Vulnerability of Gila Trout Streams to Future Wildfires and Temperature Warming

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Abstract—Climate change is projected to increase the frequency and severity of wildfires, warm stream temperatures, and negatively impact native trout habitat. Southwestern native trouts are often isolated from nonnative salmonids above conservation barriers and have a limited ability to recolonize after disturbances or move to track changing environmental conditions such as stream temperature. We combined wildfire, debris-flow, and 2080s stream temperature models to identify Gila Trout *Oncorhynchus gilae* habitats least vulnerable to these threats and guide conservation efforts. Wildfire risk, debris-flow probability, debris-flow volume, minimum 2080s mean August temperature, and kilometers of habitat with 2080s August temperatures <18.5°C were summarized for each Gila Trout stream and ranked for overall vulnerability. The vulnerability rankings can be used to inform conservation actions such as reintroductions, habitat restoration, or nonnative fish eradications while considering these climate-related threats and other factors. Conservation decisions mindful of climate resiliency will best ensure that these unique but threatened native trouts remain on the landscape in the southwestern U.S. in future climates.

Introduction

The Earth's climate is changing. The last two years, 2015 and 2016, were the warmest on record. Carbon dioxide levels in the atmosphere are higher than ever recorded. In the western United States, mountain snowpack is melting earlier, and earlier and drier springs are increasing the frequency and intensity of wildfires (Westerling et al. 2006). Streamflows during dry years are getting lower (Luce and Holden 2009), and stream and river temperatures have been increasing 0.3°C per decade (Isaak et al. 2012).

Stream salmonids can be vulnerable to wildfires (Dunham et al. 2003). Wildfires can superheat stream water, cause ash flows that alter water quality, or result in channel reorganizing debris flows, each of which can cause direct mortality (Gresswell 1999; Cannon et al. 2010). Salmonid populations with limited dispersal ability can be particularly vulnerable to wildfire due to an inability to recolonize fire-impacted habitats (Dunham et al. 2003). As ectotherms, salmonids are also particularly vulnerable to climate warming, although climate change is expected to affect populations through streamflow alteration and drought in addition to temperatures (Williams et al. 2009; Wenger et al. 2011).

In the southwestern United States, the climate is projected to warm rapidly over the next century. Kennedy et al. (2009) used a regional climate model and projected summer air temperatures to increase 2°C and a 20% decrease in precipitation by the 2050's. They used these projections to estimate that Gila Trout *Oncorhynchus gilae* habitat would decrease by 70% in that same time frame, albeit using air temperature as a surrogate for stream temperature. Concomitant decreases in humidity and more frequent drought conditions are also likely to accompany changes in temperature, thus resulting in larger and more intense wildfires (Williams and Carter 2009).

Catastrophic wildfires and number of extant populations were major factors influencing the viability of Gila Trout in the southwestern United States (Brown et al. 2001). Like other salmonids, southwestern native trouts have narrow physiological tolerances, especially thermal tolerances (Lee and Rinne 1980; Recsetar et al. 2013). Because populations are typically isolated above conservation barriers (Propst and Stefferud 1992), southwestern trouts have limited ability to respond to environmental changes through movement or recolonization and, therefore, have a high vulnerability to changes in climate (Rinne 1982; Kennedy et al. 2009).

Our objectives were to (1) summarize wildfire history within the historical range of Gila Trout, and (2) use spatially explicit wildfire, debris flow, and stream temperature models to identify Gila Trout streams least vulnerable to these threats and inform conservation efforts. The Gila Trout is listed as Threatened under the U.S. Endangered Species Act (prior to 2006 the species was listed as Endangered).

Methods

Wildfire History

We summarized fire history in New Mexico and Arizona within the historical range of Gila Trout in the southwestern United States that includes the Gila, Salt, and Verde river systems (Benke 2002). The historical range of Gila Trout surrounds the historical range of Apache Trout *O. apache* in the Black and White rivers in the headwaters of the Salt River, and we summarized fire history within this region as well. We used the Monitoring Trends in Burn Severity program database to summarize fire frequency, fire extent, and ignition timing from 1985 to 2015, the most recent year available (Eidenshink et al. 2007).

