TACCIMO
Template for Assessing Climate Change Impacts and Management Options

TACCIMO Literature Report

Literature Report - Annotated Bibliography Format

Report Date: September 03, 2013

Content Selections

Animal Communities
- Fish
  - R1: Northern
  - R2 & R4: Mountain West

How to cite the information containted within this report

Each source found within the TACICMO literature report should be cited individually. APA 6th edition formatted citations are given for each source. The use of TACCIMO may be recognized using the following acknowledgement:

"We acknowledge the Template for Assessing Climate Change Impacts and Management Options (TACCIMO) for its role in making available their database of climate change science. Support of this database is provided by the Eastern Forest Environmental Threat Assessment Center, USDA Forest Service."

Best available scientific information justification

Content in this Literature report is based on peer reviewed literature available and reviewed as of the date of this report. The inclusion of information in TACCIMO is performed following documented methods and criteria designed to ensure scientific credibility. This information reflects a comprehensive literature review process concentrating on focal resources within the geographic areas of interest.

Suggested next steps

TACCIMO provides information to support the initial phase of a more comprehensive and rigorous evaluation of climate change within a broader science assessment and decision support framework. Possible next steps include:

1. Highlighting key sources and excerpts
2. Reviewing primary sources where needed
3. Consulting with local experts
4. Summarizing excerpts within a broader context

More information can be found in the user guide. The section entitled Content Guidance provides a detailed explanation of the purpose, strengths, limitations, and intended applications of the provided information.

Where this document goes

The TACCIMO literature report may be appropriate as an appendix to the main document or may simply be included in the administrative record.

Brief content methods

Content in the Literature Reports is the product of a rigorous literature review process focused on cataloguing sources describing the effects of climate change on natural resources and adaptive management options to use in the face of climate change. Excerpts are selected from the body of the source papers to capture key points, focusing on the results and discussions sections and those results that are most pertinent to land managers and natural resource planners. Both primary effects (e.g., increasing temperatures and changing precipitation patterns) and secondary effects (e.g., impacts of high temperatures on biological communities) are considered. Guidelines and other background information are documented in the user guide. The section entitled Content Production System fully explains methods and criteria for the inclusion of content in TACCIMO.

Resource Area (Factor): Animal Communities

Fish

R1: Northern

Bear, E. A., McMahon, T. E., & Zale, A. V. (2007). Comparative thermal requirements of westslope cutthroat trout and rainbow trout: Implications for species interactions and development of thermal protection standards. Transactions of the American Fisheries Society, 136: 1113-1121.

"Our results provide evidence that rainbow trout [Oncorhynchus mykiss] would gain a distinct survival and growth advantage over westslope cutthroat trout [Oncorhynchus clarkii lewisi] if temperatures exceeded 22°C for even short periods, which possibly explains their replacement of westslope cutthroat trout in lower-elevation stream reaches. In contrast, we found no growth or survival advantage for westslope cutthroat trout over rainbow trout at cooler temperatures. We conducted our study using satiation rations, and differences in growth and survival would probably become more pronounced with the reduced food availability and growth potential (e.g., Brett et al. 1969; Van Ham et al. 2003; Li et al. 2004) characteristic of high-elevation streams during summer (Sloat et al. 2005). In turn, westslope cutthroat trout may have greater tolerance than rainbow trout to the recruitment failures that are common to higher-elevation sites because of their cold summer temperatures and short growing season (Harig and Fausch 2002)."

"Over the test temperature range of 8–18°C, both species had high survival rates of 82–100% (Figure 1) and mean survival rate did not differ. However, at temperatures of 20°C or higher, westslope cutthroat trout [Oncorhynchus clarkii lewisi] had significantly lower survival than did rainbow trout [Oncorhynchus mykiss] (Tukey's test: P <0.05). Mean survival of westslope cutthroat trout declined significantly (P<0.05) to 35.7% at 20°C, 12.5% at 22°C, and 0% at 24°C (Figure 1). In contrast, rainbow trout survival was similar (98.6– 100%) among temperatures of 8–22°C but declined significantly (P<0.05) at higher temperatures: survival was 72.8% at 24°C, 2% at 26°C, and 0% at 28°C."

