; Conroy and Peterson 2013). The objective of the Delphi method in natural resource management is to reach consensus among experts regarding ecological parameters and relationships while reducing the influence of human behaviors that can influence group dynamics, that is, to ensure no one person, or set of persons, dominates in a group setting and plays an overbearing role in defining a relationship or parameter. For example, strong personalities can dictate outcomes from group elicitation processes when done in a group setting, and other group members may not voice their judgement to avoid disagreements with others. Anonymous surveys can help circumvent these group dynamics.

Expert Elicitation to Define the Current Condition of Apache Trout

The Delphi method was used to identify Very Poor, Poor, Fair, Good, and Very Good condition classes for the three demographic and five habitat factors used to describe the current conditions for Apache Trout populations and for which data were compiled for the Apache Trout Species Status Assessment (Table 11). The Delphi method applied to Apache Trout current conditions consisted of eliciting judgement from Apache Trout experts through: Survey #1 (anonymous), a group discussion regarding the results of Survey #1, and Survey #2 (anonymous). During Survey #1 Apache Trout experts were asked to classify data categories or identify threshold values between the condition classes (Very Poor, Poor, Fair, Good, and Very Good) for each demographic and habitat factor. After Survey #1, the experts were given their individual survey responses along with a summary of all survey responses, and then the group discussed the demographic and habitat factors and survey results as a group (via conference call). After the group discussion the experts were issued Survey #2, which contained the same questions as Survey #1 and allowed the experts to revise their responses, if desired, based on the group discussion. The reason for the group discussion was to ensure survey participants (species experts) understood the rationale for the question, allow them to see if their answer represented an outlier from the group, and allow them ask questions about why their answer differed or clarify the question if desired.

The Apache Trout Experts

Apache Trout experts participating in the Delphi method to define current conditions represented approximately equally those who have primarily worked on the species on the Fort Apache Indian Reservation or the Apache-Sitgreaves National Forests (or both; Figure 26A). Participants represented the following agencies: White Mountain Apache Tribe, Arizona Department of Fish and Game, USFWS (Ecological Services and the Arizona Fish and Wildlife Conservation Office), the Apache-Sitgreaves National Forests, and a non-governmental organization (Trout Unlimited; Figure 26B).

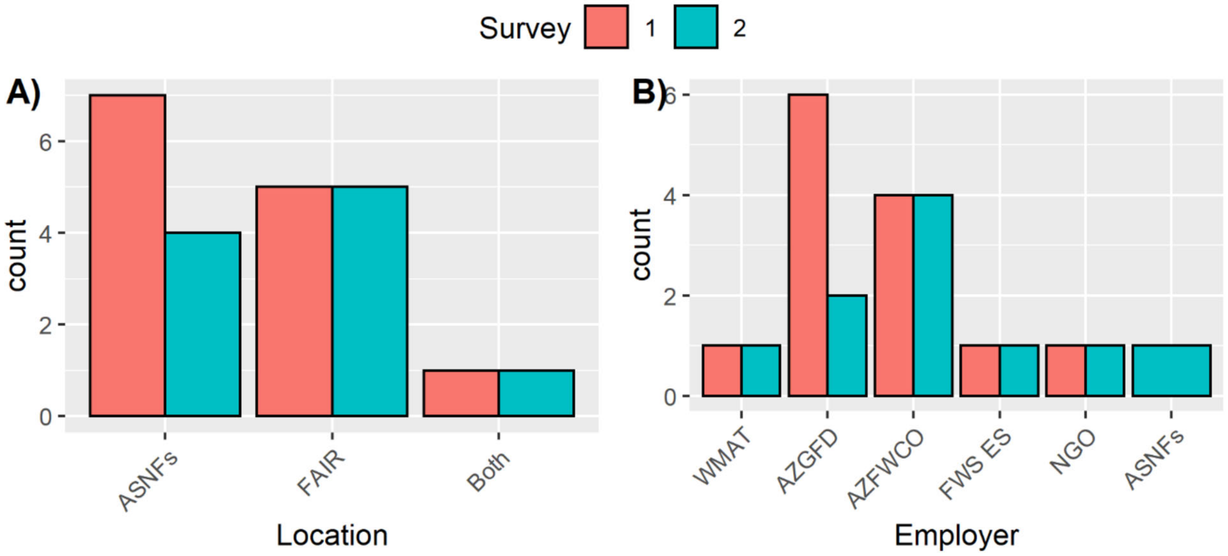

Figure 26. Frequency of work location and agency representation among experts completing Survey #1 and Survey #2 as part of the Delphi method used to assess the condition of demographic and habitat factors reflecting the current condition of Apache Trout populations. Locations are: Apache-Sitgreaves National Forests (ASNF) and Fort Apache Indian Reservation (FAIR). Employers are: White Mountain Apache Tribe (WMAT), Arizona Game and Fish Department (AZGFD), Arizona Fish and Wildlife Conservation Office (AZFWCO; USFWS), USFWS – Ecological Services (FWS ES), Non-governmental organization (NGO [Trout Unlimited]), and ASNF.

The Experts Define Current Conditions

The responses by Apache Trout experts showed less variability during Survey #2 than Survey #1 (Figure 27). This showed that there was more agreement among experts during Survey #2 (i.e., convergence on consensus but not consensus), which is expected as the discussion portion of the Delphi method is intended to reduce outliers due to misunderstanding of the ecological system or misinterpretation of the survey question(s). For example, survey participants thought Apache Trout populations that were suspected to be hybridized represented a Very Poor to Good current condition in Survey #1, but responses only ranged from Very Poor to Fair in Survey #2 (Figure 27A); this illustrates that no expert thought suspected hybridization represented a Good condition, but the lack of a singular response among the experts also illustrates the difficulty in classifying populations when there is incomplete information such as a lack of testing for genetic purity. As a second example, participants showed a lot of variation in their responses regarding the level of % Intermittency that should defined Very Poor and Poor conditions during Survey #1, but after the group discussion that variation decreased substantially and showed more coherent agreement among participants in Survey #2 (Figure 27D). The Survey #2 results were used to develop the grading criteria and grade point equivalents for each demographic and habitat factor (see section "Population Resiliency: A Grading Scale").

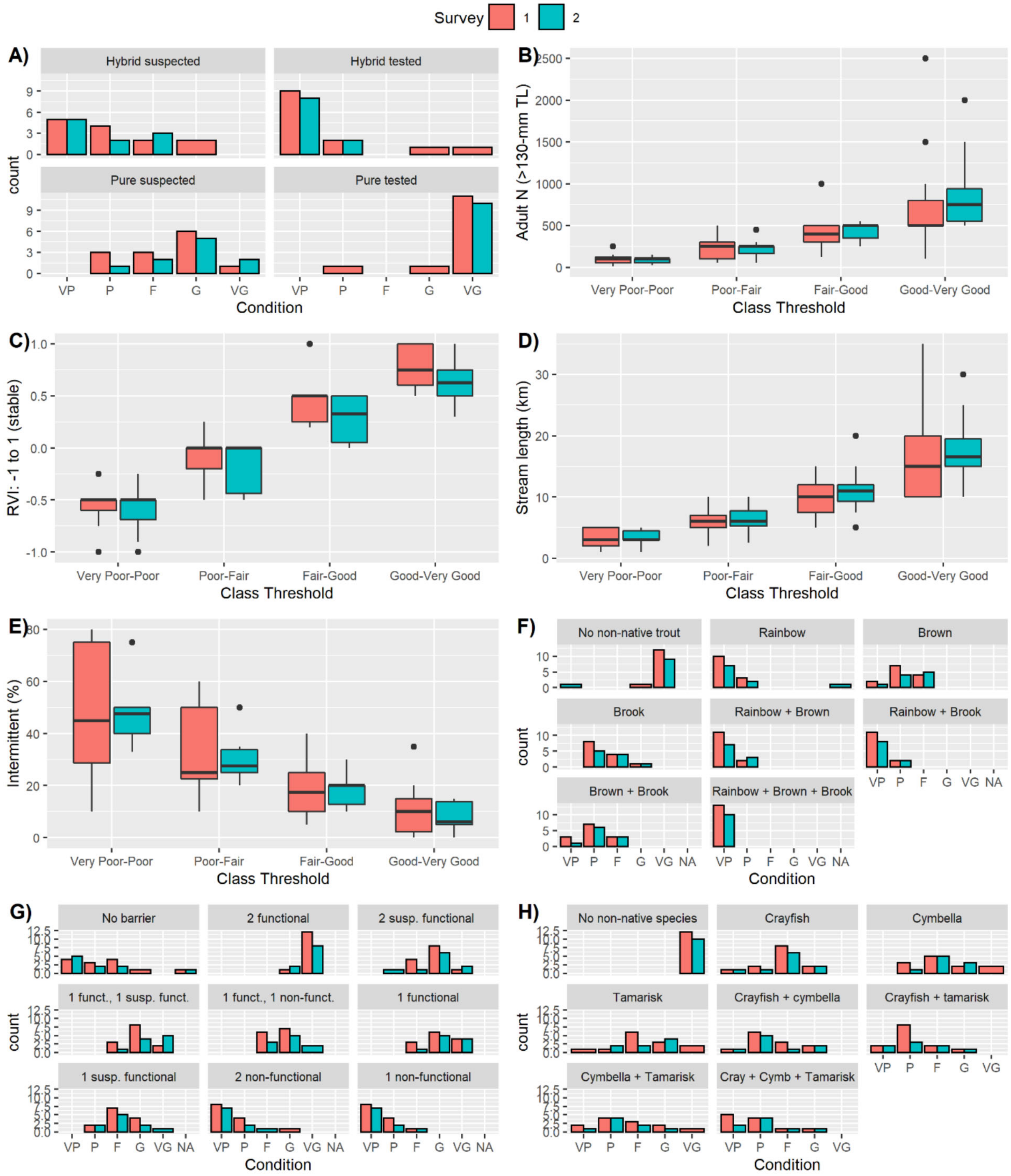

Figure 27. Survey #1 and #2 responses from a Delphi method used to classify conditions for Apache Trout populations for A) genetic purity-hybridization, B) adult abundance (≥130-mm TL), C) recruitment variation index (RVI) values (eventually omitted), D) stream length occupied (patch size), E) percent of habitat that is intermittent during severe drought, F) nonnative trout presence, G) protective barrier status, and H) nonnative (non-fish) species presence (also omitted). Condition: VP=Very Poor, P=Poor, F=Fair, G=Good, or VG=Very Good; NA = Not Available (question left blank).

Expert Elicitation: The Likelihood of Future Scenarios

Apache Trout experts were also queried via a survey instrument to rank the likelihood of each Future Condition scenario occurring over 30- and 100-year timeframes as part of the Apache Trout Species

Status Assessment (see section "Future Conditions of Apache Trout"). The experts responded to each scenario as having a likelihood of occurring as: Very Unlikely, Somewhat Unlikely, Neutral, Somewhat Likely, or Very Likely. While the scenarios were focused on a 30-year timeframe, exerts were asked about the likelihood of the scenarios occurring over both a 30-year and 100-year timeframe. This survey was only administered once and was not part of a Delphi process.

Future Scenario Likelihoods

Most Apache Trout experts thought that Scenario #3 was Somewhat Likely and Very Likely to occur over the next 30 years, whereas they thought the pessimistic (Scenario #1) and aspirational (Scenario #5) scenarios were unlikely to occur (with some exceptions; Figure 28A). Over a 100-year timeframe, species experts continued to think that Scenario #3, followed by Scenarios #2 and #4, was most likely to occur. There was considerable variation in responses regarding the likelihood of the pessimistic (Scenario #1) and aspirational (Scenario #5) scenarios, which is not surprising given the long and uncertain 100-year timeframe (Figure 28B).

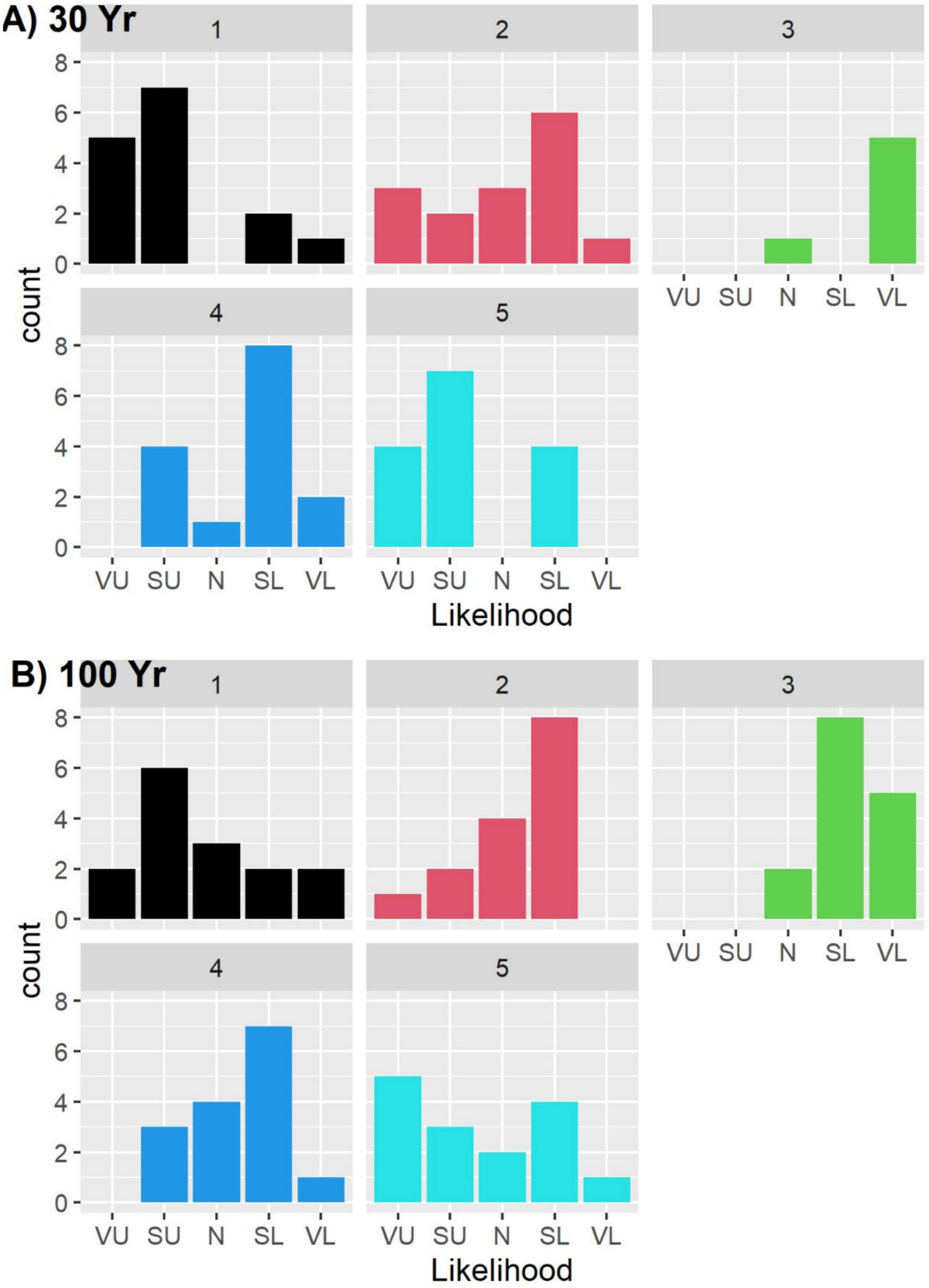

Figure 28. Frequency of responses by Apache Trout Experts regarding the likelihood of each of 5 Future Conditions Scenarios occurring in 30-year (A) and 100-year (B) timeframes. VU=Very Unlikely, SU=Somewhat Unlikely, N=Neutral, SL=Somewhat Likely, VL=Very Likely. N = 15.

