Climate Change and Western Trout: Strategies for Restoring Resistance and Resilience in Native Populations

Jack E. Williams[1], Amy L. Haak[2], Helen M. Neville[3], Warren T. Colyer[4], and Nathaniel G. Gillespie[5]

[1]Trout Unlimited, 329 Crater Lake Avenue, Medford, OR 97504; [2]Trout Unlimited, 910 W. Main Street, Suite 342, Boise, ID 83702; [3]Trout Unlimited, 1020 W. Main Street, Suite 440, Boise, ID 83702; [4]Trout Unlimited, 249 South 100 West, Providence, UT 84332; [5]Trout Unlimited, 1300 N. 17th Street, Suite 500, Arlington, VA 22209.

ABSTRACT— Global warming and associated climate change will cause unprecedented environmental challenges for cold-water dependent fishes. We model three future conditions expected to impact western trout populations most severely – warmer summer temperatures, increased winter flooding, and increased wildfires – to identify those sub-watersheds and river basins where three cutthroat trout *Oncorhynchus clarkii* subspecies are likely to be at greatest risk. Many isolated and smaller Bonneville cutthroat *Oncorhynchus clarkii utah* populations, particularly those at lower elevations, will face increased risk from higher stream temperature and winter flooding. Lowest risk areas for this subspecies occur in the Bear River basin. Colorado River cutthroat *Oncorhynchus clarkii pleuriticus* populations will be at low risk in the Upper Green River; however, all other basins include sub-watersheds at moderate to high risk. Current westslope cutthroat *Oncorhynchus clarkii lewisi* populations are in relatively better condition, but approximately one-third face high risk from increased winter flooding. We argue that management agencies should meet these threats with accelerated and strategically located actions that restore resistance and resilience to climate change in native trout populations and their habitats by protecting best remaining populations, increasing population size and habitat in isolated populations, reducing outside habitat stressors, reconnecting habitats, and restoring migratory life histories. Control of nonnative salmonids should accompany these efforts. Given future uncertainty of climate change impacts and nonnative species expansion, more consistent monitoring and dedication to adaptive management principles are critical.

INTRODUCTION

Rapid global warming and associated climate change are likely to have significant negative impacts on most native trout populations. As ectotherms, trout physiology is directly regulated by temperature, and their life history stage-specific habitat requirements make them vulnerable to the many changes predicted to occur in aquatic habitats because of climate change (Rahel et al. 1996; Poff et al. 2002; Ficke et al. 2005). Native trout species are already struggling in the face of wide-scale habitat degradation, fragmentation, and the introduction of nonnative species (Dunham et al. 2002; Lee et al. 1997). Many of these existing threats are likely to be compounded by the effects of climate change.

Perhaps the most pervasive change associated with climate change is a warming of the Earth's surface. During the late 20th century, the Earth's average surface air temperature rose 0.6°C, a rate unprecedented in the past 1,000 years (Mote et al. 2005). Warming air temperatures will cause numerous fundamental environmental changes, including increased stream and lake temperatures and increased evaporation rates. This will reduce annual snowpack and reduce water storage in mid to lower elevation watersheds (Barnett et al. 2004). Precipitation changes are also predicted to result in peak flows occurring earlier in the year and longer, lower base flows (Barnett et al. 2004; Ficke et al. 2005). In general, disturbance events such as floods, drought, and wildfire will increase as climate change progresses (Poff 2002; McKenzie et al. 2004).

Although the general trends are clear, physical characteristics of the catchment, such as topography, vegetation, and orientation, will influence impacts to local watersheds and populations. Also important in determining local impacts will be existing stressors, such as road densities and livestock grazing. The presence of nonnative fishes will add still more complexity and uncertainty. Nonetheless, the effects of a rapidly changing climate are already beginning to manifest themselves. Harper and Peckarsky (2006), for instance, report earlier mayfly and other aquatic insect emergences in Rocky Mountain streams because of reduced snowpack and earlier peak runoff during the past decade.