"The LT50 [the temperature that was lethal to 50% of test fish] of westslope cutthroat trout [Oncorhynchus clarkii lewisi] was significantly lower than that of rainbow trout [Oncorhynchus mykiss] at all time periods (nonoverlapping 95% CIs), but the difference became more pronounced with longer exposure time (Figure 2). At 20°C, westslope cutthroat trout survival was high (.90%) for 30 d and declined sharply thereafter; at 22°C and 24°C, survival declined sharply after 7 d of exposure (Figure 3). At 26°C, mortality was high during ramping and no fish survived past day 3 of the experiment. At 20–24° C, rainbow trout showed much less pronounced declines in survival over 60 d than did westslope cutthroat trout; at 26°C, rainbow trout survival remained high for 7 d before experiencing a sharp decline."

Goode, J. R., Buffington, J. M., Tonina, D., Isaak, D. J., Thurow, R. F., … & Soulsby, C. (2013). Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. Hydrological Processes, 27, 750 – 765. DOI: 10.1002/hyp.9728

"Physical habitat diversity and resistance to change are also likely to influence the sensitivity of salmonids [Oncorhynchus spp.] to climate change [at our study site in the Middle Fork of the Salmon River, located in the Northern Rocky Mountains of central Idaho]. Whereas large stochastic events may have the capacity to threaten small, spatially distributed populations, source populations in sites that are thermally or geomorphically resistant to climate change may persist. For example, high elevation zones that are far from the freezing limit are less likely to experience shifts in flow timing compared with lower-elevation sites where an increased proportion of the total precipitation is expected to fall as rain (Mote et al., 2005; Hamlet and Lettenmaier, 2007). Similarly, basin geology and structure may cause unique responses to climate change, such as highly fractured terrains where groundwater flow contributes a substantial volume of water to late summer base flow (Tague et al., 2008; Tague and Grant, 2009)."

"As expected, results show that predicted scour for all [salmonid] species [in the Middle Fork of the Salmon River, Idaho] is less when morphologic adjustment keeps pace with future changes in flow regime (Figure 5). Climate-driven increases in grain size and channel width (Equations (3a and 3b) and (6a and 6b)) decrease potential scour (Equation 1) compared with a static channel morphology. For the case of a static channel morphology, the median critical scour probability for Chinook salmon [Oncorhynchus tshawytscha] increases from 0 to 0.3 in the Composite model [a composite of 10 GCMs] and from 0 to 0.7 in the more aggressive MIROC3.2 model, but only for less frequent events (Qi6) (Figure 6a and 6c). In the case where morphologic adjustment keeps pace with future changes in flow regime, the probability of critical scour for Chinook salmon remains low for Qi2 and Qi6 [incubation-specific flood frequencies and examined scour for the 2 and 6-year flows during the incubation period] Qi6, (Figures 5a, 6b and 6d). Regardless of the differences in climate models, these results suggest that climate-related changes in streambed scour are unlikely to have negative consequences for either individual year classes (Figure 6(b),Qi2) or the overall population (Figure 6(d), Qi6) of Chinook salmon in the study basin, provided that the channel morphology can adjust in the future. "

"Median scour risks for steelhead [Oncorhynchus mykiss, in the Middle Fork of the Salmon River, Idaho] were generally similar to Chinook salmon [Oncorhynchus tshawytscha] but with increased risk in both the 2040s and 2080s (Figure 5(b)). Given the comparable egg burial depths (35 and 40 cm, respectively) and similar spawning networks for these two species, the differences in predicted scour risk are likely due to differences in incubation timing (Table I, Figure 4). Without channel adjustment in the future, individual year classes of steelhead may be impacted by streambed scour, but the population as a whole may remain unaffected (i.e. increased scour risk for Qi6 but little to none for Qi2 [incubation-specific flood frequencies and examined scour for the 2 and 6-year flows during the incubation period]; Figure 6(a and c)). Neither the steelhead population nor individual year classes will likely be at risk to streambed scour if channel morphology can fully adjust in the future (Figure 6b and d). These results for steelhead are consistent across all three climate models."