APPENDIX B. VULNERABILITY OF APACHE TROUT TO WILDFIRE AND FUTURE WARMING

The vulnerability of Apache Trout to future wildfires and stream temperature warming was evaluated as a function of future wildfire risk, debris flow risk, and future stream temperatures using the methods described in Dauwalter et al. (2017b). The objectives were to 1) summarize wildfire history within the historical range of Apache Trout, and 2) use spatially explicit wildfire, debris flow, and stream temperature models to identify Apache Trout streams least vulnerable to these future threats.

Methods

Wildfire history

We summarized fire history in within the historical range of Apache Trout in the southwestern United States that includes the White and Black Rivers above 1,800 m elevation within the Gila River drainage (Behnke 2002). We used the Monitoring Trends in Burn Severity program database to summarize fire frequency, fire extent, and ignition timing from 1985 to 2015 (Eidenshink et al. 2007). We evaluated trends in total hectares burned by years using linear regression ($\alpha = 0.05$).

Wildfire risk

We developed spatially-explicit estimates of wildfire risk for Apache Trout streams using FlamMap 5.0 software. FlamMap models fire behavior characteristics from a static set of environmental conditions: fuel moisture based on vegetation type, wind speed and direction, and topography. FlamMap models active and passive crown fire potential using weather conditions, including wind interactions with topography, and we used crown fire potential as a measure of wildfire risk. We used WindNinja software to model wind routing through the landscape and initialize wildfire behavior for input into FlamMap (Forthofer 2007). To parameterize WindNinja, we used average daily maximum wind gust speed and average wind direction using data during the fire season (April 1 through August 31; see Results) from 2010 to 2015 as summarized from six Remote Automated Weather Station (RAWS) stations representative of our study area: Greer (AZ), Mountain Lion (AZ), Alpine (AZ), Beaverhead (NM), Mogollon (NM), and Pelona Mountain (NM; http://www.raws.dri.edu/). We used an average maximum wind speed of 24 km/h (6.1-m above ground) based on observed wind speeds, and we modeled wind routing as a weighted-average of the proportion of average daily wind directions at 16 azimuthal directions (20°, 40°, 60°, 90°, 120°, 140°, 160°, 180°, 200°, 220°, 240°, 270°, 300°, 320°, 340°, 360°) across the six RAWS stations. Wind routing was implemented in WindNinja based on interactions with landscape topography (slope and aspect) from a 30-m digital elevation model. The most recent vegetation data from 2014 (includes 2014 fire season) were acquired from LANDFIRE (http://www.landfire.gov) and used as fire fuel input (Stratton 2009). Fire fuels were based on the 40 Scott and Burgan Fire Behavior Fuel Models, which represents fuel loadings based on vegetation types, size classes, and other fuels (Scott and Burgan 2005). Default fuel moisture levels were used for each vegetation type.

The spatial predictions of active and passive crown fires from FlamMap were summarized within the watershed upstream of all stream segments in the study area using the National Hydrography Dataset Plus (NHD+) version 2. The NHD+ dataset represents 1:100,000 map scale hydrography for all confluence-to-confluence stream segments; NHD+ stream segments average approximately 1-km in length. Wildfire risk was expressed as the percentage of each watershed predicted to have active or passive crown fire.

Debris flow risk

Wildfire risk and other physiographic factors were used to model post-fire debris flow probability and debris flow sediment volume (if a debris flow were to occur) using models from Cannon et al. (2010). Post-fire debris flow probability was computed as: $P_{\text{debris flow}} = e^x / 1 + e^x$, where: $x = -0.7 + 0.03 \cdot BG30 - 1.6 \cdot Rugg + 0.06 \cdot HSBurn + 0.2 \cdot Clay - 0.4 \cdot LiqLim + 0.07 \cdot StormInt$, and: BG30 is the percent watershed area with slopes greater than 30%; Rugg is the watershed ruggedness computed as watershed relief (elevation maximum – minimum) divided by square-root of watershed area; HSBurn is the percent of watershed area burned at moderate to high burn severity (here replaced with percent watershed area predicted to have active or passive crown fire as described above); Clay is the average clay content of soil in watershed; LiqLim is the average liquid limit of soils in watershed; and StormInt is the average storm rainfall intensity (mm/h) in the watershed (replaced with average 30-min storm intensity at a 2-year recurrence interval [mm/h] from National Weather Service). Watershed characteristics were computed using geospatial datasets as described in Cannon et al. (2010).

The predicted volume of debris flow material (V; units: m^3) was: $\ln(V) = 7.2 + 0.6 \cdot (BG30) + 0.7 \cdot HSBurn^{0.5} + 0.2 \cdot TotStorm^{0.5} + 0.3$, where: BG30 is as defined above; HSBurn is as defined above (also replaced with percent watershed area predicted to have active or passive crown fire); TotStorm is the total storm rainfall in watershed (mm; replaced with average 30-min storm intensity [mm/h] at a 2-year recurrence interval; Cannon et al. 2010).

Debris flow probabilities and volumes were modeled for all segments in the NHD+ dataset in our study area. Thus, each ~1-km stream segment has a debris flow probability and volume that reflects wildfire risk and other watershed characteristics.

2080s temperature risk

We evaluated stream temperature risk to climate warming using the NorWeST stream temperature model developed for Arizona (Isaak et al. 2017a). The model predicts mean August temperatures measured *in situ* using digital thermographs as a function of elevation, canopy cover, stream slope, precipitation, drainage area, latitude, lakes and reservoirs, groundwater influence, air temperatures, and streamflows using a spatial statistical modeling approach (Isaak et al. 2016; Isaak et al. 2017a). Temperature projections for the 2080s were based on August air temperature inputs from a global climate model ensemble for the A1B warming trajectory (middle of the road scenario). Model details can be found at: www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html. The Arizona model was fit using 251 site-years of data and had a root mean squared prediction error (RMSPE) of 1.06°C, suggesting the mean August temperature predictions were accurate to within ~1°C 66% and ~2°C 95% of the time. The models were used to make spatially explicit mean August temperature predictions for 1-km stream segments in the study area using NHD+ stream segments (Isaak et al. 2017a). Although the NorWeST model predicts mean August temperature, the predictions were converted to mean July temperature (mean July °C = 2.84 × 0.84[mean August °C]; $R^2 = 0.76$; see Figure 6) because July is typically warmer than August and those temperatures more relevant to Apache Trout thermal tolerances.

Apache Trout stream vulnerability

We summarized wildfire risk, debris flow risk, and 2080s stream temperature risk for all Apache Trout streams identified as potentially being useful for conservation of the species (USFWS 2009). Apache Trout stream extents were delineated using a combination of field data and professional judgement (Figure 29). Streams were classified as: relict, replicate, hybrid, or unoccupied (see "Species Current Condition"). For each stream we summarized the average percent wildfire risk, mean debris flow probability, mean debris flow volume, minimum mean July stream temperature projected for the 2080s (*i.e.*, the coldest stream segment in occupied or recovery habitat), the kilometers of each delineated stream projected to have mean July temperatures below 16.5°C in the 2080s, and percent of habitat below 16.5°C in the 2080s. These summaries were completed for each of the Apache Trout streams in the historical range of the species (Figure 29). All stream averages were length (habitat extent) or area (watershed) weighted. The temperature 16.5°C was based on the 95th percentile of all temperatures (averaged from 2002 to 2011) within Apache Trout streams and an empirical model of the Apache Trout's thermal niche (Appendix C). Each stream was ranked for each of the three wildfire and 3 temperature factors (rank=1 is lowest vulnerability), and the average rank was used to rank the overall vulnerability across the six factors (again, rank=1 is lowest overall vulnerability).

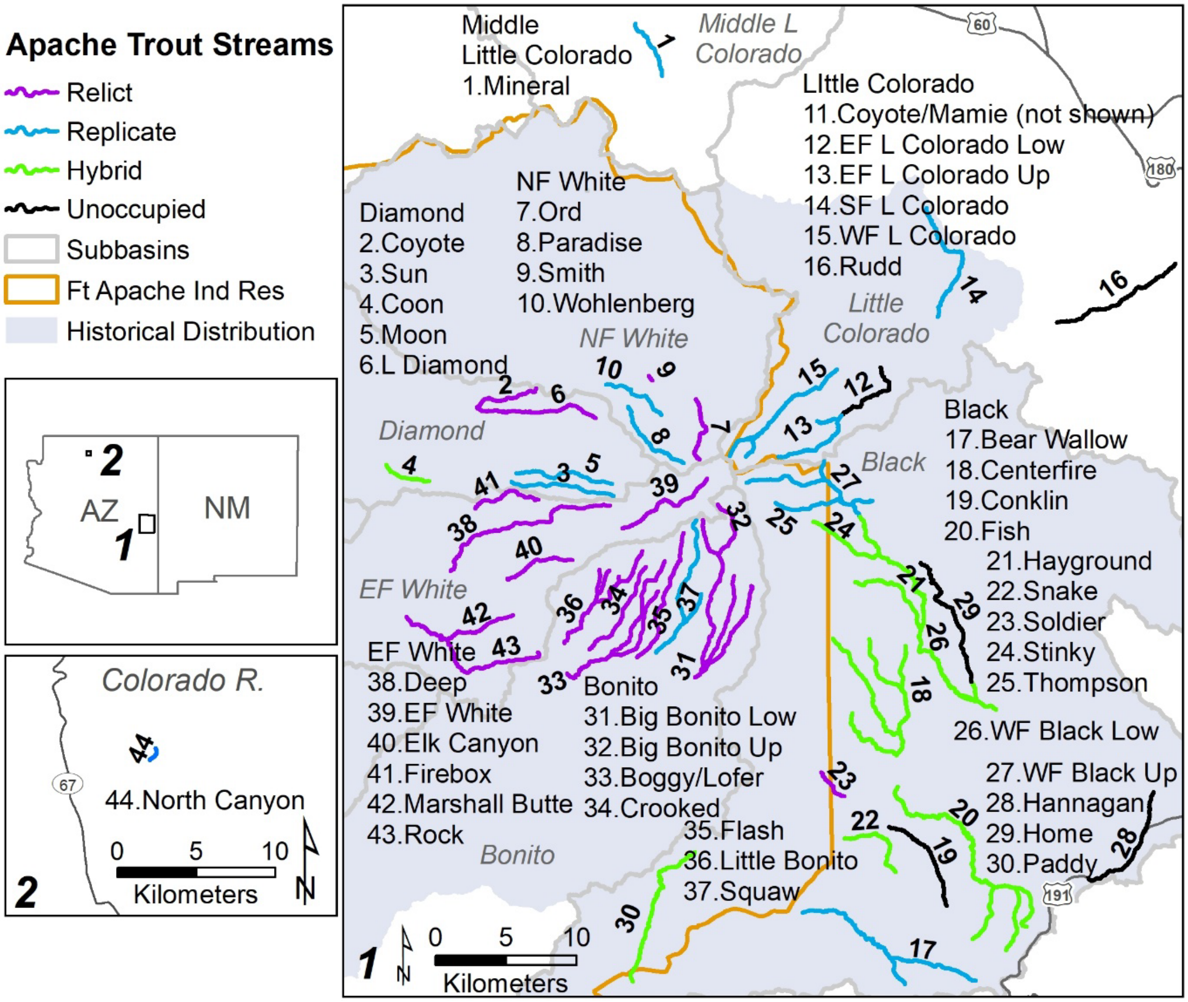

Figure 29. Apache Trout streams evaluated for future wildfire and temperature warming risk.

Results

We summarized wildfire, debris flow, and 2080s stream temperature risk information and vulnerability for 45 Apache Trout streams in Arizona that represent 17 relict populations, 12 replicated populations, 9 hybrid populations, and 7 unoccupied streams identified for future recovery efforts (Figure 29; Table 19).

Wildfire history

Within the historical range of Apache Trout in Arizona, there were 59 total fires from 1987 to 2018, and 38 of those were wildfires totaling over 335,000 hectares (top left panel of Figure 30). Wildfires started primarily in April through September (top right panel of Figure 30). The median fire size from 1987 to 2018 was 1,300 ha, with an increasing but non-significant trend in the maximum fire size and total area burned over time ($b_{Year} = 1.04$; df = 23; $P = 0.248$) that reflects the large Wallow Fire in 2011 (Figure 29; bottom panels of Figure 30).