In this paper, we present our analysis of climate change impacts – increased summer temperature, increased flood risk, and increased wildfire risk – on three subspecies of native trout in the western U.S., and suggest management strategies that will help restore resistance and resilience within populations to climate change. Despite the likely negative implications of climate change to western trout, we remain hopeful. Our hope rests on our ability to implement ecologically based restoration strategies that have proven effective for trout populations and their watersheds. We argue that strategic implementation of such strategies will increase the likelihood that native trout populations will persist in the future, even if this future is characterized by rapid environmental change. Salmonids evolved in highly dynamic environments and have substantial dispersal abilities that will aid in their survival if provided reasonable assistance.

METHODS

Our analysis models three elements of environmental change that are widely predicted to result from global warming and are likely to affect cold-water fish adversely:

1. Increased summer water temperature resulting from an increase in air temperature,
2. Larger and more frequent winter flood events resulting from an increase in rain on snow as warm midwinter air masses become more common, and
3. More frequent wildfires where longer, hotter, and drier summers aggravate a situation that is already volatile due to past management practices.

The analyses were conducted at the sub-watershed scale in a GIS environment. For each factor, each sub-watershed was scored as low, moderate, or high risk for adverse environmental affects on cold-water fish populations. A composite map of the three elements was projected across the current distribution of Bonneville cutthroat trout *Oncorhynchus clarkii utah*, Colorado River cutthroat trout *Oncorhynchus clarkii pleuriticus*, and westslope cutthroat trout *Oncorhynchus clarkii lewisi* to identify populations that are the most vulnerable to global warming induced environmental change.

Summer Temperature

The strong correlation between air temperature and water temperature and the lack of regional temperature data for streams and lakes makes air temperature a practical indicator for modeling environmental change across large geographic areas (Rahel 2002). We apply the methods of Rahel et al. (1996) who used changes in mean July air temperature to model habitat loss due to global warming for a cold-water guild of brown trout *Salmo trutta*, rainbow trout *Oncorhynchus mykiss*, brook trout *Salvelinus fontinalis,* and cutthroat trout *Oncorhynchus clarkii* in the Rocky Mountains. Analyzing average daily July temperature seems appropriate, because this is typically the hottest month in the Rocky Mountains.

The PRISM Group in the Oregon Climate Service at Oregon State University (PRISM 2007) recently published a series of national data sets of average monthly minimum and maximum temperatures from 1970 to 2000 at a resolution of 800 m. We averaged the minimum and maximum July temperatures for this 30-year period to establish a baseline from which to model change.

Before modeling the effects of increasing temperature, it was first necessary to determine the thermal limits for each of the three species evaluated that incorporate species-specific adaptations to local environmental conditions. This was accomplished through a comparison of the historic distribution (in kilometers of habitat) for each species and mean July temperature (Figure 1).

Less than 1% of the total distribution for westslope cutthroat trout and Colorado River cutthroat trout was found in streams with an average July air temperature greater than 22°C. In contrast, nearly 20% (1,400 km) of the historic distribution of Bonneville cutthroat trout was associated with a mean July air temperature greater than 22°C. The thermal distribution of Bonneville cutthroat trout was bimodal, as opposed to the bell curve exhibited by the other two species' distributions. The warmer second peak may be associated with an extensive network of lower elevation valley bottoms that historically contained Bonneville cutthroat trout populations.

Based on this analysis, an upper thermal limit of 22° C was applied to westslope cutthroat trout and Colorado River cutthroat trout, while 24° C was used for Bonneville cutthroat trout. We also identified a 'marginal' temperature range for each species that was within thermal limits but was on the upper end of the respective habitat curve. This marginal habitat range for westslope cutthroat trout and Colorado River cutthroat trout was defined as 20° C - 22° C and for Bonneville cutthroat trout as 22° C - 24° C. Any temperatures less than the lower end of these ranges were considered thermally suitable.

Our analysis of global warming impacts on thermal suitability applied a 3°-C temperature increase to the 1970-2000 mean July air temperatures. This increase has been projected as the most likely scenario for the American West within this century (Climate Impacts Group 2004). An area-weighted average temperature under the global warming scenario was calculated for each sub-watershed within the species' ranges. Using the species-specific 'suitable', 'marginal' and 'unsuitable' temperature break points previously defined, each sub-watershed was then scored for the level of risk to local populations from increased summer air temperatures: 1 (suitable, low risk), 2 (marginal, moderate risk), or 3 (unsuitable, high risk).