"In contrast to the results for Chinook salmon [Oncorhynchus tshawytscha] and steelhead [Oncorhynchus mykiss], bull trout [Salvelinus confluentus, in the Middle Fork of the Salmon River, Idaho] were consistently predicted to experience an increase in the probability of critical scour in the future for all climate models (Figures 5 and 6). The greater sensitivity of bull trout to climate change likely stems from their shallow egg burial depths (Table I). Despite similar incubation timing, bull trout have a much higher future risk of scour than Chinook salmon, which tend to bury their eggs deeper (40 cm vs. 10-20 cm for bull trout). However, differences in spawning location may also be a factor. In terms of the frequency of critical scouring events, individual year classes of both forms of bull trout (migratory and resident) may be at risk despite potential channel adjustment in all climate models (Figure 6(b and d)). If channel morphology does not adjust in the future, bull trout populations on the whole may be at risk (Figure 6(a)). "

"Results show that basin structure is also an important factor in predicting morphologic adjustment and consequences for future [fish] spawning habitat. Inspection of scour maps [for the Middle Fork of the Salmon River, Idaho] revealed consistent patterns in the locations where critical scour was likely in future climate models (Figures 8 and 9). Sites within the volcanic terrain (eastern portion of Figure 1) exhibited greater scour probability due to finer grain-size predictions and narrower width predictions compared with the granitic terrain (Equations (3a and 3b) and (6a and 6b)). This was true for both static and dynamic morphology (particularly for bull trout predictions) but with relatively low scour probability for dynamic adjustment (cf. Figures 8 and 9). Assuming that body size and associated egg burial depths are an evolutionary trait that limits mortality for relatively frequent floods (Montgomery et al., 1999; Crozier et al., 2008), species in volcanic tributaries may be adapted to bury their eggs deeper than the range we modelled."

"Valley confinement also structured the spatial variation in critical scour risk. Recall that our model limits flow depths to bankfull stage in unconfined channels, thus limiting scour to the shear stress associated with the bankfull event. As such, unconfined valleys [in the Middle Fork of the Salmon River, Idaho] (southwestern portion of Figure 1) had consistently lower predicted scour risk for all three [salmonid] species regardless of whether channel morphology was considered dynamic or static (Figures 8 and 9). Because unconfined valleys comprised 18% of the total suitable spawning range for Chinook salmon [Oncorhynchus tshawytscha] and steelhead [Oncorhynchus mykiss] but only 11% for bull trout [Salvelinus confluentus], valley morphology may more strongly buffer Chinook salmon and steelhead spawning habitat from climate-related increases in scour. However, unconfined valleys may be particularly important refuges for bull trout, given that much of their spawning habitat occurs in confined valleys that will likely magnify climate-driven changes in scour."

Isaak, D. J., Muhlfeld, C. C., Todd, A. S., Al-Chokhachy, R., Roberts, J., … & Hostetler, S. W. (2012). The past as prelude to the future for understanding 21st-century climate effects on Rocky Mountain trout. Fisheries, 37 (12), 542 – 556

"To examine how climate warming trends and recent wildfires may have affected the potential for hybridization [for cutthroat trout, Oncorhynchus clarkii lewisi], a multiple regression model was developed to predict summer stream temperatures in 1978 and 2008 for the North Fork FRB [Flathead River Basin, Northwest Montana] (Jones et al., in press). Changes between these years suggest that temperatures increased by 0.87°C, which increased the percentage of the stream network with summer temperatures ≥9°C from 15% in 1978 to 33% in 2008 (Figure 3). Over the same time period, extensive genetic surveys tracked the spread of hybridization through the North Fork FRB. Surveys in the late 1970s and early 1980s showed that most cutthroat trout populations were genetically pure, except for a few hybrids in one stream (Marnell 1988). More recent surveys suggest that hybridization has spread upstream from hybrid source populations in warmer tributaries through the mainstem of the Flathead River (Boyeret al. 2008; Muhlfeld et al. 2009c). "