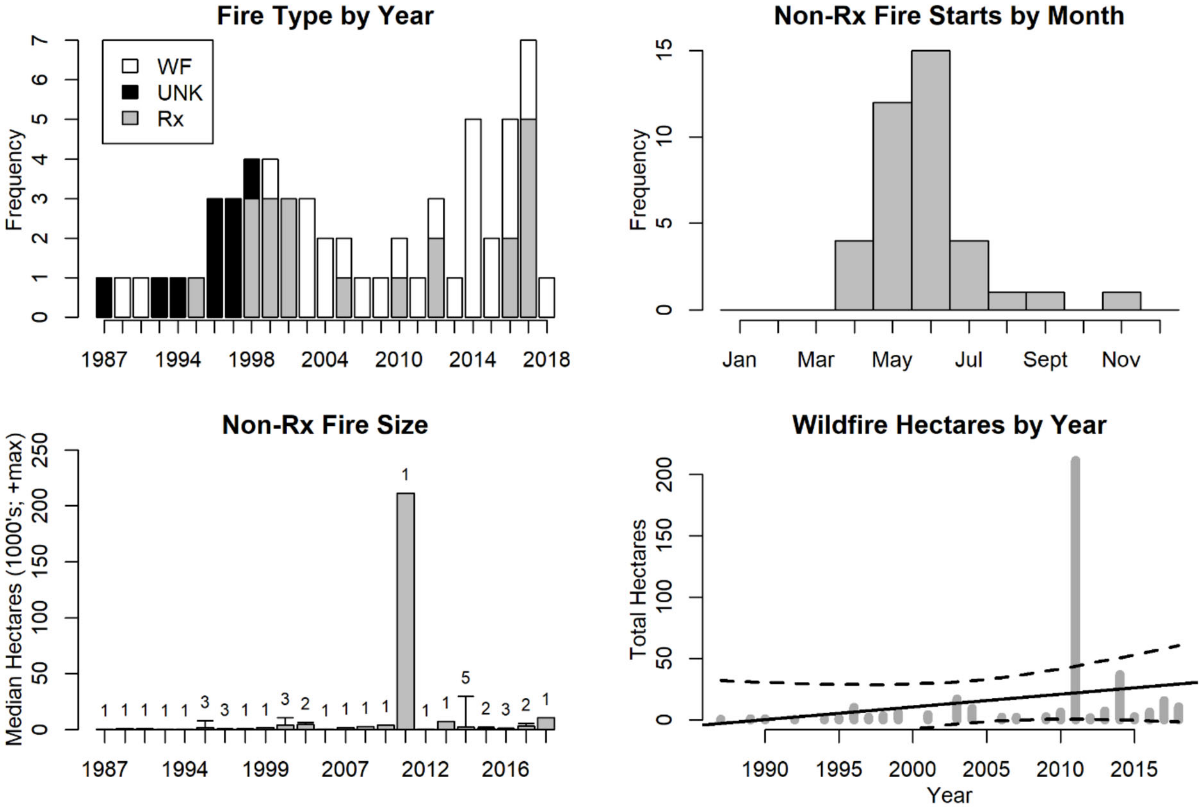

Figure 30. Frequency of wildfire (WF), prescription (Rx), and unknown (UNK; possibly wildfire or intentionally started) fire types by year (top left panel), frequency of fire starts by month (top right panel), median fire size (error bars = maximum; number of fires above bar) by year (bottom left), and total hectares burned by wildfire by year with trend line and 95% confidence intervals ($b_{Year} = 1.04$; df = 23; $P = 0.248$).

Wildfire risk

Apache Trout streams exhibited a range of wildfire risk. The percent of watershed with high wildfire risk (active and passive crown fires) ranged from 5% in Bear Wallow Creek to 50% in Smith Creek (Table 19). Unoccupied streams ranged from 5% (Hannagan) to 44% (Lee Valley) of their watershed with high wildfire risk. Not surprisingly, wildfire risk was lower within old burn perimeters such as the 2011 Wallow Fire (top panel of Figure 31).

Debris flow risk

The risk of post-fire debris flows was generally low in Apache Trout streams (Table 19). Probabilities of a debris flow occurring given modeled wildfire risk and other physiographic factors within the watersheds ranged from <0.001 (multiple streams) to 0.07 (West Fork LCR; Table 19). Watersheds with higher debris flow probabilities were clustered around Mount Baldy (Figure 29; middle panel of Figure 30). Predicted debris flow volumes, if a debris flow were to occur, ranged from 2,000 m^3 (Stinky Creek) to nearly 1.3 million m^3 (Snake Creek).

2080s temperature risk

Most Apache Trout streams had at least some stretches that remained thermally suitable into the 2080’s, and about half of them contain suitable thermal habitat of sufficient size to meet criteria for long-term persistence that have been applied to native trout in the western United States (bottom panel of Figure 32). For example, many streams had at least 11 km of habitat below 16.5°C, which is also a habitat extent (patch size) thought to represent Good to Very Good conditions for Apache Trout (Figure 27D; Figure 33; Figure 34). Only 11 streams had less than 100% of habitat <16.5°C (Table 19); 7 of these were on the Apache-Sitgreaves National Forests and 4 were on the Fort Apache Indian Reservation.

Apache Trout stream vulnerability

When the 45 Apache Trout streams were ranked according to the five wildfire, debris flow, and temperature risk factors a mix of relict and replicated populations and unoccupied streams portended their low vulnerability to wildfire and 2080s temperature increases due to climate change (Table 19). Centerfire Creek, a stream with a hybridized population of Apache Trout, showed the highest vulnerability. Boggy/Lofer, Big Bonito, Coyote and Marshall Butte represented relict populations with low vulnerability, and Paradise, Thompson, and South Fork LCR were replicate populations that were least vulnerable. Low vulnerability of streams within the Wallow Fire (2011) perimeter likely reflects the change in post-fire vegetation and fuels that are less conducive to crown fires.

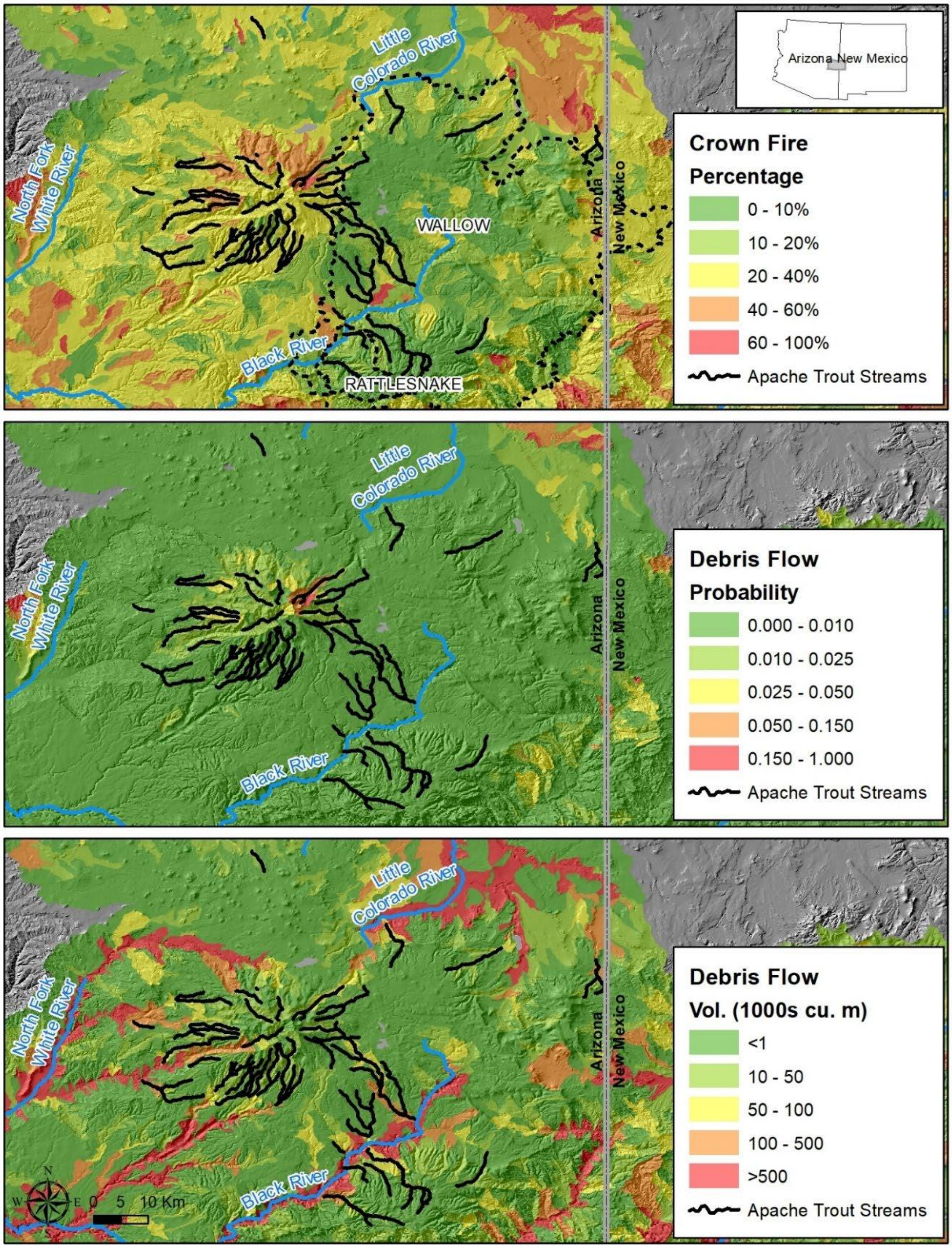

Figure 31. Example of percent watershed with high wildfire risk (active or passive crown fire) from FlamMap model (top panel), predicted debris flow probability given wildfire risk in watershed (middle panel), and predicted debris flow volume (bottom panel) for Apache Trout streams in Arizona. Wallow and Rattlesnake fire perimeters shown in top panel (black dashed line).

Table 18. Percent watershed with high wildfire risk (active or passive crown fire), mean debris flow probability given wildfire risk, debris flow volume, minimum mean July temperature in the 2080s (coldest stream segment or patch), and habitat extent (km) below 16.5°C in the 2080s, and overall vulnerability rank of Apache Trout streams (a rank of 1 being least vulnerable).

Type	Population	Crown Fire (%)	Debris Flow Probability	Debris Flow Volume (1000s m^3)	Minimum July °C (2080s)	Km <16.5°C (2080s)	% Habitat <16.5°C (Current)	% Habitat <16.5°C (2080s)	Vulner-ability Rank
Hybrid	Centerfire	10.0	<0.001	5	15.8	19	70.7	55.3	5.0
	Coon	13.6	0.001	7	14.5	4	100.0	100.0	7.0
	Fish	6.1	0.002	35	14.6	31	98.6	88.2	11.0
	Hayground	11.1	0.002	10	15.1	6	100.0	85.2	20.0
	Reservation	29.0	0.005	9	12.7	6	99.0	99.0	23.0
	Snake	12.0	0.001	1366	15.3	4	99.9	53.4	43.0
	Stinky	9.2	0.002	2	14.3	6	100.0	100.0	4.0
	WF Black (Lower)	13.9	0.002	147	14.4	14	68.6	49.1	42.0
Relict	Big Bonito (Lower)	20.5	0.004	24	12.4	32	100.0	100.0	3.0
	Big Bonito (Upper)	22.8	0.006	13	12.1	3	100.0	100.0	15.5
	Boggy Lofer	21.3	0.004	12	13.4	21	100.0	100.0	1.0
	Coyote	23.5	0.005	6	14.3	6	100.0	100.0	15.5
	Crooked	25.2	0.007	20	13.1	8	100.0	100.0	21.5
	Deep	42.4	0.022	36	12.8	16	99.3	99.3	40.5
	East Fk White	29.7	0.020	73	12.2	12	100.0	100.0	33.5
	Elk Canyon	32.3	0.013	19	13.4	8	100.0	100.0	35.0
	Firebox	24.8	0.003	16	14.7	5	100.0	100.0	24.0
	Flash	31.3	0.007	37	13.3	10	100.0	100.0	25.0
	Little Bonito	31.3	0.010	22	12.9	17	100.0	100.0	17.5
	Little Diamond	44.5	0.024	35	12.3	11	100.0	100.0	32.0
	Marshall Butte (DP)	26.4	0.004	12	14.9	6	100.0	100.0	29.0
	Ord	38.4	0.010	16	10.5	6	100.0	100.0	27.0
	Rock	22.2	0.002	51	14.9	10	87.3	53.8	40.5
	Smith	50.0	0.024	25	11.5	1	100.0	100.0	44.0
	Soldier	44.0	0.002	4	15.7	3	100.0	100.0	33.5
Replicate	Bear Wallow	5.2	0.001	42	14.3	17	75.2	74	13.0
	East Fk LCR (Upper)	23.2	0.005	6	14.6	8	100.0	100.0	14.0
	Mineral	32.0	0.001	7	14.8	6	100.0	100.0	19.0
	Moon	41.7	0.014	15	13.0	9	100.0	100.0	28.0
	North Canyon	--	--	--					
	Paradise	34.4	0.011	34	12.4	6	77.3	44.7	30.0
	South Fk LCR	10.4	<0.001	39	14.7	6	100.0	100.0	36.0
	Squaw	20.6	0.007	16	13.3	14	100.0	100.0	8.5
	Sun	48.9	0.026	20	12.8	10	100.0	100.0	37.0
	Thompson	31.9	0.013	5	11.3	2	100.0	100.0	21.5
	West Fk Black (Upper)	26.0	0.015	25	12.0	18	100.0	100.0	10.0
	West Fk LCR	48.0	0.074	37	7.1	14	100.0	100.0	31.0
	Wohlenberg	43.6	0.009	8	10.6	6	100.0	100.0	17.5
Unoccupied	Conklin	8.2	0.002	15	15.1	8	100.0	100.0	6.0
	Coyote/Mamie	19.3	0.002	40	14.2	15	100.0	71.6	12.0
	East Fk LCR (Lower)	19.0	0.002	13	15.6	5	100.0	100.0	38.5
	Hannagan	5.3	0.001	9	14.7	9	92.0	83.0	2.0
	Home	7.0	<0.001	9	15.2	11	100.0	100.0	8.5
	Lee Valley	43.7	0.027	4	13.5	3	47.0	47.0	38.5
	Rudd	11.4	<0.001	32	14.0	7	100.0	100.0	26.0

*No overall rank due to lack of fire risk or debris flow data.