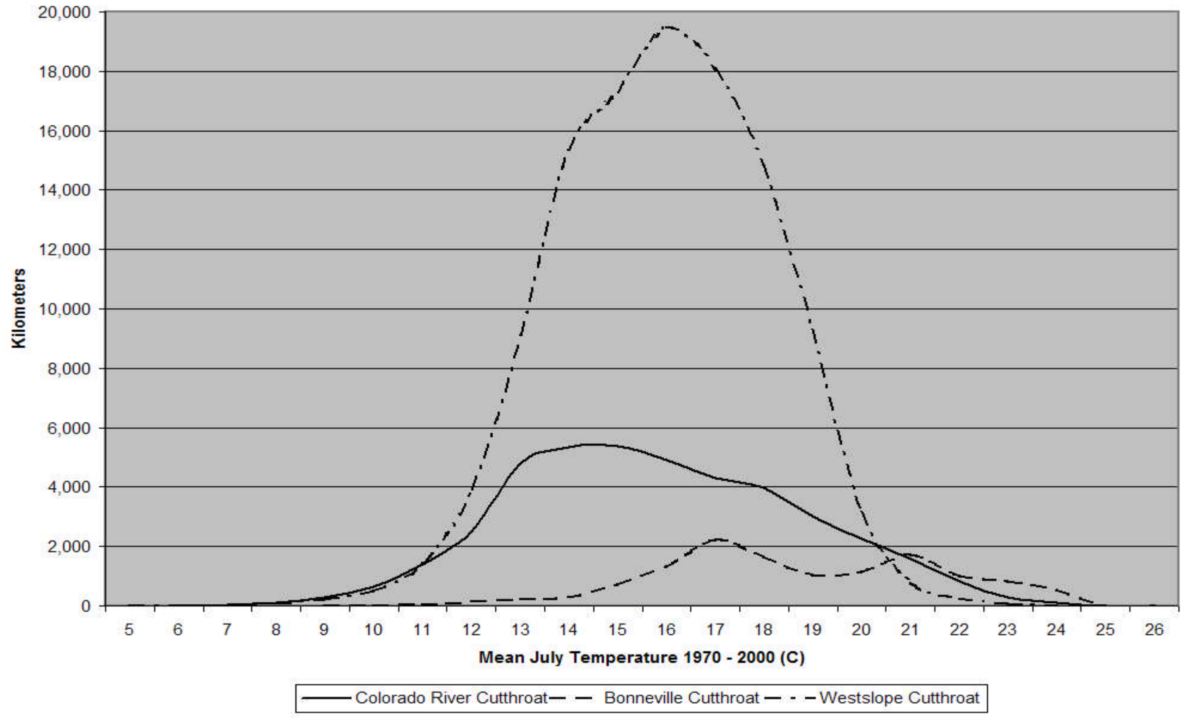

Figure 1. Historic distribution of Colorado River, Bonneville, and westslope cutthroat trout as measured in kilometers of stream habitat relative to July air temperature.

Increased Flood Risk

Hamlet and Lettenmaier (in review) modeled uncharacteristic winter flood events for basins of the Pacific Northwest as a result of global warming. Their analysis recognized three types of winter precipitation regimes for basins in the Pacific Northwest: rain dominant, snow dominant, and transient. Winter flooding in rain-dominant basins is a function of the individual storm event and the size and runoff characteristics of the catchment. Snow-dominant basins do not typically flood in mid-winter but rather flooding occurs later as spring run-off. Transient basins, where both rain and snowstorms occur, are the primary location of significant mid-winter flooding events. The magnitude of the flood event is dependent on the intensity and duration of the rainstorm and the antecedent snow pack.

Given the uncertainty of climate models with regard to future precipitation patterns, it is not possible currently to model increased flood risk as a function of changes in precipitation amounts. However, warmer winter temperatures will likely result in increased winter flooding due to increases in rain on snow events as snow-dominant watersheds shift to transient precipitation regimes.