"Bull trout [Salvelinus confluentus] have thermal niches that are several degrees colder than those of other trout and char species in the Western United States (Selong et al. 2001), so natal spawning and rearing habitats are often fragmented and constrained to the coldest headwater streams (see BRB [Boise River Basin] case history below; Rieman andMcIntyre 1995; Dunham and Rieman 1999). Bull trout are also fall spawners, which means that eggs and alevins are vulnerable to high winter flows that may mobilize stream substrates and crush eggs or displace newly emerged fry (Shellberg et al. 2010). This vulnerability may explain why bull trout populations often fare poorly in streams with frequent high winter flows (Wenger et al. 2011b) and suggests that recent increases in winter flood risks across portions of the FRB [Flathead River Basin] are a cause for concern (Figure 2; Hamlet and Lettenmaier 2007). These shifts in hydrologic regimes may have played a role in declining populations over the last 20 years, although most declines are probably due to expanding population of nonnative lake trout (Ellis et al. 2011)."

Jones, L. A., Muhlfeld, C. C., Marshall, L. A., McGlynn, B. L. & Kershner. (2013). Estimating thermal regimes of bull trout and assessing the potential effects of climate warming on critical habitats. River Research and Applications, DOI: 10.1002/rra.2638

"In a laboratory study, Selong et al. (2001) reported that 95% of the peak feeding and growth temperatures for bull trout [Salvelinus confluentus] occurred in the range of 10.9–15.4°C and decreased significantly above and below this range. More specifically, peak consumption was predicted at 13.3°C, and estimates decreased significantly below 10.3°and above 16.3°C. In addition, studies in the natural environment show that bull trout occurrence is typically rare where maximum temperatures exceed 15° C (Fraley and Shepard, 1989; Rieman et al., 1997; Rieman and Chandler, 1999). Our results [from a nonspatial model, a spatial flow-routed model, and a spatial hierarchical model used to predict August stream temperatures throughout the Flathead River Basin, USA and Canada] support the optimal thermal ranges for feeding and growth, where peak thermal preferences during the month of August for FMO [foraging, migrating, and overwintering] were predicted at >10°C and <14°C, decreased significantly below 10°C (3.6%), and ceased to exist above 16°C."

"Isaak et al. (2010) employed spatially explicit, spatial statistical models to retrospectively estimate the effects of climate change and wildfire on stream temperatures and critical bull trout [Salvelinus confluentus] habitats in the Boise River Basin in central Idaho. The models estimated that from 1993 to 2006 bull trout lost 11–20% of headwater spawning and rearing streams"

"We found [using a nonspatial model, a spatial flow-routed model, and a spatial hierarchical model used to predict August stream temperatures throughout the Flathead River Basin, USA and Canada] that a conservative climate warming scenario (ECHAM5), as defined by the CSES [University of Washington – Center for Science in the Earth System], estimated a potential 58% loss of FMO [foraging, migrating, and overwintering] habitat [for bull trout, Salvelinus confluentus] and a 36% loss of SR [spawning and rearing] habitat if air temperatures were to rise by 3.28°C. Correspondingly, our [spatial hierarchical] model predicted a potential 86% loss of currently designated FMO habitat and a 76% loss of SR habitats if air temperature increases by 5.5°C"