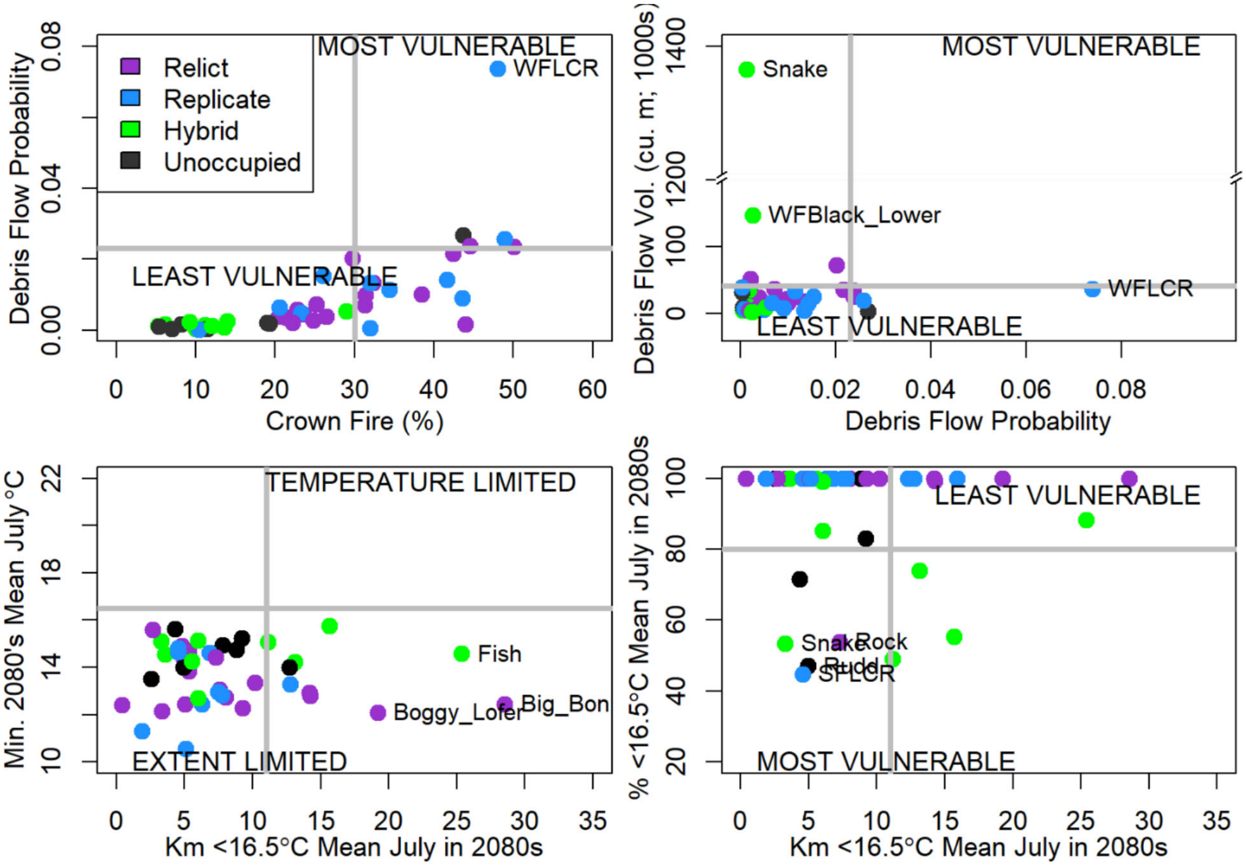

Figure 32. Crown fire percentage versus predicted debris flow probability (top left), debris flow probability versus predicted debris flow volume (top right), length of habitat predicted to have mean July temperatures <16.5°C in the 2080s versus the minimum predicted mean July temperature in the 2080s (bottom left), and length of habitat <16.5°C in the 2080s versus percent of habitat <16.5°C in the 2080s (bottom right) for Apache Trout streams. See Table 19.

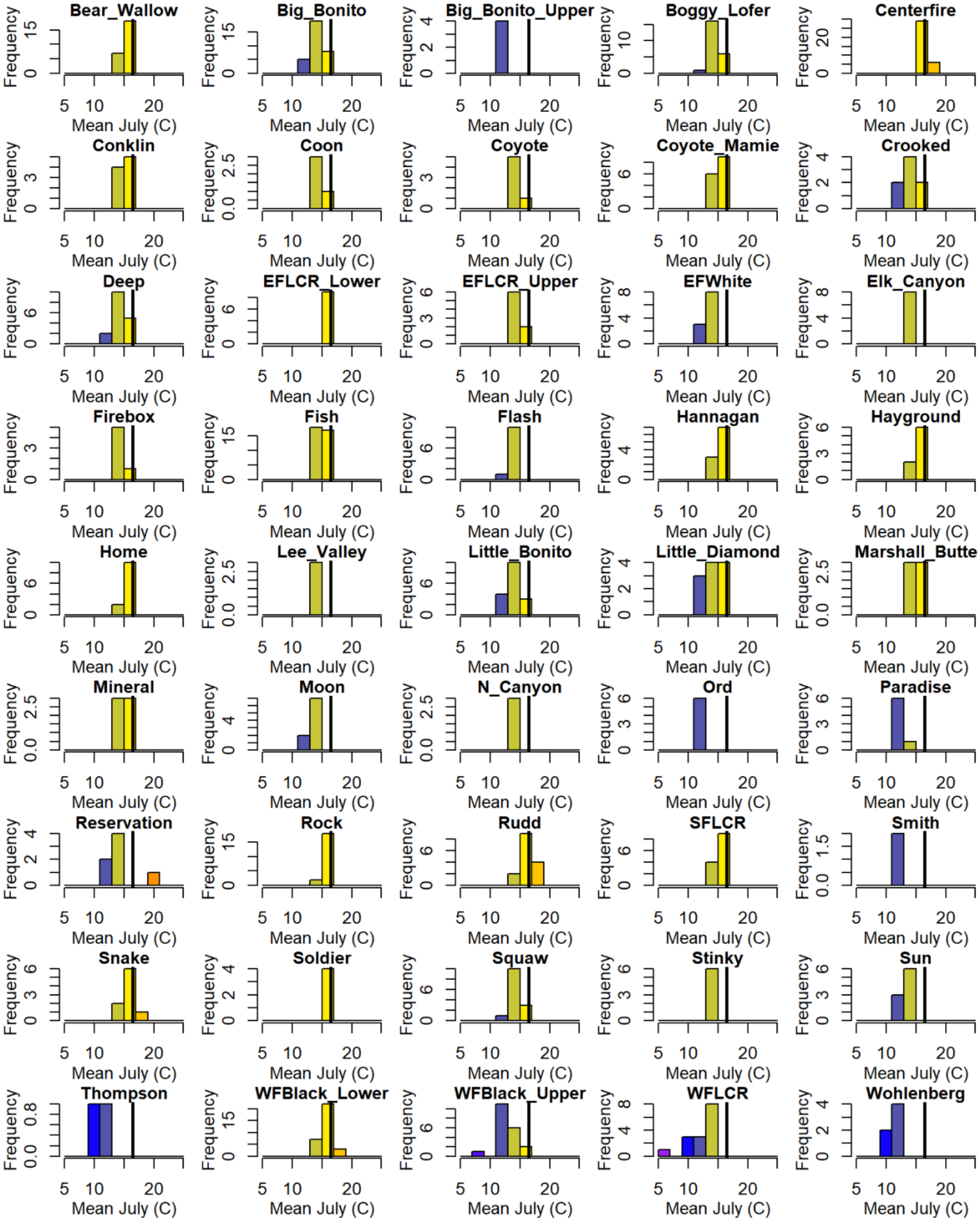

Figure 33. Distribution of present-day mean July temperatures within each Apache Trout population from the NorWeST stream temperature model for Arizona. Vertical black line is 16.5°C.

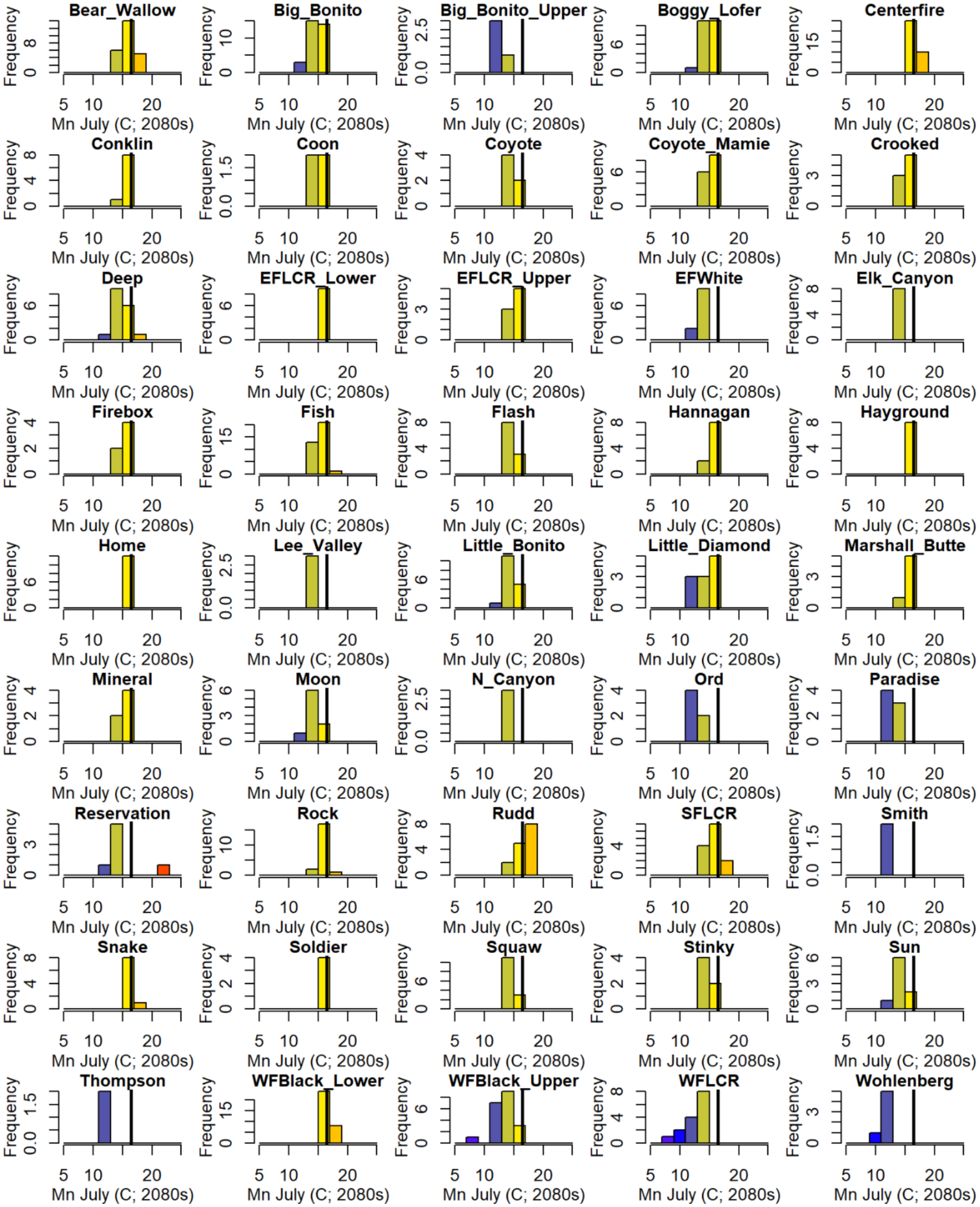

Figure 34. Distribution of predicted 2080s (A1B scenario) mean July temperatures within each Apache Trout population from the NorWeST stream temperature model for Arizona. Vertical black line is 16.5°C.

APPENDIX C. CLIMATE INFLUENCES ON APACHE TROUT DISTRIBUTION AND IDENTIFICATION OF CLIMATE RESILIENT HABITATS

The global climate has changed when compared to historical records, and it is projected to continue to change due to increases in atmospheric carbon dioxide and other greenhouse gasses (USGCRP 2017). In the western U.S., snowpack has decreased, late-winter mean temperatures (January to March) have increased, and snowmelt run-off occurs earlier (Barnett et al. 2008). There has also been an eight-fold increase since 1985 in the amount of land burned at high severity during wildfires (Parks and Abatzoglou 2021). These trends are projected to continue into the future resulting in novel climatic conditions (Gonzales et al. 2018; Crausbay et al. 2020). They are expected to have substantial impacts on aquatic ecosystems and fisheries (Gresswell 1999; Myers et al. 2017), particularly on the distribution and abundance of cold-water, stenothermic organisms such as salmonids (Williams et al. 2009; Kovach et al. 2016). For example, Wenger et al. (2011) used climate model projections to show that suitable habitat for Cutthroat Trout *Oncorhynchus clarkii* across the interior western U.S. will decrease by 50% by the 2080s due to increasing temperatures, changing flow regimes, and interactions with nonnative trout. Climate impacts on salmonids are reviewed by Kovach et al. (2016).

The Southwest has the hottest and driest climate in the U.S. The Fourth National Climate Assessment suggests climate change will impact the Southwest in ways similar to the western U.S. Air temperatures are projected to increase by 8.6°F (4.8°C; RCP8.5 model) in the Southwest by 2100, and some areas could see an increase of up to 45 more days of 90°F or hotter annually (Vose et al. 2017; Gonzales et al. 2018). Precipitation, which falls as snow in mountainous areas but also during summer monsoons (Mock 1996), is expected to decrease in winter and spring (snow) with a shift from snow to rain in cold seasons (Easterling et al. 2017); some models have projected annual precipitation to decrease by 0.05 mm/d by the 2080s (Seager et al. 2007). Although there is some model uncertainty in how future precipitation will change, future streamflows are expected be lower in part due to increased temperatures alone as precipitation is not the sole driver of instream flows (Udall and Overpeck 2017). A recent study showed that the current drought is one of the worst in the last 1,200 years, is exacerbated by climate warming, and future droughts will be longer, more severe, and more widespread (Williams et al. 2020). Stream temperatures are expected to warm 0.6°C for every 1.0°C increase in air temperature by the 2080s (Isaak et al. 2017a). Changes to streamflow and stream temperatures are expected to influence aquatic ecosystems in myriad ways (Overpeck and Bonar 2021).

Three salmonid species are native to the southwestern U.S. The Rio Grande Cutthroat Trout *O. clarkia virginalis* occupies only 12% of its historical range, and recent predictions have shown that only 11% of 121 remaining populations are expected to have over a 75% chance of persisting into the 2080s; however, increased stream temperatures were only predicted to affect 9% of these existing 121 populations, whereas nonnative species and other factors influences persistence of the other populations (Zeigler et al. 2019). Thermally suitable habitat for the Gila Trout *O. gilae* during the warm-season was projected to decrease by 70% in the next 40–90 years when assessed using a climate-envelope approach (Kennedy et al. 2009), and some streams may no longer be suitable at all based on a 1-km resolution stream temperature model (Dauwalter et al. 2017b).