Our analysis of uncharacteristic winter flooding due to global warming assumed the same 3°-C temperature increase used in our model of thermal impacts. For winter flooding we used mid-winter temperatures (January – March) as our baseline. We again relied on the PRISM average monthly minimum and maximum temperatures for 1970 – 2000. These data sets were processed to establish a mid-winter average temperature across the ranges of our three species of interest.

In addition to temperature data, we also acquired average annual and monthly precipitation data for the same time period. For each sub-watershed, the area weighted mean of three variables was calculated: annual precipitation, winter precipitation, and winter temperature. Sub-watersheds where the three months of winter precipitation comprised less than 25% of the annual precipitation were classified as having a non-winter-dominant precipitation regime and therefore were at low risk for uncharacteristic winter flooding.

Once the sub-watersheds dominated by winter precipitation were identified, we classified them by type - rain, snow, or transient - using the data on mean winter air temperature. We assumed that sub-watersheds with a mean winter temperature less than -1° C were snow dominant while those with a mean winter temperature greater than +1° C were rain dominant. The remainder of the sub-watersheds was classified as transient.

A 3°-C temperature increase was added to the current winter mean temperature and the sub-watersheds were reclassified. The change in basin type between current temperatures and the global warming scenario served as the basis for scoring the risk of uncharacteristic winter flooding. The highest score was assigned to sub-watersheds that change from snow dominant to transient or rain dominant. Sub-watersheds that change from transient to rain were assigned a moderate risk score because they would be likely to experience more flood events (and currently are) in the near term as they continue to receive some snow along with an increasing frequency of warm mid-winter storm events until they ultimately become rain dominant. Once this occurs, the winter flood risk may actually decline since there will no longer be an antecedent snow pack to contribute to high run-off. Sub-watersheds that remain as either snow or rain dominant, or are non-winter precipitation dominant, received the lowest risk score.

Increased Wildfire Risk

Recognizing that fire is a part of the western landscape and fire risk will continue to increase as predicted under a warming climate, the increased wildfire risk analysis sought to identify areas at greatest risk for uncharacteristic wildfire. Several factors contribute to increased risk for uncharacteristic wildfire, including changes in fuel loads, and vegetation type, composition, and structure. Past land management practices have resulted in the removal of large, fire-resistant native conifers and the spread of invasive, and highly flammable, species such as cheatgrass, resulting in an increase in the frequency, duration, and intensity of western wildfires (DellaSala et al. 2004).

To identify those areas that have been the most altered and are therefore at greatest risk for uncharacteristic fires, we used the Fire Regime Condition Class Departure Index developed by the Forest Service LANDFIRE program. The Index uses a scale of 0 – 100% to depict departure from the presumed historical vegetation reference conditions incorporating plant composition, structure, and disturbance regimes (Hann et al. 2004). Area weighted means of the departure index were calculated for each sub-watershed and grouped into three classes of risk: low is less than 50% departure, moderate is 51 – 75% departure, and high risk is greater than 75% departure.

Composite Climate Risk

The sub-watershed risks for each of the three elements (increased summer temperature, increased flood risk, and increased wildfire risk) were combined to generate a composite score for risk of habitat loss due to environmental change from global warming. Each sub-watershed was scored as low, moderate, or high risk based on the highest score from each of the three elements modeled and then evaluated against the current distribution of each subspecies. This allowed us to quantify potential habitat loss due to global warming and identify populations at greatest risk.

RESULTS

Bonneville Cutthroat Trout

For a 3^{o}-C increase in temperatures predicted with climate change, 77% of sub-watersheds with existing populations were modeled to be at moderate or high composite risk for Bonneville cutthroat trout (Table 1). A disproportionately large share of remaining habitat was projected to face thermal challenges in the West Desert and Southern Bonneville basins, where many remaining populations already are fragmented and occupy small stream segments. Stream habitats in the Bear River and Northern Bonneville basins were mostly at lower risk for thermal problems, except along the lower-elevation western flanks of those basins.