"Use of FMO [foraging, migrating, and overwintering] habitat as migratory corridors is essential to maintaining genetic and life history diversity for bull trout [Salvelinus confluentus], whereas cold headwater spawning and rearing streams are vital for survival and reproduction (Rieman et al., 2006). Model simulations [from a nonspatial model, a spatial flow-routed model, and a spatial hierarchical model used to predict August stream temperatures throughout the Flathead River Basin, USA and Canada] show that lower portions of the FRB [Flathead River Basin] drainage (FMO habitat) may become thermally unsuitable and upstream habitats (SR) [spawning and rearing] could become isolated because of increasing thermal fragmentation during the summer months (Figure 5). How the bull trout populations will respond to these changes is uncertain; however, climate warming may shift the habitat distributions both spatially and temporally. Spatial shifts may be caused by decreases in food availability, increased competition with species, thermal refugia, and prey availability. Temporal shifts may occur in timing of life history transitions, such as spawning and feeding migrations (Rieman and Isaak, 2010)."

R2 & R4: Mountain West

Cooney, S. J., Covich, A. P., Lukacs, P. M., Harig, A. L., & Fausch, K. D. (2005). Modeling global warming scenarios in greenback cutthroat trout (Oncorhynchus clarki stomias) streams: Implications for species recovery. Western North American Naturalist, 65(3), 371-381.

"Growing seasons were extended for GCT [greenback cutthroat trout, Oncorhynchus clarki stomias] in these streams [in the central Rocky Mountains] in both global warming scenarios. Spawning activity was predicted to begin from 2.0 (s = 1.6) to 3.3 (s = 1.7) weeks earlier in the 2°C and 4°C scenarios, respectively."

"Warmer water temperatures in global warming scenarios resulted in higher probabilities of translocation success (Fig. 5) [for the greenback cutthroat trout, Oncorhynchus clarki stomias, in the central Rocky Mountains]. Five streams would currently have <50% chance of translocation success, and 7 of the 10 would have <75% chance. The average increase for these streams was 11.2% for the +2°C warming scenario, and 21.8% for the +4°C scenario, for the 5 streams with <50% probability of translocation success. In the 7 streams with <75% current chance of translocation success, the percentage increase was 12.6% for the +2°C scenario and 22.7% for the +4°C scenario."

"Given that GCT [greenback cutthroat trout, Oncorhynchus clarki stomias] are currently restricted to cold, unproductive systems, global warming may potentially aid these populations and make more headwater habitat suitable for GCT reintroduction."

"Increased air temperature and seasonal changes in precipitation may lead to increased intermittency of Rocky Mountain streams in the summer (Hauer et al. 1997). Increased intermittency, in turn, may lead to water temperature increases and deoxygenation in remaining pools (Gu et al. 1999), which may be detrimental to headwater cutthroat trout [Oncorhynchus clarkii] populations. Populations of cutthroat trout isolated in headwater reaches are likely to be highly susceptible to stochastic perturbations (Kruse et al. 2001). This effect may be exacerbated in the case of the GCT [greenback cutthroat trout, Oncorhynchus clarki stomias], as recolonization from downstream is not effectively possible for this species."

Isaak, D. J., Luce, C. H., Rieman, B. E., Nagel, D. E., Peterson, E. E., Horan, D. L., Parkes, S., & Chandler, G. L. (2010). Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological Applications, 20 (5), 1350-1371.

"Rainbow trout [Oncorhynchus mykiss] habitats encompassed much of the [Bosie River basin] stream network in 1993 and the total amount of estimated habitat was not substantially affected by warming trends (Table 5, Fig. 6). The most notable changes were small habitat gains at higher elevations (sometimes accelerated within wildfire perimeters) as unsuitably cold areas became thermally suitable. "

"For a relatively mobile species such as rainbow trout [Oncorhynchus mykiss], which has widely distributed and well connected habitats in the BRB [Boise River basin], the effects may be relatively benign. With some exceptions associated with structural barriers, rainbow trout populations should be able to track upstream shifts in habitat. Moreover, the wildfires associated with climate change may increase stream productivity, the availability of important forage items, and increase fish growth rates and densities (Rieman et al. 1997a, Dunham et al. 2007, Koetsier et al. 2007). Upstream habitats that become thermally suitable for rainbow trout may also be in better physical condition than lower elevation streams that tend to be more accessible and compromised by human activities (e.g., Rieman et al. 2000)."