The Apache Trout *O. apache* is also native to the Southwest and was listed as endangered under the U.S. Endangered Species Act in 1967 before being downlisted to threatened in 1975 (USFWS 2009). No studies have specifically evaluated climate change impacts on Apache Trout distribution and abundance, but lab and field studies have described Apache Trout thermal tolerances and thermal habitat selection (Recsetar 2011; Recsetar and Bonar 2013; Recsetar et al. 2014; Petre and Bonar 2017), as well as how changes in riparian vegetation could influence stream temperatures (Baker and Bonar 2019). Others have documented an increase in stream drying and intermittency in Apache Trout habitat (Robinson et al. 2004), which is expected to become more of an issue in the future with increased water use and less precipitation (Williams and Carter 2009). Our goal was to understand how climate change will impact the Apache Trout into the 2080s. Our objectives were to: 1) understand if and how stream temperature and precipitation influences the occurrence of juvenile Apache Trout (<125-mm TL) in eastern Arizona, 2) understand how changes in future climates influence the habitat suitability of streams designated for recovery of the species, and 3) identify habitat that is likely to be most resilient and support Apache Trout into the 2080s (USFWS 2009).

Study Area

The Apache Trout is endemic to the White River, Black River, and the Little Colorado River drainages in the White Mountains of east-central Arizona. The exact historical distribution is not known with certainty, but Rinne and Minckley (1985) estimated the species to occupy streams from 1,800 to 2,100 m elevation. Apache Trout currently occupy headwater streams, many of which are upstream of natural and artificial barriers that likely reflects a reduction from historical distribution due to nonnatives, habitat alterations, and other factors (Avenetti et al. 2006; USFWS 2009). Mount Baldy (3,475 m) and Mount Ord (2,461 m), from which many Apache Trout streams originate, are remnants of an extinct Tertiary volcano and the underlying geology of Apache Trout streams is primarily basalts, but there are also sedimentary rocks underlying the eastern fringe of Apache Trout distribution and there are Tertiary and Quaternary glacial deposits in five valleys on Mount Baldy's northern flank (Long et al. 2006). Precipitation in the White Mountains primarily occurs as snow during winter and rain during summer monsoons (Mock 1996). Vegetation also shifts from spruce *Picea* spp. and fir *Abies* spp. to Ponderosa Pine *Pinus ponderosa* or mixed conifer as elevation decreases. Riparian vegetation is typically Ponderosa Pine or mixed conifer and willow *Salix* spp., alder *Aldus* spp., Red-Osier Dogwood *Cornus stolonifera*, and other shrub species; meadows occur from valley fill and other geomorphic processes and are often dominated by grasses, and streamside meadow vegetation exists as grass, woody shrubs or both, but typically lacks large coniferous trees (Clarkson and Wilson 1995; Long et al. 2006).

Methods

We developed a species distribution model for juvenile Apache Trout to evaluate how climatic and other factors influence the distribution of Apache Trout and how climate change might impact the species into the 2080s. We chose to focus on juveniles, similar to other climate-salmonid studies (Isaak et al. 2015), and the 2080s is a common benchmark timeframe for climate projections. Although critical thermal maximum for Apache Trout declines slightly from age-0 to adults (Recsetar et al. 2012), juveniles are typically more sedentary and reflect the long-term thermal history of stream segments. We identified juveniles as individuals less than 125-mm TL because Harper (1978) identified the smallest female Apache Trout with eggs as 130-mm TL.

Fish Survey Data

To build the model, we first compiled a fish survey database from within the range of the Apache Trout in east-central Arizona. The database contains 1638 records whereby fishes were sampled using backpack electrofishing from 1987 to 2020 (Dunham et al. 2009; Figure 35). Two-hundred thirty-one surveys were conducted as part of Apache Trout monitoring using a systematic design where fish were sampled within 100-m reaches (Dauwalter et al. 2017a), 309 using a basin-wide visual estimation technique (BVET) protocol whereby fishes were sampled at the channel unit scale (riffle, run, pool, etc.; limited to channel units ≥25 m in length) within longer stream segments (Dolloff et al. 1993), and 568 at spatially distributed sites within streams according to general aquatic wildlife survey (GAWS) protocol where fishes were sampled within 50-m reaches (or sometimes 100-m; Robinson et al. 2004). We also included electrofishing surveys where Apache Trout were collected for genetic analysis (n=9) to determine if introgression had occurred with Rainbow Trout or Cutthroat Trout (Carlson and Culver 2009), and we included 494 electrofishing surveys targeted at removal of nonnative trout (mean site length = 356 m). Last, 27 surveys were of unknown protocol. All trout species were identified, counted, and measured for total length during each survey.

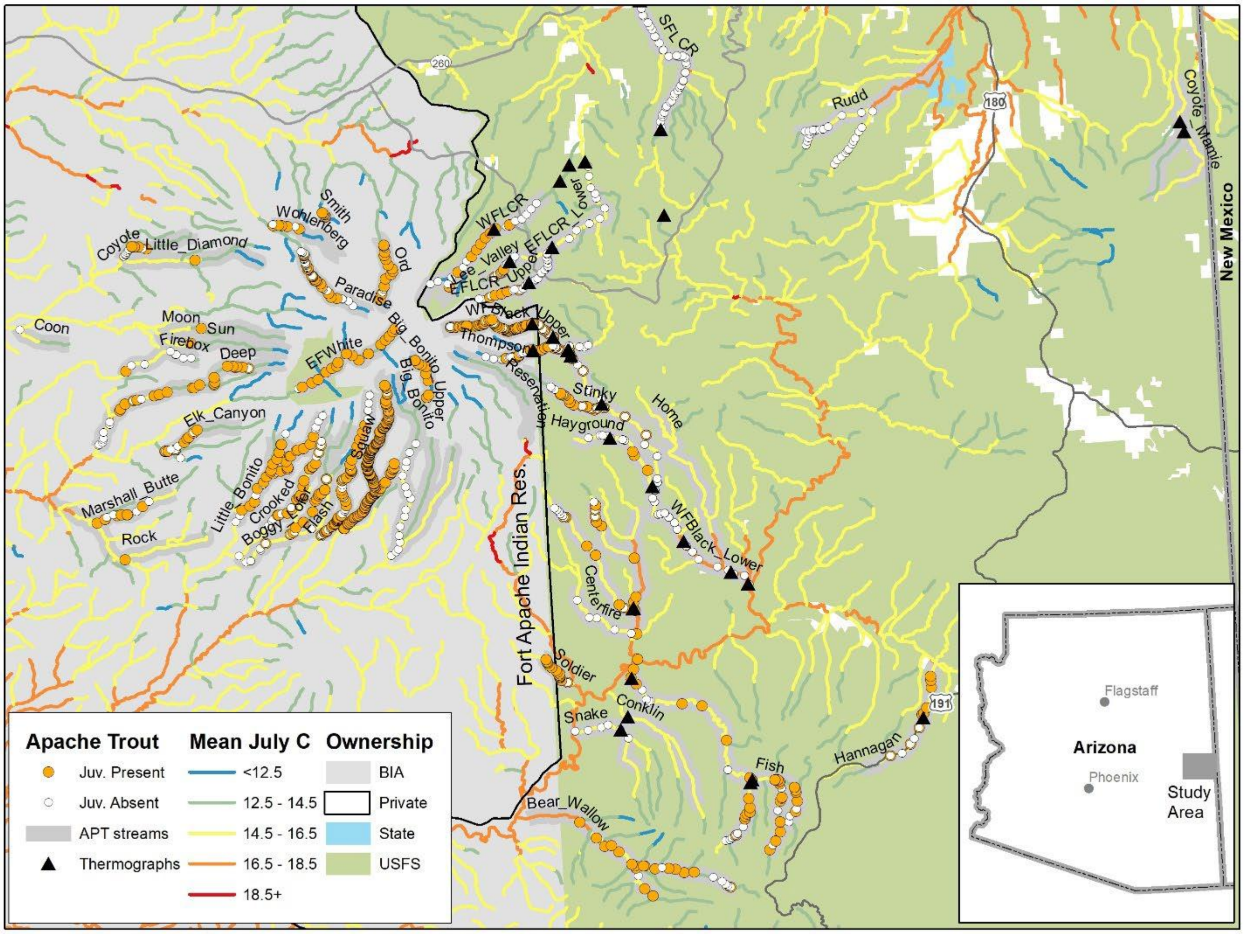

Figure 35. Presence and absence of juvenile Apache Trout (<125-mm TL) during fisheries surveys, and mean July stream temperature predictions, in east-central Arizona.

Species Distribution Model

The downstream boundary of fish survey locations was associated with a National Hydrography Dataset Plus (NHD+) 1:100,000 scale flowlines that were attributed with mean July temperature (°C), stream segment slope (%), and mean annual precipitation (dm). Mean July temperature was predicted from mean August temperature available from the spatially explicit NorWeST model (Isaak et al. 2017a) using an empirical relationship derived from in-situ temperature data from Apache Trout streams on the Apache-Sitgreaves National Forests (mean July °C = 2.84 + 0.84[mean August °C]; $R^2 = 0.76$, n = 49 site-years). Mean annual precipitation was from the Parameter-elevation Regressions in Independent Slopes dataset (PRISM: www.prismclimate.org) and summarized for watersheds draining each flowline (McKay et al. 2012). Percent slope for each segment was associated with the NHD+ dataset. Each fish record was also attributed with the presence of Rainbow Trout, Brook Trout, and Brown Trout from the fish surveys. Predictor variables initially considered for inclusion in a global generalized linear mixed model predicting the presence or absence of juvenile Apache Trout (<125-mm TL) in each fish survey were: mean July temperature (°C; including a quadratic term), percent slope, percent canopy, mean annual precipitation (dm), elevation (m), and presence or absence of nonnative trout; exploration of the global model with

Rainbow Trout, Brown Trout, and Brook Trout presence as separate terms showed that Brook Trout presence and Brown Trout presence had near the same effect size (parameter estimate) so they were combined into one variable in a global model with slightly more support (ΔAIC = 2.0) to reduce the number of parameters and candidate models. Elevation was correlated with mean July temperature (spearman rank $r_s = -0.82$) and percent canopy with slope (r_s=0.65) and each was removed to avoid potential issues with multicollinearity; we retained mean annual precipitation despite a moderate correlation with mean July temperature ($r_s = -0.74$) because of its link to climate (but no significant variance inflation factor; see below). The global generalized linear mixed model predicting Apache Trout presence and absence was fit with the remaining variables scaled and centered as a generalized linear model (logit link) and the unique ID of each flowline segment (COMID) as a random effect to account for spatial autocorrelation. Candidate models were constructed of all combinations of predictor variables, except mean July temperature (and quadratic term) were included in every candidate model because of the known sensitivity of Apache Trout to temperature and unimodal shape of the thermal niche for salmonids when modeled across landscapes using empirical field data (Isaak et al. 2017b; Petre and Bonar 2017). Candidate models were evaluated for plausibility using Akaike's Information Criterion for small samples (AICc). Models were considered plausible if they were within 4 AICc units of the best model (i.e., ΔAICc<4), and Akaike weights were used to assess the probability that each model is the top model (Burnham and Anderson 2002). Fit of the most-plausible model was assessed using the area under a receiving operator characteristic (ROC) curve for in-sample and 10-fold cross-validation samples (Hosmer and Lemeshow 2000).

Habitat Suitability and Climate Resiliency

The most-plausible model predicting Apache Trout occurrence was used to predict occurrence probabilities across the modeling domain, make predictions into the 2080s based on future climate projections, and identify climate resilient habitats. Predictions were made for current (present-day) conditions, as well as for two 2080s scenarios on 1:100,000 NHD Hydrography. The 2080s scenarios were based on an A1B middle-of-the-road emissions scenario and contained no nonnative trout. Scenario 1 solely included changes in stream temperature as projected in the NorWeST stream temperature model. The NorWeST model projects mean August stream temperatures for the 2080s based on projected changes in air temperature from a global climate model ensemble (10 models) and streamflow projections from Variable Infiltration Capacity (VIC) hydrological model projections at gaging stations (Hamlet et al. 2013; Isaak et al. 2017a). As before, mean August temperatures for 2080 were translated to mean July temperatures using the empirical relation from Apache Trout streams described above. In Scenario 2, where precipitation was also projected to decrease, mean annual precipitation was decreased by 5%. Seager et al. (2007) used an ensemble of climate models under an A1B scenario to show that precipitation was expected to decrease by -0.05 mm/day and primarily in winter (90 d) across the southwestern U.S., and when this value was compared to the mean annual precipitation at sites on Apache Trout streams (mean = 85.9 mm; 1 SD = 12.2 mm) it represented a 5% decline by the 2080s.

Habitat suitability and climate resiliency were based on predicted occurrence probabilities within habitat patches delineated for extant populations and unoccupied recovery streams. Extant Apache Trout populations and unoccupied recovery streams were delineated by species experts based on habitat suitability, occupancy, and the location of protective barriers (updated from 2009 recovery plan; USFWS 2009). Habitat suitability for each was defined for current conditions and both 2080s scenarios using model predictions of occurrence probability. Suitable habitat was defined as stream segments (~1 km) that were predicted to have a juvenile Apache Trout occurrence probability greater than or equal to 0.25. Climate resiliency was defined as the amount (km) of suitable habitat in the 2080s (Scenario 2) within defined patches as: <3.35 km = Very Poor; 3.35 – 6.55 km = Poor; 6.55 – 11.25 km = Fair; 11.25 – 17.60 km = Good; >17.60 km = Very Good. These patch size thresholds for Apache Trout long-term persistence were defined by species experts through a Delphi process (Delbecq et al. 1975; Conroy and

Peterson 2013). They are intermediate to other patch size thresholds recommended for long-term western native trout persistence (Hilderbrand and Kershner 2000; Peterson et al. 2014).

Results

Fish Survey Data

The fish database we compiled included 1638 surveys from 1987 to 2020 on 148 unique 1-km stream segments (Figure 35). Juvenile Apache Trout were present at 815 sites (48.9%). Rainbow Trout were present in 3.6% of all surveys, Brown Trout at 22.9%, Brook Trout at 11.2%, and at least one of the three nonnative trout at 35.3%.