Areas of moderate to high risk for winter flooding were modeled to occur primarily in the Southern Bonneville and Northern Bonneville basins. Much of the West Desert will be in moderate risk while much of the Bear River and eastern portions of the Northern Bonneville basins are likely to remain as snow-form precipitation and therefore at low risk of increased winter flooding. Wildfire models suggest that highest risk areas are found in the lower elevations of the Bear River and Southern Bonneville basins. In general, the composite risk analysis showed that most of the West Desert, Southern Bonneville, and Northern Bonneville basins were in the moderate to high-risk range. Only populations in the extreme eastern portion of the Northern Bonneville basin, and most of the Bear River basin were modeled to be at low risk (Figure 2).

	Increased Summer Temperature			Increased Flooding			Increased Wildfire			Composite Risk		
Cutthroat trout subspecies	High	Mod	Low	High	Mod	Low	High	Mod	Low	High	Mod	Low
Bonneville	8	16	76	48	7	45	13	37	50	57	20	23
Colorado River	5	23	72	12	0	88	1	20	79	14	27	59
Westslope	3	35	62	31	7	62	3	42	55	36	31	33

Table 1. Percent of currently occupied sub-watersheds in low, moderate, and high risk category for each of the climate change factors.

Colorado River Cutthroat Trout

Colorado River cutthroat trout are more isolated in headwater tributaries that are less susceptible to thermal changes. Historically, 89% of stream habitat occupied by Colorado River cutthroat trout was less than or equal to 19^{o}C, and this percentage decreases only to 72% with the 3^{o}-C increase projected from climate change. Twenty-eight percent of currently occupied sub-watersheds were likely to be at thermal risk with the 3^{o}-C increase (23% of sub-watersheds occur in 19-22^{o}C range, and 5% in greater than 22^{o}C). All basins will be affected by increased temperature but a greater relative impact is likely in the Upper Colorado, Gunnison, Yampa, and Dolores river basins.

Increased risk for winter flooding was identified in habitats at lower elevations within the Lower Green, Yampa, Upper Colorado, Gunnison, Dolores, Lower Colorado, and San Juan river basins. All of the Upper Green and higher elevation habitats all other basins were modeled at low risk for increased flooding. Increased wildfire risk was generally lower and more scattered within the range of Colorado River cutthroat trout, but those basins in the eastern portion of the range had a higher percentage of sub-watersheds in the moderate and high risk categories. In general, the composite risk analysis showed mostly low risk in the Upper Green basin. Higher elevation zones of other basins were mostly in low risk categories despite increased risk for wildfire in scattered sub-watersheds (Figure 2).