Wildfire Risk

We developed spatially-explicit estimates of wildfire risk for Gila 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 stream temperature models developed for New Mexico and Arizona. These models predict 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). Temperature projections for the 2080s were based on August air temperature inputs from a global climate model ensemble for the A1B warming trajectory. Model details can be found at: www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html. The New Mexico model was fit using 755 site-years of data, and the Arizona model was fit using 251 site-years of data. The New Mexico model had a root mean squared prediction error (RMSPE) of 1.03°C and the Arizona model had a RMSPE of 1.06°C, each 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.

Gila Trout Stream Vulnerability

We summarized wildfire risk, debris flow risk, and 2080s stream temperature risk for all Gila Trout streams identified as potentially being useful for conservation. Gila Trout stream extents were delineated using a combination of field data and professional judgement. Streams were classified as: current population; recently restored population, recently extirpated (due to recent fires), and potential recovery stream. For each stream we summarized the average percent wildfire risk, mean debris flow probability, mean debris flow volume, minimum mean August stream temperature projected for the 2080s, and the kilometers of each delineated stream projected to have mean August temperatures below 18.5°C in the 2080s. These summaries were completed for each of 57 Gila Trout streams (or stream segments) identified for conservation purposes within the historical range of the species. All stream averages were length (habitat extent) or area (watershed) weighted. The temperature 18.5°C was based on the 95th percentile of all temperatures (averaged from 2002 to 2011) within Gila Trout streams classified as having a current, recently extirpated, or recently restored population where mean August temperatures were presumably suitable.

Results

We summarized wildfire, debris flow, and 2080s stream temperature risk information and vulnerability for 57 Gila Trout streams or stream segments in New Mexico and Arizona that represent 14 current populations, three recently restored populations, and four recently extirpated populations, as well as 25 streams identified as having potential for species reintroductions (Figure 1; Table 1).

Wildfire History

Within the broad historical range of Gila Trout in New Mexico and Arizona, there were 272 fires from 1985 to 2015, and 238 of those were wildfires totaling over 1.3 million ha (top left panel of Figure 2). Wildfires started during all months of the year, but a majority started in June at the onset of the monsoon season (top right panel of Figure 2). The median fire size from 1985 to 2015 was 1,300 ha, with an increasing trend in the maximum fire size and total area burned over time that reflects the recent and large catastrophic Rodeo (2002), Wallow (2011),