"Bull trout appear to be more vulnerable. Our results suggest that climate change may be rendering 8–16% of thermally suitable natal stream lengths unsuitably warm each decade. If recent trends continue in the future (when most climate models project accelerated warming), bull trout may lose half of their habitat in the BRB [Boise River basin] mid-century. These losses would be exacerbated by fragmentation of large habitat patches and decreases in connectivity among remaining habitats (Rieman et al. 2007). Because the occurrence of bull trout [Salvelinus confluentus] populations is strongly associated with the size and isolation of habitat patches (Rieman and McIntyre 1995, Dunham and Rieman 1999), ongoing reductions would almost certainly be problematic for persistence of many populations."

"Despite a smaller estimated effect, however, the wildfires within the BRB [Boise River basin] effectively doubled or tripled stream warming rates relative to basin averages and caused some of the most dramatic shifts in thermal habitat. If the frequency and extent of wildfires continues to increase (McKenzie et al. 2004, Westerling et al. 2006), greater overlap with shrinking bull trout [Salvelinus confluentus] habitats could foreshadow a difficult future for the conservation of this species in some portions of its range (Rieman et al. 2007)."

"Bull trout [Salvelinus confluentus] natal habitats, in contrast [to rainbow trout], initially encompassed approximately half the BRB [Boise River basin] stream network and experienced systematic declines because these areas already occurred at the upper terminus of the network and losses in low-elevation sites were not offset by gains farther upstream (Table 5, Fig. 6). The total length of thermally suitable stream based on mean temperature criteria decreased by 11–20% (8–16%/decade), and the size of remaining natal patches was reduced by 10–18%. The greatest reductions occurred within wildfire perimeters and for the coldest, high-quality habitats because these areas comprised a smaller area at the outset of the study and changes relative to this baseline were amplified."

Isaak, D. J., Muhlfeld, C. C., Todd, A. S., Al-Chokhachy, R., Roberts, J., … & Hostetler, S. W. (2012). The past as prelude to the future for understanding 21st-century climate effects on Rocky Mountain trout. Fisheries, 37 (12), 542 – 556

"Stream temperature increases [in the Boise River Basin] had different effects on thermally suitable habitats for bull trout [Salvelinus confluentus] and rainbow trout [Oncorhynchus mykiss] (Figure 4, panels c and d). Rainbow trout habitats, constrained to lower elevations by cold temperatures, shifted upstream as warming occurred and reductions in the total amount of habitat did not occur (Isaak et al. 2010). Bull trout distributions, in contrast, were located further upstream and constrained by stream slope and small size at the upstream extent of the network. As streams warmed, therefore, net reductions in bull trout habitat occurred, which were estimated to be 8–16% per decade (Isaak et al. 2010)."

"Remaining populations of CRCT [Colorado River cutthroat trout, Oncorhynchus clarkii plueriticus] are highly fragmented [in the Green River Basin] and often inhabit only isolated headwater stream sections (usually < 10 km; Figure 6) above natural and anthropogenic barriers that prevent upstream invasions from nonnative trout, brown trout (Salmo trutta), and rainbow trout [Oncorhyncus mykiss] (Fausch et al. 2006; Hirsch et al. 2006). Ironically, this fragmentation may limit the negative effects of temperature increases because the downstream boundaries of CRCT populations are often determined by other factors. Moreover, the upper extents of many streams across the GRB are currently too cold to support recruitment of juvenile fish (Coleman and Fausch 2007a, 2007b), and these areas could become more suitable with temperature increases (Harig and Fausch 2002; Cooney et al. 2005)."