Species Distribution Model

The most plausible model describing juvenile Apache Trout presence or absence, in addition to mean July temperature with a quadratic term included in all candidate models, included mean annual precipitation (dm), slope (%), and the presence of Rainbow Trout. A model with the presence of Brook Trout and/or Brown Trout (either one or both species) was nearly as plausible as the best model (ΔAICc<2), and another model with no nonnative trout covariates was within 4 AICc units but contained little support (Table 20). We chose to draw inferences based on the model that contained the BrookBrown model term to estimate its effect size given the documented and perceived impacts of nonnative trout and active management to remove them (Rinne et al. 1981; Avenetti et al. 2006; USFWS 2009). This model fit the data well, as the in-sample AUC = 0.85, and 10-fold cross-validated AUC = 0.81. Variance inflation factor for all retained covariates was low (VIF<2.61). Model parameters showed Apache Trout to have the highest occurrence probability at a mean July temperature of 17°C (Table 20; Figure 36). Surprisingly, the model showed occurrence probability to be ~0.30 at the warmest mean July temperature observed in the dataset used to fit the model (21.0°C). The model showed a higher occurrence probability at higher stream slopes and with more annual precipitation (Figure 36). Both Brook Trout and Brown Trout presence together and Rainbow Trout presence each had a negative effect on Apache Trout occurrence at a stream survey site. Rainbow Trout had a stronger negative effect (Table 21; Figure 36). Standardized parameter estimates showed Rainbow Trout presence and Precipitation to influence juvenile Apache Trout occurrence most (Table 21).

Table 19. Number of parameters (k), log-likelihood (Log(L)), Akaike's Information Criterion correct for small samples (AICc), change in AICc from the most plausible model (ΔAICc), and Akaike weights (w_i) for the four most plausible generalized linear models (logit link) predicting the presence of Apache Trout at a stream size as a function of mean July temperature (including a quadratic term), stream slope, presence of Brook Trout or Brown Trout, and presence of Rainbow Trout. Candidate models with a July temperature quadratic effect also included a main effect term.

Candidate Models	k	Log(L)	AICc	ΔAICc	w_i
$JulyC^2$ + Precip + Slope + Rainbow	7	-903.927	1821.9	0.00	0.543
$JulyC^2$ + Precip + Slope + BrookBrown + Rainbow	8	-903.552	1823.2	1.27	0.288
$JulyC^2$ + Precip + Slope	6	-906.891	1825.8	3.91	0.077
$JulyC^2$ + Precip + Slope + BrookBrown	7	-906.422	1826.9	4.99	0.045
$JulyC^2$ + Precip + Rainbow	6	-907.954	1828.0	6.04	0.027

Table 20. Parameter estimates, standardized parameter estimates, z-values, and P-values for the most plausible generalized linear model (logit link) predicting Apache Trout presence or absence at stream sites in east-central Arizona.

	Estimate (±1SE)			
Parameter	Un-standardized	Standardized	z-value	P-value
Intercept	37.518 (12.711)	-0.252 (0.225)	--	--
JulyC	3.331 (1.213)	0.811 (0.250)	3.241	0.001
JulyC2	-0.096 (0.040)	-0.194 (0.076)	-2.539	0.011
Slope (%)	0.250 (0.093)	0.543 (0.200)	2.714	0.007
Precipitation (dm)	0.965 (0.208)	1.171 (0.253)	4.628	<0.001
BrookBrown (Present=1)	-0.136 (0.165)	-0.143 (0.165)	-0.866	0.386
Rainbow (Present=1)	-1.461 (0.671)	-1.475 (0.673)	-2.191	0.028

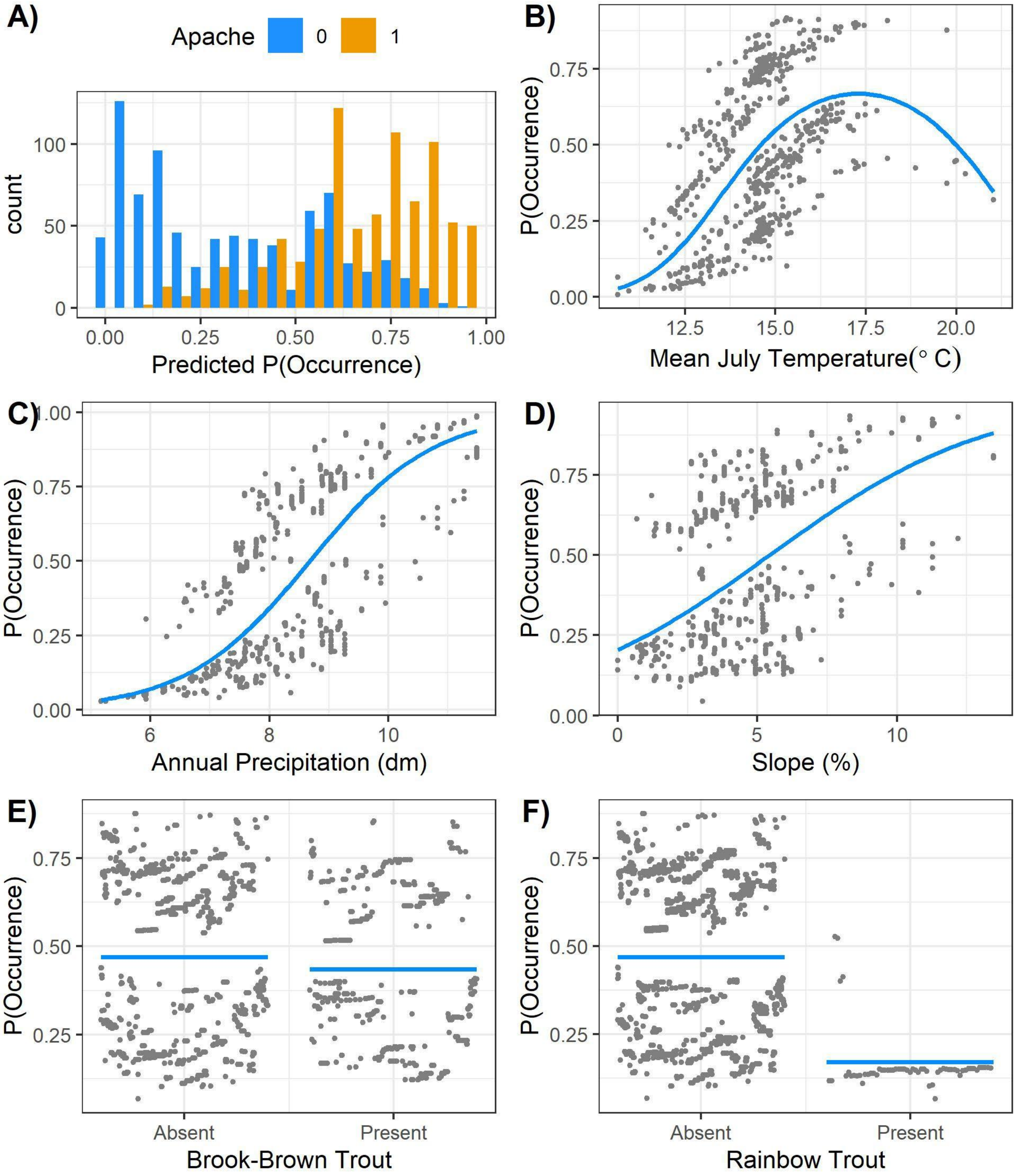

Figure 36. Frequency of predicted probabilities of occurrence for Apache Trout at survey sites where the species was present versus absent (A), predicted occurrence probabilities of Apache Trout as a function of mean July temperature (B), stream slope (C), when Rainbow Trout are present versus absent (D), and when Brook Trout or Brown Trout were present (E). All other variables were held at their median values. Predicted occurrence probability shown in blue, and partial residuals shown in gray.

Habitat Suitability and Climate Resiliency

Model predictions showed the highest occurrence probabilities around the Mt. Baldy, an extinct volcano that represented the highest elevation with the coldest stream temperatures in the modeling domain. Aside from Mount Baldy, predicted probabilities were quite variable across streams, even those occupied by Apache Trout populations (Figure 37). Stream habitat occupied by Apache Trout populations or identified as a [unoccupied] recovery streams ranged in extent from 0.4 to 28.8 km, and the amount of suitable habitat predicted by the model (occurrence probability >0.25) for current conditions was 0.0 to 26.9 km (Figure 38A). The amount of suitable habitat predicted for the 2080s ranged from 0.0 to 28.8 km in the temperature only scenario, and suitable habitat ranged from 0.0 to 25.3 km when temperature and precipitation changes were considered (Figure 38A). In the temperature only scenario (Scenario 1) the model predicted increases in suitable habitat for 9 populations and recovery streams, but when declines in annual precipitation were included also (Scenario 2) the amount of suitable habitat never increased but decreased for ten streams (-100 to -5.9% change; Figure 38B). Given the 2080s changes in temperature and precipitation and predicted km of suitable habitat, only three populations were considered to have Very Good climate resiliency: Fish Creek, Centerfire Creek, and Big Bonito (Figure 39). Five populations (or streams) had Good climate resiliency, 10 were considered Fair, 8 were Poor, and 19 Very Poor.

Discussion

Our model suggested that most streams currently occupied by Apache Trout, or unoccupied but designated as recovery streams, are not temperature limited, and that suitability only improved when 2080s projections of temperature alone were considered because some headwater reaches appeared to be too cold for occupancy. It was only when future changes in precipitation were considered as well that habitat suitability decreased into the 2080s. Many habitat patches that are currently occupied by the species are projected to remain suitable into the 2080s, which suggests their resiliency is only limited by the size of the patch they currently occupy (Peterson et al. 2014; Isaak et al. 2015).

Surprisingly, we found that most habitat patches were not limited by warm stream temperatures because the habitat designated for species recovery is upstream of protective fish passage barriers (Avenetti et al. 2006; USFWS 2009) that are far enough upstream to not be temperature limiting now or into the 2080s. In fact, the effect of temperature on juvenile Apache Trout occupancy suggested that streams can be too cold, and model projections of stream temperature in the 2080s increased the amount of suitable habitat in some streams because of the unimodal response to temperature. This suggests cold temperatures can be limiting Apache Trout populations in some streams, and any warming may benefit them in headwater reaches – at least up until the 2080s. However, when projections of reduced precipitation were also considered, habitat suitability only decreased in Apache Trout streams. This is not surprising given that stream intermittency and drought have impacted some populations in the past (Robinson et al. 2004; Williams et al. 2020), and less precipitation, and thus streamflow, would exacerbate these impacts, especially since the Southwest is anticipated to experience novel and mega-drought conditions in future climates (Crausbay et al. 2020; Williams et al. 2020).

The shape of the temperature effect on juvenile Apache Trout occupancy we observed is likely due to the distribution of our fish survey data. Most Apache Trout populations are located above barriers that protect them from nonnative trout downstream (Avenetti et al. 2006; USFWS 2009), and these barriers appear to be located in places where temperatures are not currently limiting and are not likely to be limiting in the 2080s. In addition, nearly all Apache Trout monitoring occurs above barriers within these protected populations that are identified for species recovery purposes (USFWS 2009). Apache Trout populations downstream from these barriers are considered or are known to be hybridized with Rainbow Trout, or they are considered to be very small and unlikely to persist because of interactions with other nonnative trout species that occur downstream of barriers (Carmichael et al. 1995). Thus, Apache Trout that may occur below barriers are not the focus of the species' recovery and therefore are not typically monitored or survey for other reasons. As a result, the downstream distribution of Apache Trout is considered to be limited by protective barriers and nonnative trout as opposed to temperature, and the absence of fish survey data from warmer downstream reaches likely prohibited our model from precisely defining the warm tail (right side) of the thermal niche curve (Figure 36B).

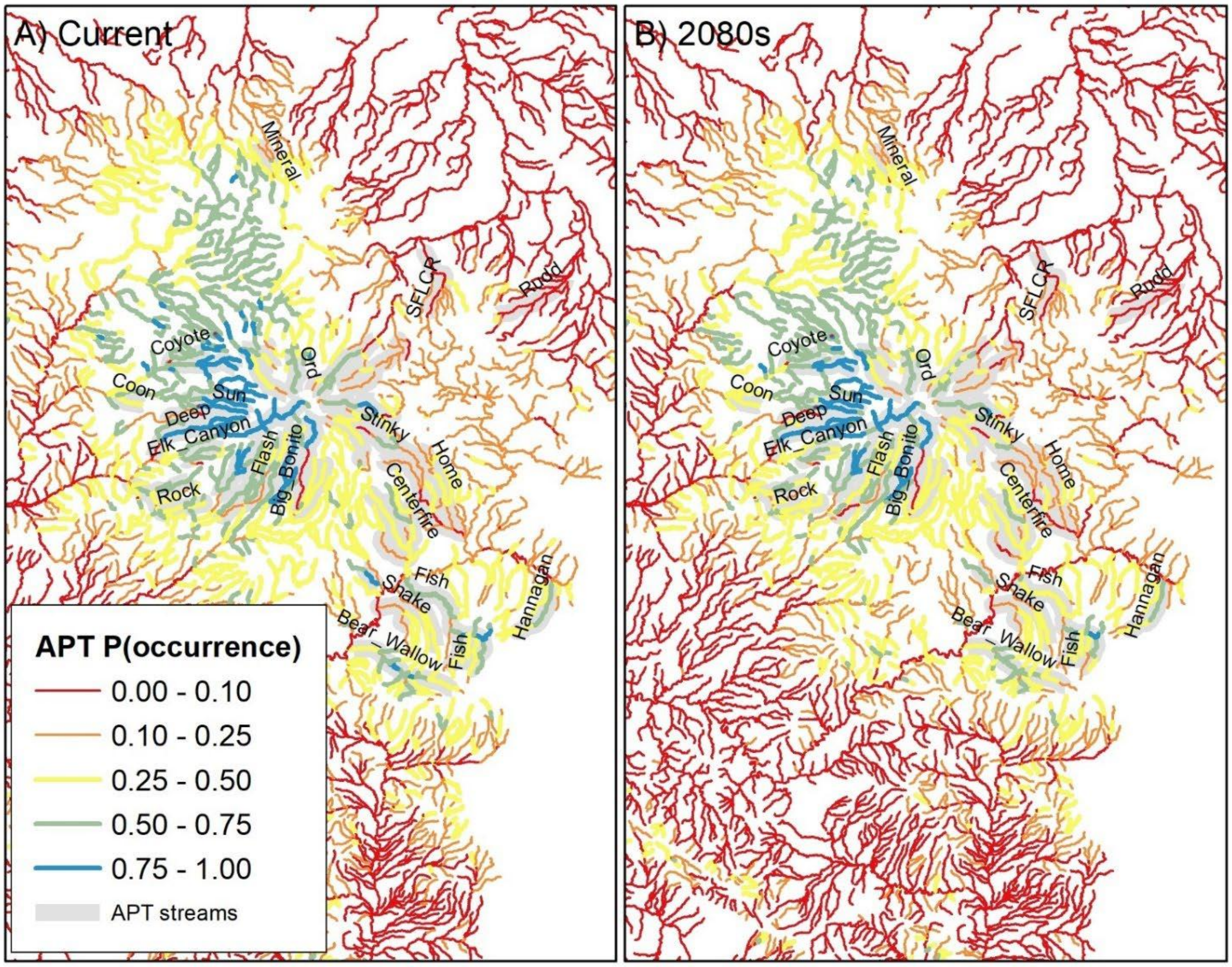

Figure 37. Current (left panel) and 2080s (right panel) predicted probabilities of Apache Trout occurrence as a function of stream slope, mean July temperature, and Rainbow Trout presence-absence in streams within the historical range of the Apache Trout. Extant Apache Trout populations (and unoccupied recovery streams) shown in grey and labeled.