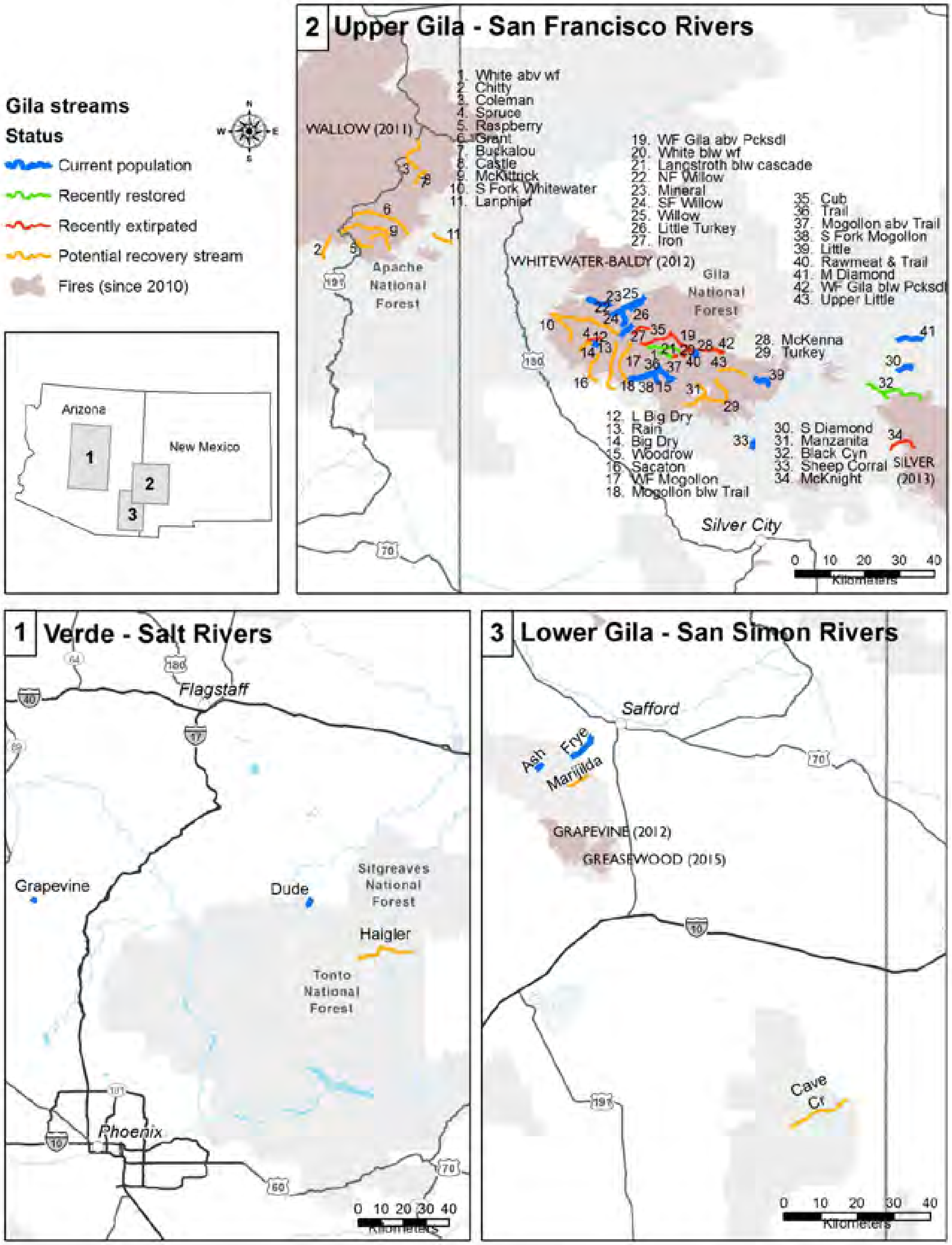

Figure 1. Gila Trout streams by population status in New Mexico and Arizona. Fires from 2010 to 2015 shown.

Table 1. Percent watershed with high wildfire risk (active or passive crown fire), mean debris flow probability given wildfire risk, debris flow volume, minimum mean August temperature in the 2080s, and habitat extent (km) below 18.5°C in the 2080s, and overall vulnerability rank of Gila Trout streams (a rank of 1 being least vulnerable).