"The limited potential for negative temperature effects on CRCT [Colorado River cutthroat trout, Oncorhynchus clarkii pleuriticus] populations [in the Green River Basin] does not make them immune to other risks posed by climate change. In particular, the small size of the streams occupied by many populations makes them vulnerable to declines in summer discharge (Figure 2). Because discharge scales directly with habitat volume (McKean et al. 2010), there may be 20% less summer habitat in the GRB now than there was in 1950 based on historical trends (Clow 2010; Leppi et al. 2011). Where the upstream extent of populations is currently constrained by stream size rather than temperature, declining flows may shift the transition point between perennial flow and intermittency downstream or cause stream drying in places that fragment historically perennial reaches (Lake 2003). Summer flow declines could also reduce stream productivity by decreasing macroinvertebrate drift rates (Harvey et al. 2006) or interactions with riparian zones (Baxter et al. 2005; Riley et al. 2009), which could impair fish growth and survival during the brief summer season (Jenkins and Keeley 2010)."

Keleher, C. J. & Rahel, F. J. (1996). Thermal limits to salmonid distributions in the Rocky Mountain region and potential habitat loss due to global warming: A geographic information system (GIS) approach. Transactions of the American Fisheries Society, 125, 1 – 13.

"Based on fish distribution information contained in the Wyoming Game and Fish Department database, the coldwater fish guild was determined to be limited to areas where mean July air temperatures do not exceed 22°C. This is similar to limits reported by MacCrimmon and Campbell (1969) for brook trout [Salvelinus fontinalis] in their native range of eastern North America (mean July air temperature ≤ 21°C) and by Stefan et al. (1992) for the coldwater fish guild in Minnesota temperature (summer weekly mean temperature ≤ 23.4°C). Also, Barton et al. (1985) reported that a maximum summer water temperature below 22°C was the critical factor distinguishing trout from nontrout streams in Ontario."

"Our analyses [using data on fish distributions and maximum summer air temperature to identify the upper thermal limit for a coldwater fish guild composed of four species of salmonids: rainbow trout (Oncorhynchus mykiss), brown trout (Salmo trutta), brook trout (Salvelinus fontinalis), and cutthroat trout (Oncorhynchus clarki)] indicate that salmonid distributions may be noticeably affected by global warming both on a regional and local scale in the Rocky Mountains. This loss of habitat would occur even if thermal limits are 1- 2°C higher than the 22°C mean July air temperature we determined to be the thermal limit of the coldwater fish guild in Wyoming (Table I). Studies in other geographic regions also predict a significant loss of habitat for coldwater stream fishes should climate warming occur."

"In the Rocky Mountain region, coldwater fish species may migrate to colder upstream regions but still could experience a loss of habitat and population fragmentation. For example, even if species occupy the same length of stream but at higher elevations, the total habitat would probably decline because stream size generally decreases as elevation increases (Hubert and Kozel 1993). Furthermore, restriction of fish to headwater stream reaches would fragment populations which, in turn, would increase the risk of extinction from stochastic environmental factors and genetic inbreeding (Mills and Smouse 1994). Rahel et al (in press) [1996] hypothesized that a 3°C increase in summer water temperatures would fragment the coldwater fish guild in the upper North Platte River in Wyoming into a series of small , isolated populations, restricted to headwater tributaries where thermal conditions would remain suitable."

"For a 1-5 °C increase [in air temperature], loss of suitable [salmonid] habitat in Wyoming would be 16.2 - 68.0% based on geographic area but only 7.5-43.3% based on stream length. This discrepancy reflects the fact that for Wyoming and other arid regions with great topographic relief, streams are more abundant at higher elevations than at lower elevations (Derbyshire 1976; Chorley et al. 1984). Thus, as low elevation areas become too warm for coldwater fish, a relatively small proportion of the total stream length is affected. These results suggest that estimates of habitat loss due to climate warming based on stream length will be more conservative than estimates based on geographic area for regions where streams are concentrated at higher elevations. "

Rahel, F. J., Bierwagen, B., & Taniguchi, Y. (2008). Managing aquatic species of conservation concern in the face of climate change and invasive species. Conservation Biology, 22(3), 551-561.