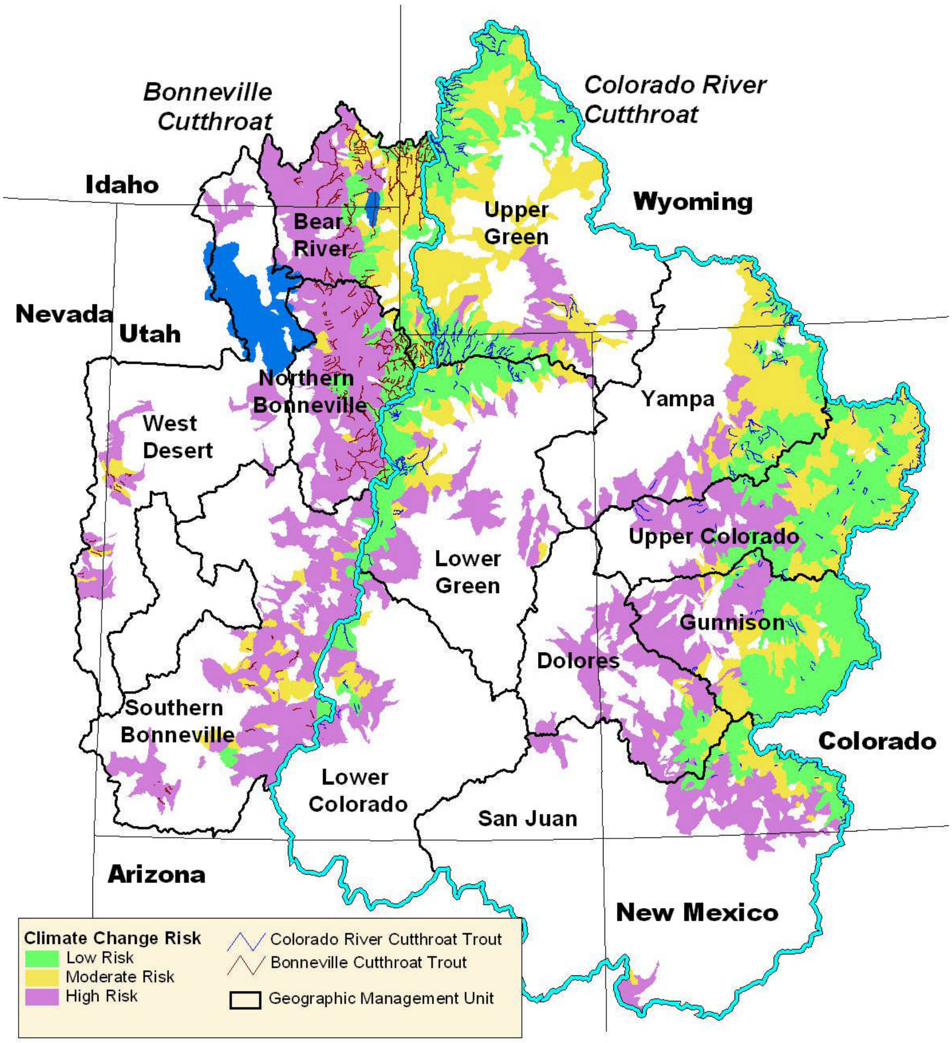

Figure 2. Composite climate change risks for Bonneville cutthroat and Colorado River cutthroat trout. Sub-watersheds within historic and current range were scored as low, moderate, or high risk. The range for the Colorado River cutthroat trout is outlined by double line; the range of the Bonneville cutthroat trout is shown to the left.

Westslope Cutthroat Trout

When the 3°-C temperature increase was applied to the 1970-2000 mean July temperatures, results for westslope cutthroat trout show 3% of sub-watersheds within the current range at high risk from increased temperatures and 35% at moderate risk (Table 1). Current westslope cutthroat trout populations are less fragmented and occupy many lower elevation streams that are moderately vulnerable to temperature increases over the next century. Most thermal risks occur in the Upper Missouri, Clearwater, and Coeur d'Alene river basins, as well as the Oregon portions of the range. Most existing habitat in the Salmon and much of the Clark Fork Basin was modeled at low risk from summer temperature increase.

High risk from winter flooding was identified in 31% of the current range, especially within the Clearwater, Coeur d'Alene, Clark Fork, Kootenai river basins, as well as those portions of the range in Washington and Oregon. Remaining basins were primarily at low risk from flooding. Increased risk from wildfire was more variable, but at high risk levels in much of the Marias, Upper Missouri, and Middle Missouri river basins. In the composite risk analysis, the Salmon and Madison river basins were at the lowest composite risk to climate change impacts. Highest risk areas were predicted in the Marias, northeastern portions of the Upper Missouri, northern portions of the Middle Missouri, and much of the range in Washington. The Clearwater, Coeur d'Alene, Kootenai, western portions of the Clark Fork, and the range in Oregon were mostly in the moderate or high composite risk categories (Figure 3).