Status	Population	Stream	Crown Fire (%)	Debris Flow Probability	Debris Flow Vol. (1000s m³)	Min. °C (2080s)	Km <18.5°C (2080s)	Vulnerability Rank
Current	Ash	Ash	16.7	0.027	16	11.2	3	18
	Big Dry	Big Dry	41.7	0.003	20	12.6	2	20
	Dude	Dude	--	--	--	16.3	3	53*
	Frye	Frye	1.8	0.002	7	21.2	0	26
	Grapevine	Grapevine	--	--	--	17.4	2	55*
	Iron	Iron	25.7	0.008	12	10.2	4	16
	Little	Little	50.2	0.026	713	18.8	0	52
	Main Diamond	Main Diamond	60.0	0.238	234	14.9	10	45
	McKenna	McKenna	21.6	0.011	192	16.6	2	40
	Mineral	Mineral	37.9	0.005	44	14.7	9	22
	Mogollon	Mogollon above Trail	49.5	0.088	194	16.7	5	48
		Mogollon below Trail	58.2	0.020	983	17.6	9	46.5
		South Fork Mogollon	45.6	0.004	43	16.5	4	34
		Trail	62.9	0.006	20	15.4	4	32
	Sheep Corral	Sheep Corral	51.7	0.007	26	18.2	1	44
	South Diamond	South Diamond	60.0	0.015	96	13.9	11	31
	Willow	Little Turkey	3.1	0.001	10	13.5	7	1
		NF Willow	21.4	0.002	6	11.9	4	7
		SF Willow	26.0	0.003	9	11.2	7	6
		Willow	8.1	0.004	37	14.3	8	14.5
Eliminated	McKnight	McKnight	51.2	0.008	41	12.8	10	23
	Spruce	Spruce	49.1	0.024	20	12.1	4	29.5
	West Fork Gila	Cub	20.8	0.006	18	11.7	10	5
		Langstroth below cascade	44.9	0.019	30	15.9	2	38
		Rawmeat & Trail	23.4	0.016	33	16.0	2	35
		WF Gila above Packsaddle	24.6	0.026	447	16.5	6	39
		WF Gila below Packsaddle	42.7	0.023	9927	17.4	12	37
		White below waterfall	32.1	0.009	274	16.1	3	41
	Whiskey	Whiskey	14.7	0.011	13	11.1	5	8
Recovery		Buckalou	25.5	0.001	3	15.4	4	14.5
		Castle	33.9	0.001	32	16.8	3	28
		Cave Creek	--	--	--	11.1	9	42*
		Chitty	15.6	0.006	27	13.1	8	12.5
		Coleman	12.0	<0.001	32	14.6	15	2
		Grant	23.0	0.002	33	12.9	17	3
		Grant (Low)	54.4	0.005	165	18.5	1	51
		Haigler	--	--	--	18.3	2	56*
		Haigler (Low)	--	--	--	19.3	0	57*
		KP	23.2	0.003	59	13.0	15	9.5
		Lanphier	39.9	0.005	51	14.9	8	27
		Lower Big Dry	49.9	0.012	82	14.7	8	33
		Manzanita	63.3	0.248	59	15.7	6	46.5
		Marijilda	30.0	0.115	86	14.9	5	36
		McKittrick	30.9	0.002	23	13.8	8	12.5
		Rain	59.2	0.002	22	10.2	9	11
		Rain (Low)	66.7	0.003	145	18.2	2	50
		Raspberry	20.4	0.002	11	14.5	9	4
		Sacaton	58.2	0.003	30	11.3	9	17
		South Fork Whitewater	44.8	0.055	43	12.3	12	24.5
		Turkey	59.4	0.144	85	15.4	9	43
		Turkey (Low)	68.0	0.081	643	19.7	0	54
		Upper Little	55.5	0.169	147	17.4	8	49
		West Fork Mogollon	55.0	0.006	86	12.7	12	24.5
		Whitewater	48.0	0.018	96	9.8	20	19
Restored	Black Canyon	Black Canyon	48.9	0.007	409	11.7	25	21
	West Fork Gila	Langstroth above cascade	36.8	0.015	25	14.3	4	29.5
	White	White above waterfall	21.4	0.004	26	13.6	9	9.5

*High overall ranking due to no fire risk or debris flow data.