"Cutthroat trout [Oncorhynchus clarkii] are species of conservation concern in the Rocky Mountain region. In many drainages cutthroat trout have been relegated to cold, headwater reaches by invading brook trout [Salvelinus fontinalis], which dominate warmer, downstream reaches. The species aggressively vie for feeding locations, suggesting that interference competition mediated by temperature could influence the distribution of these species. In the laboratory, the 2 species are nearly equal competitors at 10 C, but brook trout show a clear competitive dominance over cutthroat trout at 20 C (De Staso & Rahel 1994). At the warmer temperature, brook trout are more aggressive, consume more food, and occupy the lead position in a dominance hierarchy more often than cutthroat trout. In addition, brook trout maintained equilibrium longer during a thermal challenge test, suggesting they are more tolerant of heat stress than Colorado River cutthroat trout. "

Rahel, F. J., Keleher, C. J. & Anderson, J. L. (1996). Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: Response to climate warming. Limnology and Oceanography, 41 (5), 1116 – 1123.

"Our analysis of fish distributions [in the North Platte River drainage in Wyoming] in relation to water temperature [using approaches based on the use of summer air temperature or water temperature to define the thermal limits of cold water species] indicated that the cold water guild was limited to stream reaches where the maximum July water temperature was ≤21 °C. This is similar to thermal limits reported by other researchers for cold water species. For example, a maximum summer water temperature <22°C was the critical factor distinguishing trout from nontrout streams in Ontario (Barton et al. 1985). In extensive monitoring of fish distributions in two southern Ontario streams, the thermal limits of brook trout were 23-24°C (Meisner 1990a). A comparison of fish distributions and stream temperature data throughout the U.S. found that the highest weekly mean water temperatures associated with the presence of cold water species was 22.3°C for brook trout, 24.1°C for brown trout, and 24.O°C for rainbow trout (Eaton et al. 1995)."

"Our estimate of thermal limits [for cold water species in the North Platte River drainage in Wyoming] is supported by fish survey data from the South Platte River drainage in Colorado. There, Propst (1982) reported that 1,524 m was the lowest elevation at which brown trout [Salmo trutta] were found. On the basis of our regression models, this elevation would correspond to a maximum July water temperature of 20.8°C and a mean July air temperature of 23.1°C. Although the choice of thermal limit does influence the estimate of habitat loss (Table 2), it seems clear that even if the thermal limit of the cold water fish guild is slightly higher than our estimate, climate warming will noticeably reduce the amount of thermally suitable habitat for cold water fish in the Rocky Mountain region."

"In conclusion, although the three approaches we used varied in their results, all predict a noticeable decline in thermally suitable habitat for cold water fish [in the North Platte River drainage in Wyoming] with even modest increases in temperature due to climate warming. Remaining cold water fish populations would become restricted to increasingly higher elevations and would become fragmented, resulting in inbreeding effects and stochastic environmental fluctuations that would increase the risk of population extinctions. Although our analysis centered on several species of salmonids, the results should apply to other cold water organisms including nongame fish species and benthic invertebrates."

Williams, J. E., Haak, A. L., Neville, H. M. & Colyer, W. T. (2009). Potential consequences of climate change to persistence of cutthroat populations. North American Journal of Fisheries Management, 29, 533 – 548. DOI: 10.1577/M08-072.1.

"Changes associated with a rapidly warming climate already are apparent in the streams and watersheds in the Rocky Mountains of the western USA. In Colorado, earlier emergence of a mayfly Baetis bicaudatus has been observed since 2001 because of earlier peak stream runoff associated with warmer stream temperatures during dryer years (Harper and Peckarsky 2006). Since the mid-1980s, there has been a 60% increase in the frequency of large wildfires in the northern Rockies that is associated with increased spring and summer temperatures and earlier spring snowmelt (Westerling et al. 2006). Such observations increase the importance of analyzing increased risk to native trout populations in these areas."