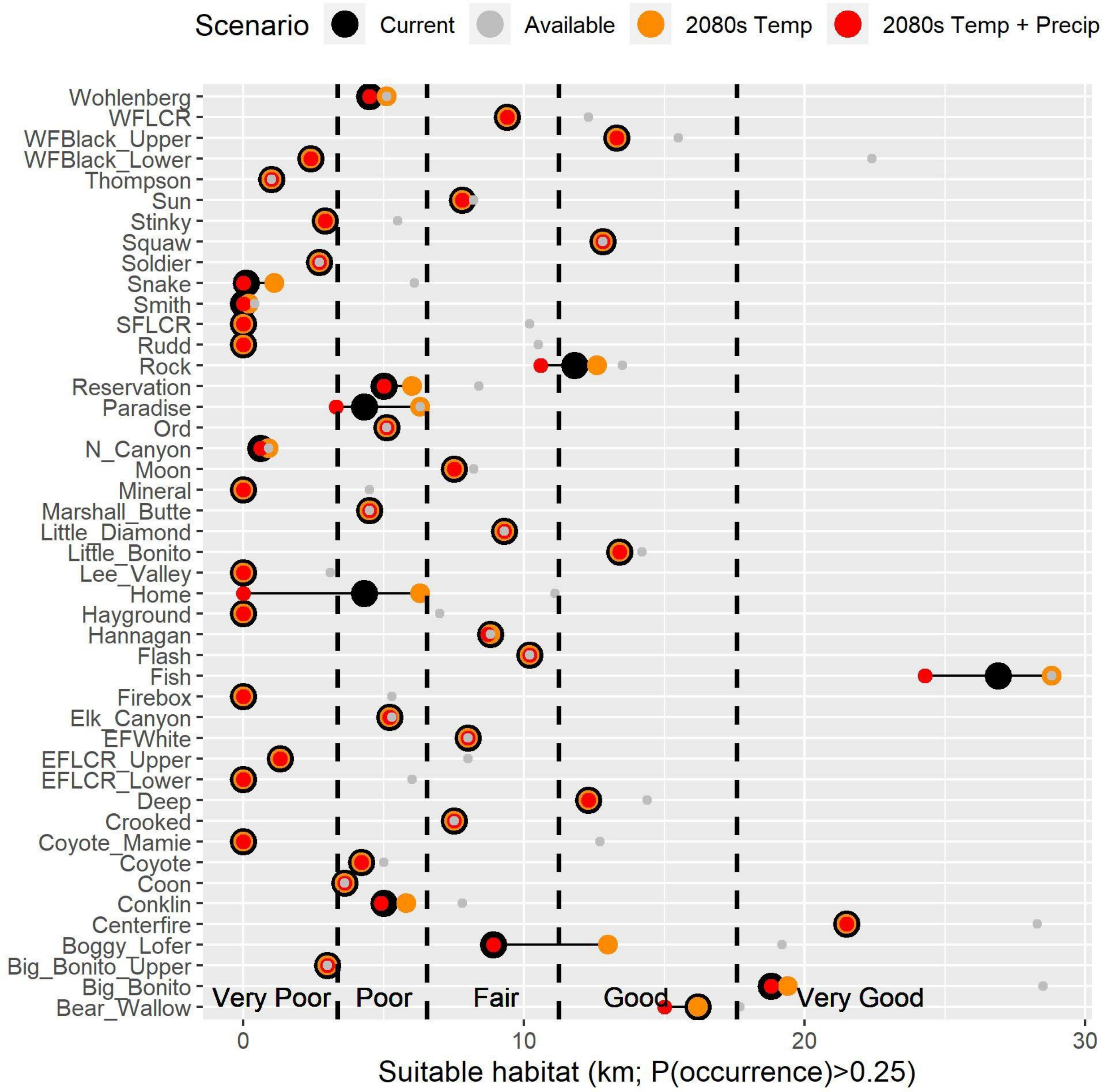

Figure 38. Kilometers in suitable habitat for Apache Trout under current (present-day; black) conditions and in the 2080s with projected changes in July stream temperatures only (orange) and changes in temperature and precipitation (red). Total kilometers of habitat available to a population shown in grey. Suitable habitat was defined as occurrence probability ≥ 0.25.

There appears to be flexibility in barrier management since warming does not appear to affect the suitability of downstream habitats available to most Apache Trout populations. However, moving barriers further downstream could only occur if suitable site conditions exist for barrier construction and nonnative fishes can effectively be removed, but this may be a viable near-term option to increase patch size, and therefore population resiliency and viability, where it is limiting (Fausch et al. 2009). Streams like the lower WFBR may be an exception where temperatures, and thus suitability, already appear to only support occupancy at low levels; however, these larger systems are often considered to be seasonal movement corridors that could facilitate metapopulation dynamics among tributary populations if nonnatives could be removed or suppressed (Williams and Carter 2009). In the upper WFBR, spatial heterogeneity in stream temperatures has been observed at a spatial scale smaller than can be revealed by our analysis using the 1:100,000 scale NDH hydrography, as thermal imaging has identified cold groundwater inputs in reaches that were thermally marginal (Bonar and Petre 2015). It is unclear how common cold groundwater inputs are across Apache Trout streams, but they could serve as local coldwater refugia during extreme warm periods if streams temperatures become thermally stressful in downstream warmer reaches of recovery streams (Torgersen et al. 2012).

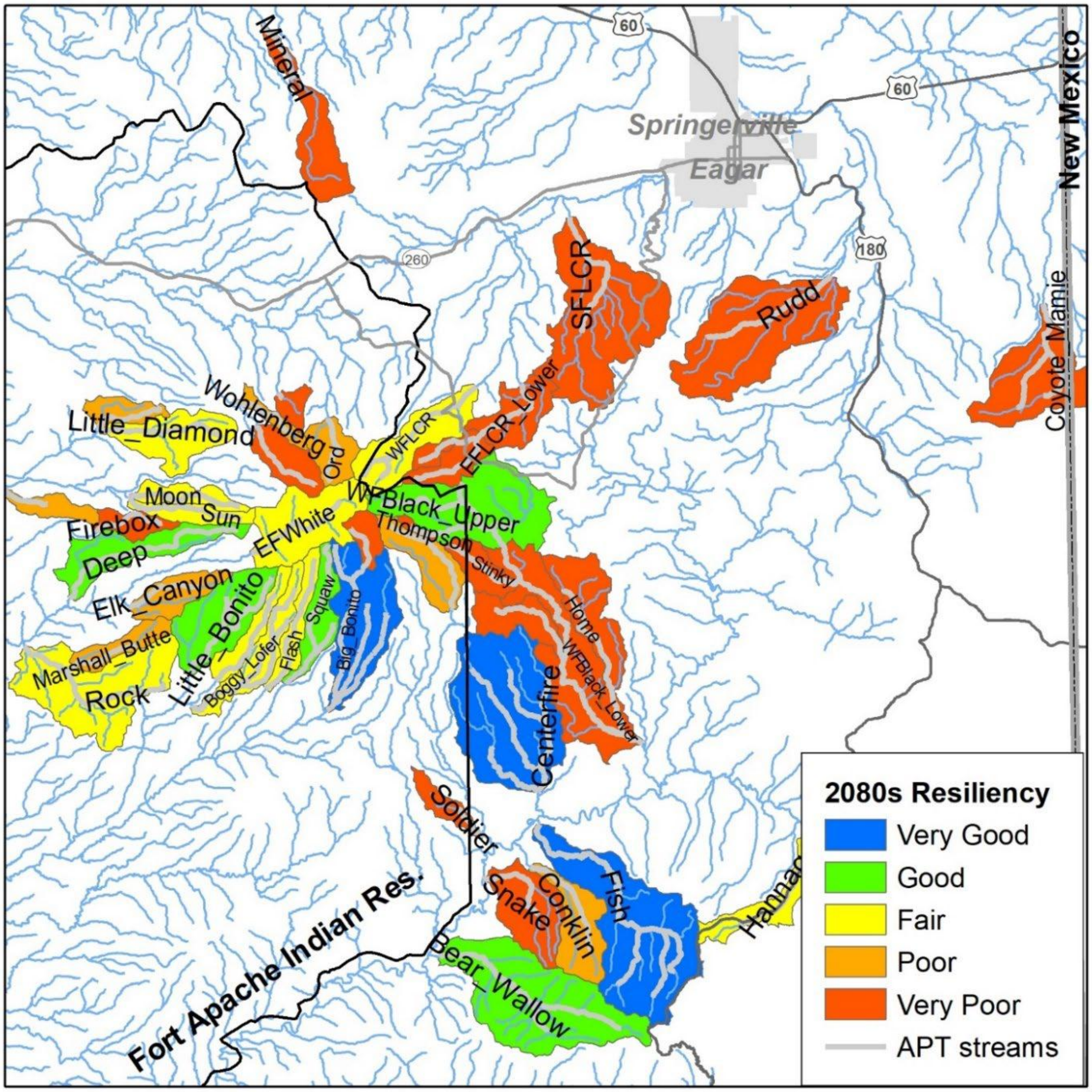

Figure 39. Resiliency of extant Apache Trout (APT) populations and unoccupied recovery streams to projected climate change in the 2080s based on amount (km) of suitable habitat available as predicted from a species distribution model.

In contrast, Apache Trout occupancy appeared to be limited by cold summer temperatures in headwater reaches of recovery streams. Studies have shown that survival of age-0 *Oncorhynchus* spp. during their first winter is dependent on their size entering winter and, thus, is dependent on emergence timing and summer-to-autumn growth. While over-wintering mortality has not been studied for the Apache Trout, two age and growth studies have been conducted. In upper Big Bonito Creek (mean July = 12.8°C) mean length at the first annulus averaged 41.5 mm TL (SD = 6.7) from 1970–75 (Harper 1976), whereas in the lower East Fork White River (mean July = 13.6°C) mean length at first annulus averaged 55.6-mm TL

(SD=9.7) from 2009–2016 (Quist et al., in press). Size-dependent mortality of trout in their first winter has been shown to be higher where temperatures are colder and habitat is less thermally suitable (Meyer and Griffith 1997). Coleman and Fausch (2007) found that age-0 Cutthroat Trout winter survival and recruitment was limited in cold high-elevation streams with 800–900 Celsius degree-days, equivalent to mean July temperatures of ~8.0–9.0°C, and that less than 800 degree-days were unsuitable; their study showed Cutthroat Trout fry typically needed to be 30-mm TL or larger at the onset of winter to have greater than 50% winter survival. The potential for recruitment bottlenecks to limit juvenile occupancy in Apache Trout streams where mean July temperatures are 11°C or colder needs further research.

Annual precipitation had a stronger effect on juvenile Apache Trout occurrence than did temperature as revealed by the standardized model parameter estimates (for main effects). Precipitation is also a predictor in the NorWeST stream temperature model we used, and there was a moderate negative correlation between mean July temperature and mean annual precipitation associated with our fish survey dataset (r_s=-0.74; but impact on variance inflation was low). So, the effect of precipitation on temperature is already accounted for in the NorWeST stream temperature model. That our model showed annual precipitation to be important in addition to temperature suggests an independent and largely spatial effect of precipitation manifested through flow volume in Apache Trout streams. However, annual precipitation as used in our model integrates precipitation over an annual time-step and does not account for the form of precipitation that varies between rain and snow by season (Mock 1996).

Precipitation in the White Mountains primarily falls as winter snow and summer monsoon rain (Mock 1996). However, decreases in precipitation due to climate change are expected to occur in winter in the form of snow (Easterling et al. 2017), and decreases in snowpack are likely to negatively impact stream baseflows and, thus, summer temperatures. Hydrologic models linked to climate models show future precipitation increasingly falling as rain, higher frequency of rain-on-snow, and increased snowmelt rates, all of which lead to increased overland runoff to streams and less infiltration to groundwater. Less groundwater storage leads to less groundwater discharge to streams in late summer and early autumn (Huntington and Niswonger 2012). The summer monsoon season can add precipitation, but at much warmer temperatures regardless of whether it occurs as overland flow or through shallow groundwater discharge pathways.

While snow melt can result in overland flow during spring runoff, it also infiltrates into groundwater and does so at near freezing temperatures (at or just above 0°C; Potter 1991). Thus, any groundwater contributions to streams that originate from snowmelt are likely to have a stronger cooling effect on stream temperatures released over longer time periods than overland flow from either snowmelt or monsoon rains. If snowpack is reduced in future climates it is likely that groundwater return flows may occur earlier and be less overall, thus providing less of a cooling effect into late summer, especially prior to monsoon rains (Overpeck and Bonar 2021). Climate impacts to precipitation amount, type, and timing will play a large role in determining how accurate the stream temperature model we used really is and whether headwater reaches of Apache Trout streams will provide the resiliency that our model suggests into the 2080s.

Our model also showed nonnative trout to negatively influence juvenile Apache Trout occupancy, which was expected. Initial model exploration suggested that Brook Trout and Brown Trout had nearly the same effect on site occupancy, but that their effect was nearly five times less than that of Rainbow Trout as revealed by parameter estimates. The lack of a stronger effect of Brook Trout and Brown Trout could be an artifact of our data since both species are the focus of electrofishing removal programs that sometimes occurred close in time to population monitoring surveys on some streams, which may have influenced the data used to fit the model and resulting parameter estimates; there could also be a lag before nonnative trout removal results in a compensatory response by an Apache Trout population to reduced competition and predation. Rainbow Trout are typically not the focus of removal programs because their presence is often assumed to result in hybridization and, thus, lost Apache Trout populations because they do not meet recovery criteria of genetic purity (USFWS 2009); genetic testing may show inaccurate phenotypic identification of hybrids, that some genetically pure individuals remain despite some hybridization, and that Apache Trout populations may purge nonnative alleles through backcrossing over time (Carmichael et al. 1993). Populations presumed to be hybridized are not monitored until they can be re-established following chemical treatments to eradicate Rainbow Trout and a protective barrier is in place (Carmichael et al. 1995; Avenetti et al. 2006).