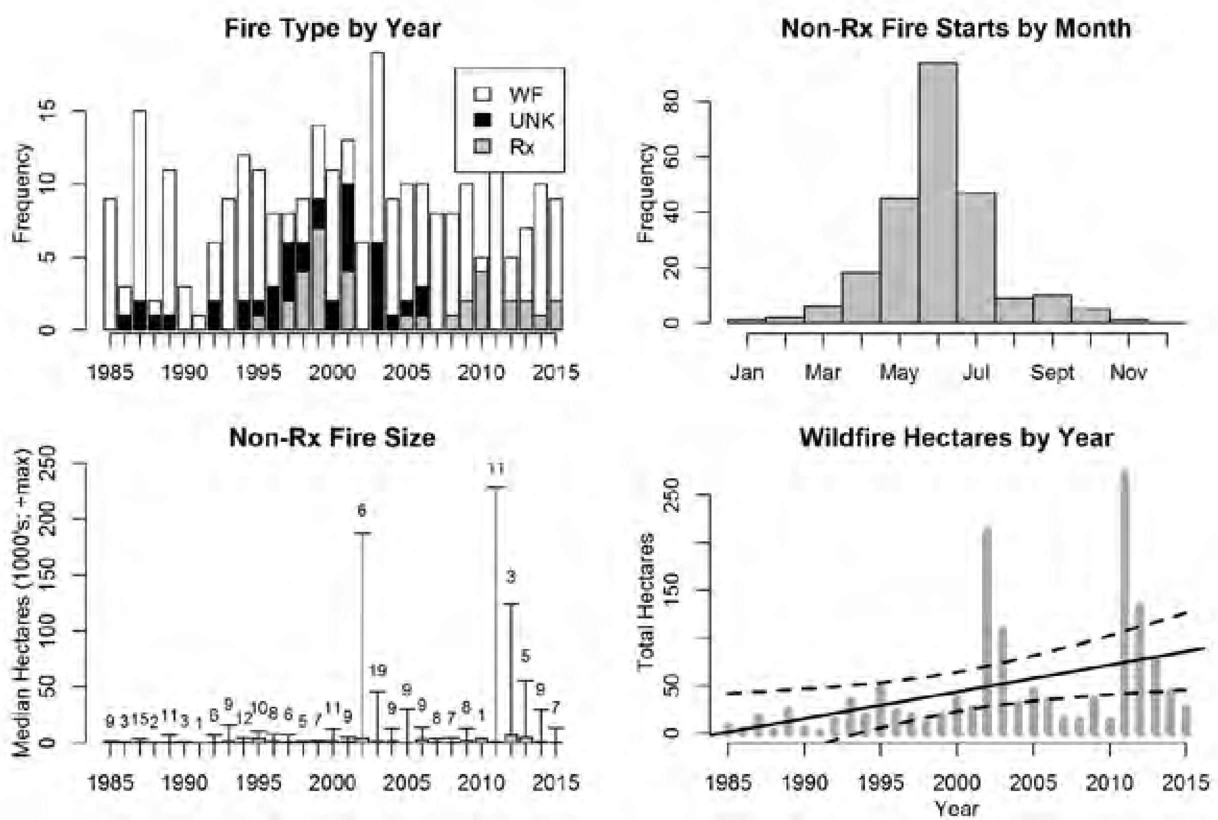

Figure 2. Frequency of wildfire (WF), prescription (Rx), and unknown (UNK) fire types by year (top left panel), frequency of fire starts by month (top right panel), median fire size (error bars = maximum; number of fires above bar) by year (bottom left), and total hectares burned by wildfire by year with trend line and 95% confidence intervals (b_{Year} = 2.82; df = 29; P = 0.019).

Whitewater-Baldy (2012), and Silver (2013) fires (Figure 1; bottom panels of Figure 2).

Wildfire Risk

Gila Trout streams exhibited a wide range of wildfire risk. The percent of watershed with high wildfire risk (active and passive crown fires) ranged from 2% in Frye Creek to 63% in Trail Creek for current and recently restored populations, and from 12% (Coleman) to 68% (Lower Turkey) for potential recovery streams (Table 1). Streams with Gila Trout populations extirpated by recent fires still had from 15% (Whiskey) to 51% (McKnight) of their watershed with high wildfire risk. Not surprisingly, wildfire risk was low within old burn perimeters where burn severity was highest (not shown), such as at high elevations on Mount Baldy within the 2012 Whitewater – Baldy fire perimeter (top panel of Figure 3).

Debris Flow Risk

The risk of post-fire debris flows was generally low in Gila Trout streams (Table 1). Probabilities of a debris flow occurring given modeled wildfire risk and other physiographic factors within the watersheds ranged from 0.001 or less (multiple streams) to 0.25 (Manzanita; Table 1). Watersheds with higher debris flow probabilities were clustered in certain drainages, such as the Turkey – Manzanita drainage in the eastern Mogollon Mountains (Figure 1; middle panel of Figure 2). Predicted debris flow volumes, if a debris flow were to occur, ranged from 3,000 m^3 (Buckalou) to nearly 10 million m^3 (lower West Fork Gila River). The Gila Trout streams with the highest probability of a debris flow generally had a moderate predicted debris flow volume; likewise, streams with the highest predicted volumes generally had less than a 3% chance of a debris flow occurring (top panel of Figure 4).