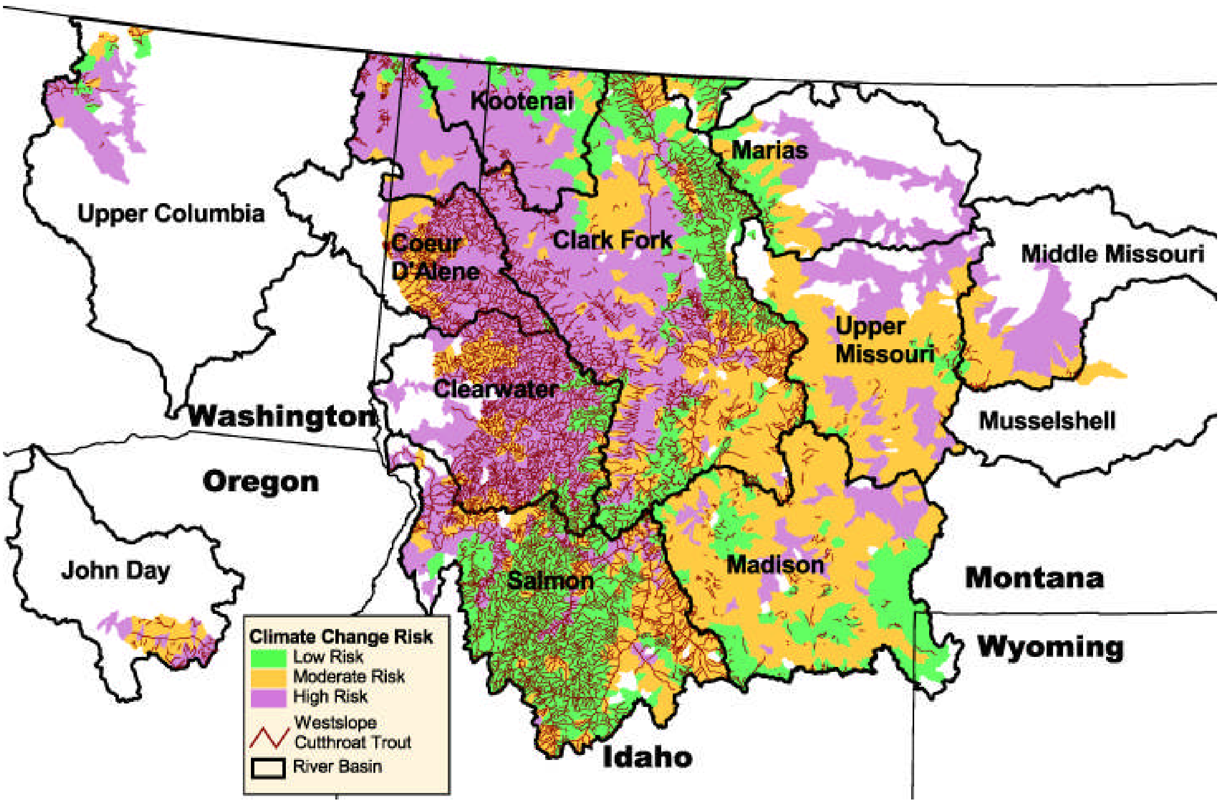

Figure 3. Composite climate risk map historic and current range for westslope cutthroat trout that combines risk of increased summer temperature, winter flooding, and wildfire.

For all subspecies, local stream-specific impacts were unpredictable in our analysis because of the scale of the data and the categorization by sub-watershed. Nonetheless, many sub-watersheds and larger river basins were identified at high risk of significant impacts to stream populations from climate change events. This does not mean that restoration efforts should be abandoned from these regions. Much to the contrary, our analysis illuminates those regions that should receive immediate actions to expand habitats and populations – that is, restore resistance and resilience to climate change – so that the genetic, life history, and population diversity within these subspecies can be maintained in the face of a rapidly changing climate.

Strategies to Restore Resistance and Resilience

While we may not be able to stop a rapidly changing climate, we can implement measures designed to increase the likelihood of native trout persistence. We describe six strategies that draw on existing and proven methodologies and will increase the ability of habitat and populations to withstand rapid environmental change (**resistance)**, and improve the ability of habitats and populations to rebound after disturbance (**resilience)**. These strategies generally fit within what can be described as a "protect-reconnect-restore" model of fisheries sustainability, where emphasis is to **protect** the best remaining habitats and populations, **reconnect** fragmented habitats by removing in-stream barriers and reestablishing in-stream flows, and **restore** vital mainstem river and riparian habitats. Trout Unlimited has encouraged implementation of these strategies as a contingency plan to prepare for future climate change impacts.

Strategy 1: Protect remaining population and habitat strongholds

The first rule of strategic restoration is to protect remaining core strongholds (Frissell 1997; Williams et al. 1997). Existing trout strongholds should be maintained in high quality condition because these areas will have the greatest likelihood of resisting climate change and will be key to future population expansions. Similarly, watersheds that produce reliable supplies of cold water should be protected, because these areas will be key to maintenance of suitable downstream conditions.