Our assessment of Apache Trout habitat suitability is based on a spatially explicit stream temperature model that is accurate across the Arizona model domain (Isaak et al. 2017a). However, Apache Trout streams only occur within a small portion of this domain. Likewise, the effect of annual precipitation in our model, while informative, is still coarse, and desiccation models that have been developed elsewhere could provide more resolution on flow permanence in Apache Trout streams (Schultz et al. 2017; Gendaszek et al. 2020). Given the threatened status of the Apache Trout, *in situ* temperature monitoring should be included as part of ongoing management to ensure future temperature predictions, and future coarse-scale habitat suitability projections such as those we present here, are in fact accurate – especially at downstream extents most likely be become thermally stressful. *In situ* monitoring will also reveal daily fluctuations and maximums during summer that may be more relevant to Apache Trout thermal tolerances (Recsetar and Bonar 2013; Recsetar et al. 2014), and fine-scale thermal mapping during hot periods may reveal local thermal refugia as discussed earlier (Bonar and Petre 2015). Temperature monitoring, along with flow monitoring, may thus inform management decisions in the future at finer scales than can be afforded by our predictive model.

Last, while there is desire to manage certain Apache Trout habitat in ways that facilitate habitat connectivity and metapopulation dynamics (Williams and Carter 2009), protective barrier management will remain important to the conservation of the species. Since many populations are isolated above barriers, many populations will have to persist in place rather than shift in space to adapt to future climates (Thurman et al. 2020). While much of the historical genetic diversity at the major watershed level is represented today across populations (no Little Colorado River lineage remains), many populations were founded with a small number of individuals and thus have only a subset of the genetic diversity of parent populations and lineages (Wares et al. 2004). This may restrict the ability of populations to adapt in place and may require some genetic management (Whiteley et al. 2015; Weise et al. 2020). Adaptation potential should be considered in concert with the reality that many populations reside in small habitat patches. This can constrain long-term viability and is one of the trade-offs that comes with isolation management (Fausch et al. 2009), but our identification of climate resilient habitats incorporated patch size as a driver of long-term persistence. Habitats with high resiliency could also be the focus of active habitat management, such as riparian vegetation management and habitat restoration (Williams et al. 2015; Baker and Bonar 2019), to improve or ensure their climate resiliency into the 2080s and beyond while society works towards reduced greenhouse gas emissions that will allow the Earth to reach a stationary climate (Angel et al. 2018; Overpeck and Bonar 2021).

Appendix C Supplement 1: Thermal characteristics of, and validation of the NorWeST model, in Apache Trout streams.

Methods

We summarized the thermal characteristics of Apache Trout streams using *in situ* temperature monitoring and used the *in situ* data to validate the NorWeST temperature model. Stream temperature was monitored at 30 sites from 2013 to 2018 (49 site-years) on 16 streams on the Apache-Sitgreaves National Forests in east-central Arizona. Thermographs were deployed year-round and were set to log temperatures once every 0.5 h. Temperature data were summarized daily into mean, minimum, and maximum temperatures and these daily summaries were used to compute the following metrics: mean July, mean August, maximum average weekly maximum (MWMT), mean daily range June, mean daily range July, maximum daily range June, and maximum daily range July. Number of days exceeding 23°C and 26°C were also computed. We explored the relationships between mean July and mean August to assess whether one month was warmer than the other. We also explored the relationship between mean July and mean daily temperature range in July to see if daily temperatures fluctuated more in warmer streams, mean July and MWMT to see if daily maximums were closely related to mean July temperatures, and maximum daily ranges for June and July to see whether daily ranges were higher in one month versus the other. The latter relationships were explored because summer monsoon rains that begin in late June-early July can add flow volume and dampen daily temperature fluctuations. Linear regression was used to evaluate all relationships. Significance (slope = 0) was only evaluated for those where a significant relation was of interest; other relationships were evaluated by comparing confidence intervals of the slope estimate to a 1:1 line.

We validated the NorWeST stream temperature model prediction using mean July and mean August temperatures from *in situ* monitoring. Again, the NorWeST model predicts mean August temperature from a suite of predictors reflecting landscape features that influence stream temperatures, and the model is used to predict mean August temperature for every 1-km stream segment in a modeling domain. The Arizona model was fit using 251 site-years of data and had a root mean squared prediction error (RMSPE) of 1.06°C, suggesting the mean August temperature predictions were accurate to within ~1°C 66% and ~2°C 95% of the time. We used the NorWeST model developed for the Arizona modeling domain and compared the model prediction for the stream segment at which *in situ* monitoring occurred. While the NorWeST model contains predictions for each year used to fit the model, we used the 2002–2011 average August temperature predictions for validation as it reflects the most recent time window corresponding to *in situ* monitoring. To do so, we used the linear regression between mean August and mean July to compute mean July temperatures from mean August NorWeST predictions (mean July = 2.8 + 0.84×mean August). As a measure of model accuracy, we computed the root mean squared error (RMSE).

Results

The *in situ* temperature data showed mean August temperatures to predict mean July temperatures reasonably well (mean July = 2.8 + 0.84×mean August; r^2=0.768). August temperatures were cooler than mean July temperatures as shown by the best fit line against the 1:1 line (Table 5; Figure 40), which is why we used this empirical relationship to predict mean July from mean August in the NorWeST dataset. There was a positive association between mean July temperature and MWMT, but the relationship was highly variable (r^2=0.23; Figure 40). Temperature fluctuated daily in July, on average, from 3.5 to 11°C and maximum daily ranges were as high as 19°C in one stream, but there was no significant association between mean July temperature and average daily range in July temperatures (P=0.653; Figure 40). The maximum daily range observed was higher in June than in July (Figure 40).

The NorWeST model predicted in situ temperatures well. The RMSE for mean July was 1.01°C, and RMSE for mean August was 0.94°C. Using only 2016 – 2018 data, data not used to fit the NorWeST model, RMSE for mean July was 1.14°C and RMSE for mean August was 0.83°C. Comparisons of observed in situ versus NorWeST predicted mean July and mean August temperatures showed that in warm Apache Trout streams predicted temperatures were cooler than observed but that cold streams were predicted to be warmer than observed by about 1°C (Figure 41).

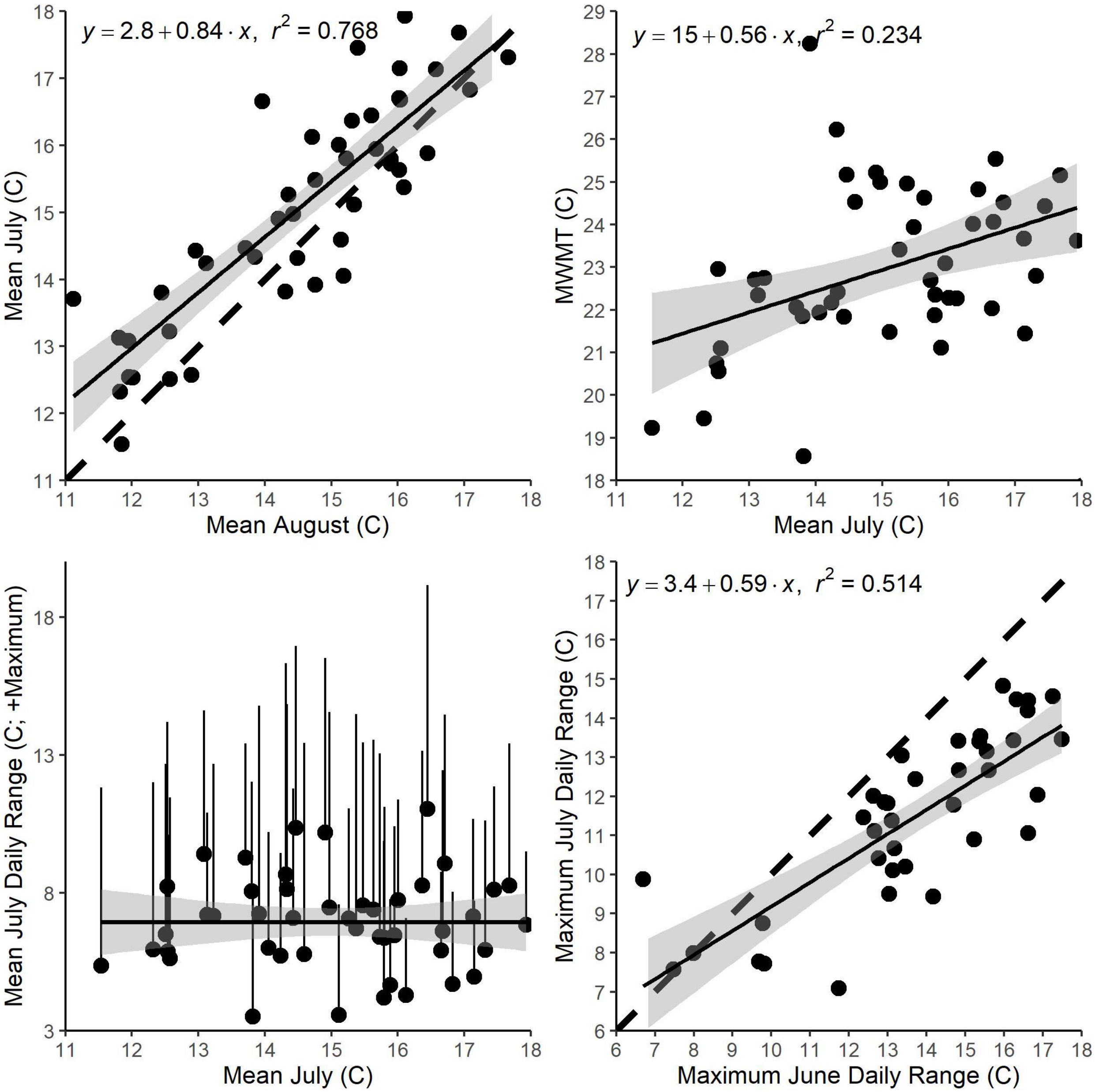

Figure 40. Relationships between mean August and mean July stream temperatures (upper left), mean July and maximum of average weekly maximum temperature (MWMT; upper right), mean July and mean daily temperature ranges in July (lower left), and maximum daily temperature ranges in June and July (lower right) for 49 site-years of data from 16 Apache Trout streams on the ASNF, east-central Arizona. Data credit: J. Ward, ASNF.

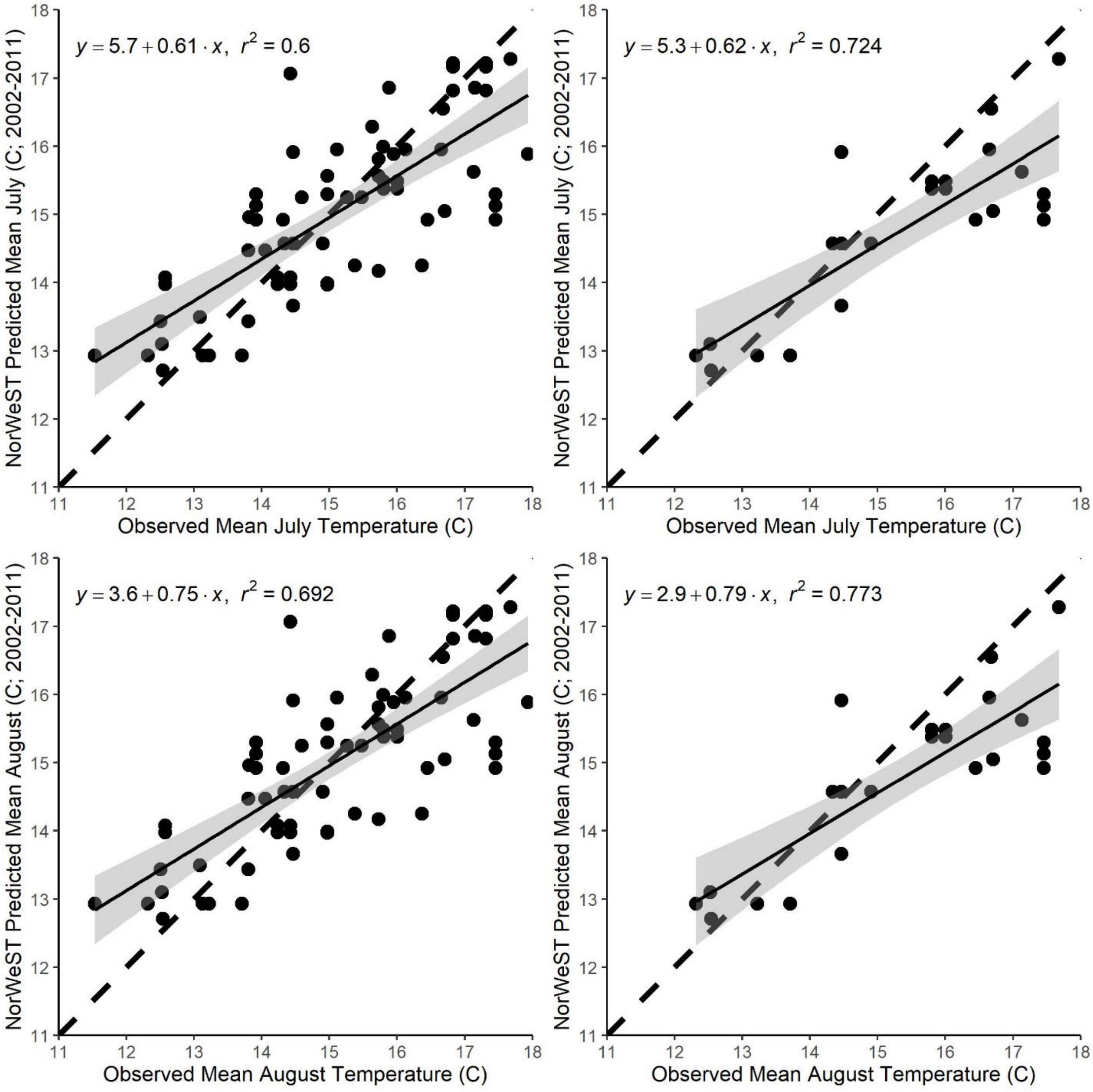

Figure 41. Comparison of in situ mean August and mean July stream temperatures versus predicted temperatures from the NorWeST model for 49 site-years of data from 16 Apache Trout streams (2013–2018 ;left panel) and 23 site-years of data from (2016–2018; right panel) on the ASNF, east-central Arizona. Data credit: J. Ward, ASNFs.