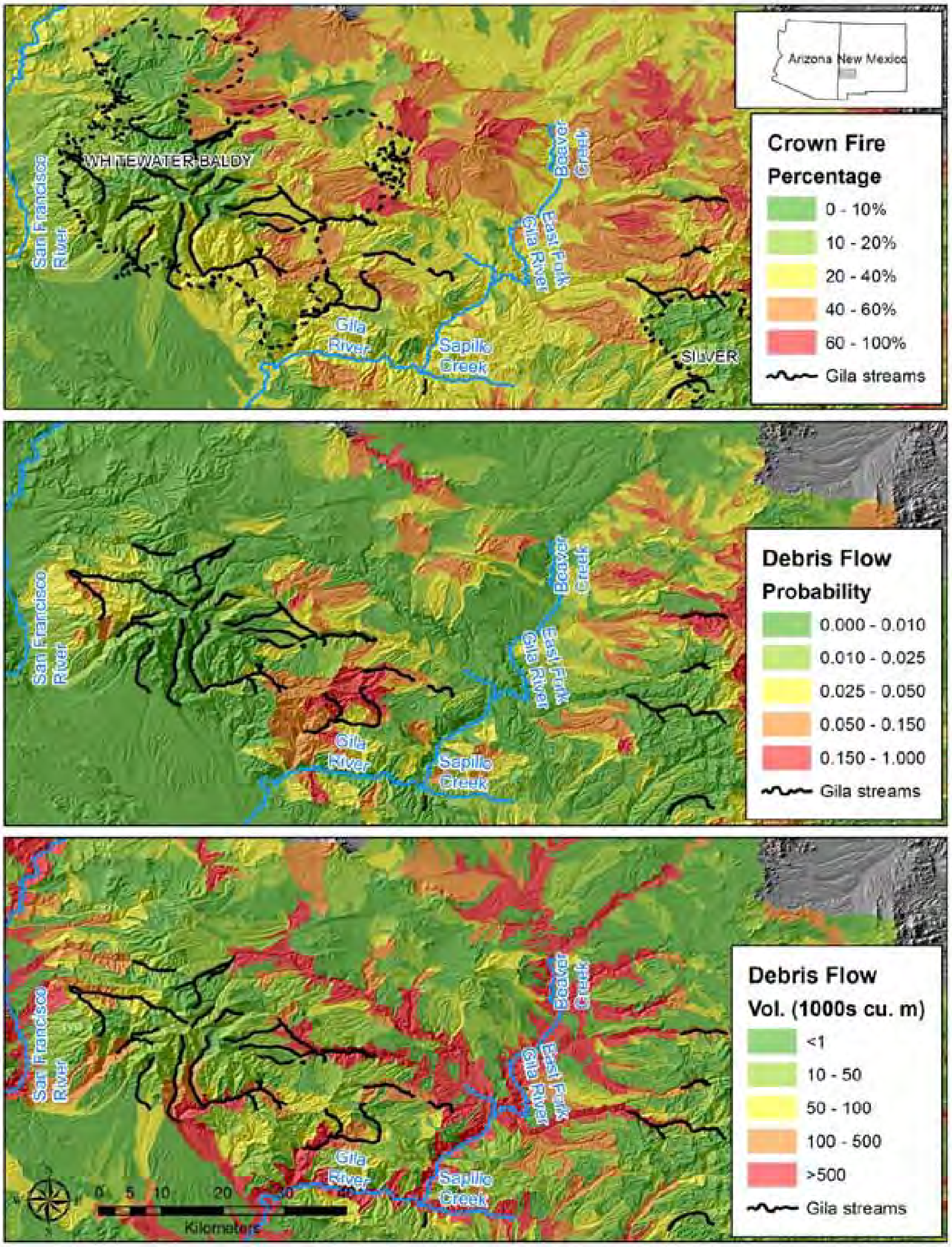

Figure 3. Example of percent watershed with high wildfire risk (active or passive crown fire) from FlamMap model (top panel), predicted debris flow probability given wildfire risk in watershed (middle panel), and predicted debris flow volume (bottom panel) for Gila Trout streams in New Mexico. Whitewater – Baldy and Silver fire perimeters shown in top panel (black dashed line).