Strategy 2: Maintain genetic and life history diversity

Genetic and life history diversity help buffer populations against environmental changes by allowing populations to maintain broad suites of behavioral characteristics, increasing the likelihood that some individuals will be better adapted to novel conditions (Schlosser and Angermeier 1995). Restoring life history diversity, especially migratory forms, serves the dual purpose of maintaining genetic diversity and increasing the ability of a population to explore and colonize habitats that had recovered from earlier disturbance (Dunham et al. 2003; Colyer et al. 2005; Neville et al. 2006). Larger, migratory individuals also have higher fecundities and therefore are better able to resist outside stressors such as non-native species.

Strategy 3: Increase size and extent of existing populations

Small, fragmented populations are at greater risk of extinction because of habitat limitations as well as demographic and environmental variability (Hilderbrand and Kershner 2000; Rieman and Allendorf 2001). Many populations of native trout have been relegated to smaller, upper elevation streams by degraded downstream habitat and advances from nonnative salmonids. Climate change is likely to exacerbate these threats by increasing environmental variability and reducing suitable water quality and quantity (Poff 2002; Poff et al. 2002). Populations occurring over larger geographic areas, or greater stream lengths, will be more stable and more resistant to local extinction.

Strategy 4: Minimize outside stressors

For many watersheds, climate change will add stress to drainages that are already impacted by a multitude of anthropogenic disturbances such as roads, overgrazing by livestock, poor timber harvest practices, off-road vehicle use, mining, pollution, and agriculture. The cumulative effect of climate change impacts may deteriorate some watersheds to the point that they will not be able to rebound following disturbance events, or may move watershed conditions to new and reduced-integrity thresholds following floods, drought, wildfire, or other major changes. Restoration of natural conditions and ecological processes will improve the ability of populations to rebound after catastrophic events, including increased floods, particularly when focused on restoring riparian habitats, floodplains, and reconnecting streams to larger river systems (Williams and Williams 2004).

Strategy 5: Manage at watershed scales to reconnect stream systems

Restoring connectivity within and among watersheds by removing barriers to dispersal or by restoring in-stream flows will facilitate the recovery of migratory life histories, and increase the likelihood of fish finding suitable habitat conditions. Restoring connectivity in watersheds helps to reverse the habitat fragmentation and isolation of small populations, often cited as principal causes of population loss among cold-water fishes (Dunham et al. 1997; Hilderbrand and Kershner 2000). As waters warm in response to climate change, increasing access to suitable habitat conditions will become critical to survival for many populations. However, because nonnative species can expand as connectivity increases, site-specific decisions will have to be made that weigh this factor among potential gains (Fausch et al. 2006).

Strategy 6: Increase monitoring and improve adaptive management

Langston (1995) appropriately characterized successful adaptive management as “listening to the land,” with managers being responsive to monitoring results and acting on new knowledge by modifying management programs appropriately. Climate change will add variability to natural systems that are already exceedingly complex and subject to synergistic effects of human actions that further confound management. Nonnative species and pathogens are present in many watersheds harboring native trout and the response of these animals to climate change may be particularly hard to predict. If carefully designed, monitoring programs should be valuable in unraveling the complexities that climate change will add to natural systems (Kershner 1997).

Conclusion

The impacts of climate change on western trout populations and particularly native trout will be significant. Many of the current ranges of these fishes already have been greatly reduced from historic conditions. For example, based on sub-watersheds, Colorado River cutthroat trout occupy 18% of their historic range, Bonneville cutthroat trout 37% and westslope cutthroat trout 56%. Yet our modeling shows significant portions of this remaining range at high risk from climate change (57% of Bonneville cutthroat trout range is at high climate change risk, 14% of Colorado River cutthroat trout, 36% westslope cutthroat trout). Modeling increased risk factors can help identify those areas where existing populations are at greatest risk and where restoration and reintroduction efforts should be expanded. These models can be useful in determining how climate change may compound current stresses, and in developing strategies to protect, reconnect and restore populations of Bonneville cutthroat trout, westslope cutthroat trout and Colorado River cutthroat trout. Monitoring will be critical in understanding local stream impacts and appropriately placing streams within broader basin-wide strategies.

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