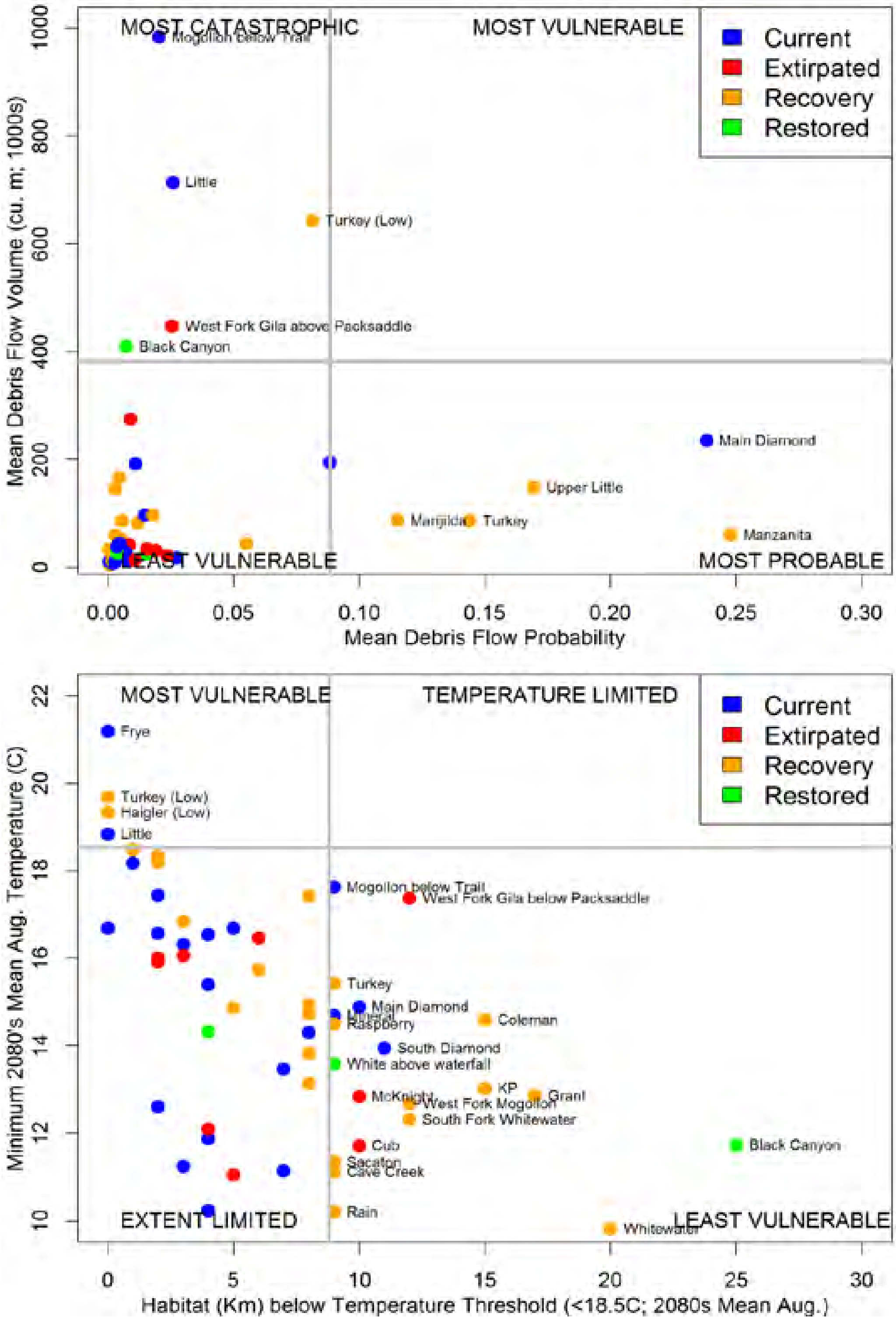

Figure 4. Mean predicted debris flow probability versus mean predicted debris flow volume (top panel) for Gila Trout streams, and length of habitat predicted to have mean August temperatures <18.5°C in the 2080s versus the minimum predicted mean August temperature in the 2080s across all stream segments (bottom panel) per Gila Trout stream. Streams symbolized by current population, recently restored population, population recently extirpated, and potential recovery stream.

2080s Remperature Risk

Gila Trout streams had varying risk to climate warming. Some streams had 0 km projected to have 2080s mean August stream temperatures below 18.5°C (Frye, Lower Turkey, Haigler, and Little), a temperature threshold that represents 95% of stream segments currently occupied by extant Gila Trout populations (bottom panel of Figure 4). Other streams have minimum projected 2080s mean August temperatures that are barely below that threshold. In contrast, a few potential recovery streams, such as Whitewater Creek, have large extents of habitat below that threshold and have minimum August temperatures projected to be less than 12°C in the 2080s. In fact, many streams had at least 8.8 km of habitat below 18.5°C, which is a habitat extent threshold commonly associated with a high likelihood of trout population persistence (Haak and Williams 2012).

Gila Trout Stream Vulnerability

When the 57 Gila Trout streams were ranked according to the five wildfire, debris flow, and temperature risk factors, a mix of potential recovery streams and current populations portended their low vulnerability to wildfire and 2080s temperature increases due to climate change. Little Turkey Creek ranked as the least vulnerable (overall rank = 1; Table 1). Together, the Willow Creek system containing Little Turkey, North Fork Willow, and South Fork Willow creeks appears to represent a stream network resilient to future wildfires, post-wildfire impacts (debris flows), and projected impacts of climate warming. Coleman and Grant creeks were also potential recovery streams that ranked in the top five for being least vulnerable. Interestingly, Cub Creek and Whiskey Creek now have low vulnerability despite recently being extirpated due to impacts from the Whitewater – Baldy Fire in 2012. This likely reflects the change in post-fire vegetation and fuels that are now not conducive to crown fires.

Discussion

Efficient conservation requires strategic investments of resources. Increasingly, climate change is playing a larger role in natural resource planning, as wildfires become more intense, streamflows decline, and stream temperatures warm (Williams et al. 2009; Isaak et al. 2015). We used wildfire, debris flow, and stream temperature models to identify Gila Trout streams least vulnerable to these future threats for use in planning conservation actions.

Establishing additional viable populations within the historical range has long been a goal of the recovery plan for Gila Trout, including replication of the different genetic lineages (USFWS 2003; Wares et al. 2004). Our analysis suggests that several recovery streams already identified as potential reintroduction streams are likely to be least vulnerable to future wildfires and projected changes to stream temperatures. For example, Grant and Coleman creeks showed low risk to wildfire impacts and had over 8 km of habitat with suitable stream temperatures in the 2080s. Conservation efforts focused on recovery streams should consider their vulnerability to future wildfire and climate warming impacts.

Gila Trout streams with moderate vulnerability rankings may benefit from strategic restoration efforts to offset wildfire impacts and climate warming. The wildfire, debris flow, and temperature models all have elements representing landscape features that can be influenced by management. For example, forest vegetation can be managed to promote forest health and reduce wildfire severity in drainages with high potential for crown fires (Gresswell 1999). Watersheds with higher susceptibility to debris flows could receive high priority for post-fire revegetation efforts (Cannon et al. 2010). Restoration actions that reconnect streams to floodplains, restore riparian areas, and improve instream habitat all have the potential to buffer the impacts of climate warming on stream temperatures (Williams et al. 2015).

Others have built fire risk and future temperature predictions into decision support tools for native trouts. Falke et al. (2015) developed a vulnerability assessment for Bull Trout *Salvelinus confluentus* in the Wenatchee River system, Washington, under current and future climate scenarios that account for wildfire risk, projected changes to stream temperatures, and other factors. The assessment was used to evaluate different forest vegetation, riverine connectivity, and nonnative species management scenarios to determine where and what types of management would best benefit Bull Trout persistence in the watershed. The wildfire, debris flow, and temperature models we developed herein could similarly be integrated into a decision support tool to guide conservation actions. Such a tool should not only account for the climate related factors described herein but also include factors such as streamflows, instream habitat, nonnative species to formally and completely compare and contrast Gila Trout conservation actions and guide decision-making.

Southwestern trouts are in peril. Both Gila Trout and Apache Trout have a limited number of extant populations that occupy a small portion of their historical range and each species is listed as Threatened under the Endangered Species Act. Strategic conservation will not only require the replication of genetic lineages and elimination of threats from nonnative salmonids, but it should also consider the vulnerability of native trout habitats to future wildfire and climate warming, among other factors, to ensure conservation actions across the landscape are climate resilient and long lasting.

Supplementary Materials

Available: http://www.tu.org/gila-vulnerability

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