Global Warming of Salmon and Trout Rivers in the Northwestern U.S.

Road to Ruin or Path Through Purgatory?

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Introduction

Large rivers constitute small portions of drainage networks but provide important migratory habitats and fisheries for salmon and trout when and where temperatures are sufficiently cold. Management and conservation of cold-water fishes in the current era of rapid climate change require knowing how riverine thermal environments are evolving and the potential for detrimental biological impacts. We mined the NorWeST database (Chandler et al. 2016; Isaak et al. 2017) to extract river temperature records with >10 years of data in the northwestern U.S. and supplemented those records with additional data contributed by professional biologists from eighteen agencies. Long-term records were available for 391 river sites and were examined for trends in monthly averages during the 40-year period of 1976–2015 (Figure 1). To understand those trends, monitoring records were also summarized for the same period at 168 air temperature stations in the Global Historical Climate Network-Monthly dataset (website: http://www.ncdc.noaa.gov/ghcnm/v3.php) and 299 river discharge gages from the National Water Information System dataset (website: http://waterdata.usgs.gov/nwis; Figure 2).

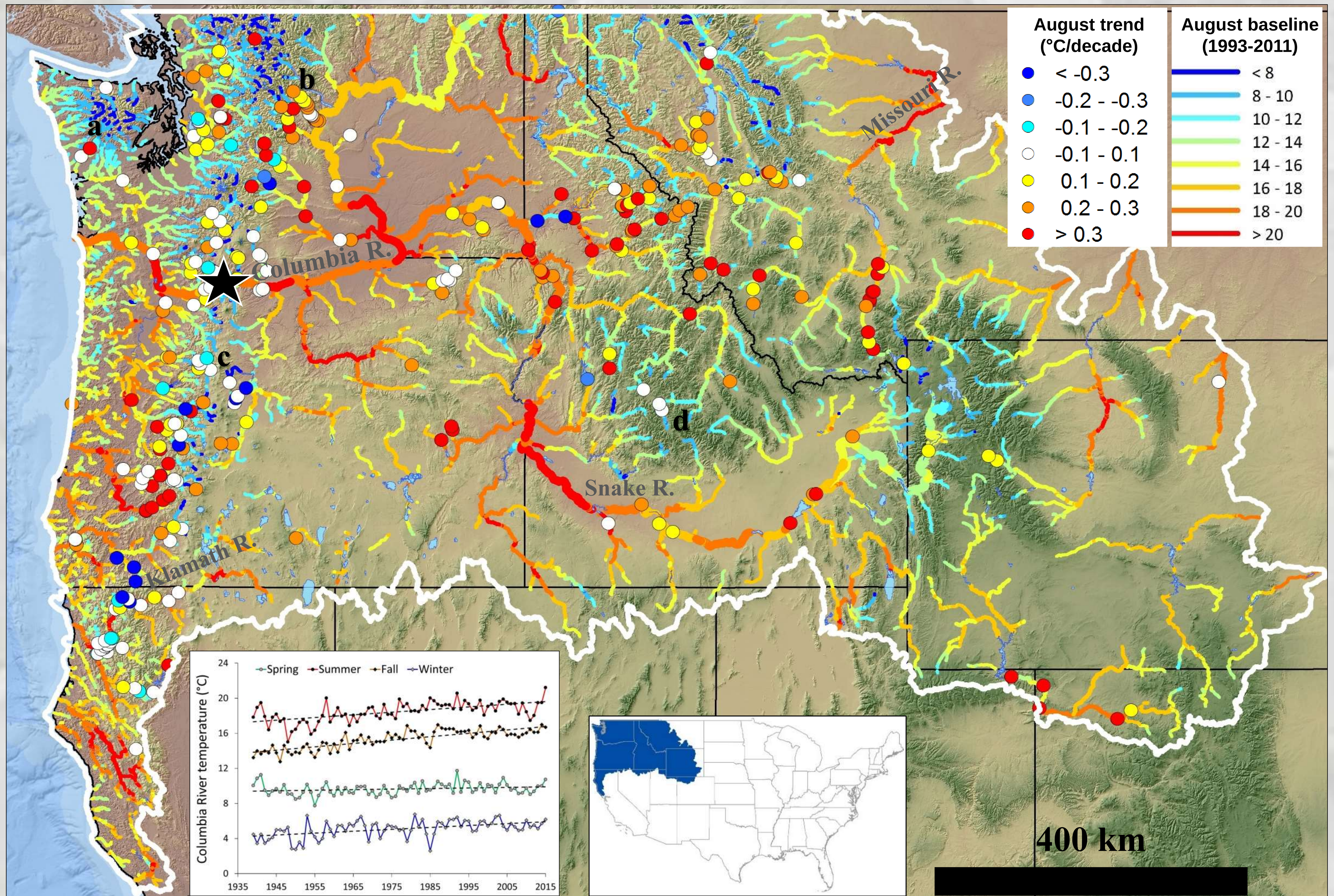


FIGURE 1. Study area extent showing 56,500 km of rivers with annual flow >100 cfs classified by mean August temperature for a baseline climate period of 1993–2011. Colored circles depict August temperature trends during the 40-year period of 1976–2015 at monitoring sites with >10 years of data. Monitoring sites with cooling trends (blue circles) occur downstream of large dams with cold hypolimnetic water releases, which indicates that increasing amounts of cold water were released during this period. Many of the cooling trends occur in association with rivers known to have thermally stressful summer temperatures for salmon and trout (Klamath River, Rogue River, Yakima River, Clearwater River) and often indicate efforts by local water managers to offset gradual long-term temperature increases. Inset graph shows trends in seasonal temperatures at Bonneville Dam on the Columbia River (black star denotes location) for 1939–2015, which is the longest continuous monitoring record in the region.

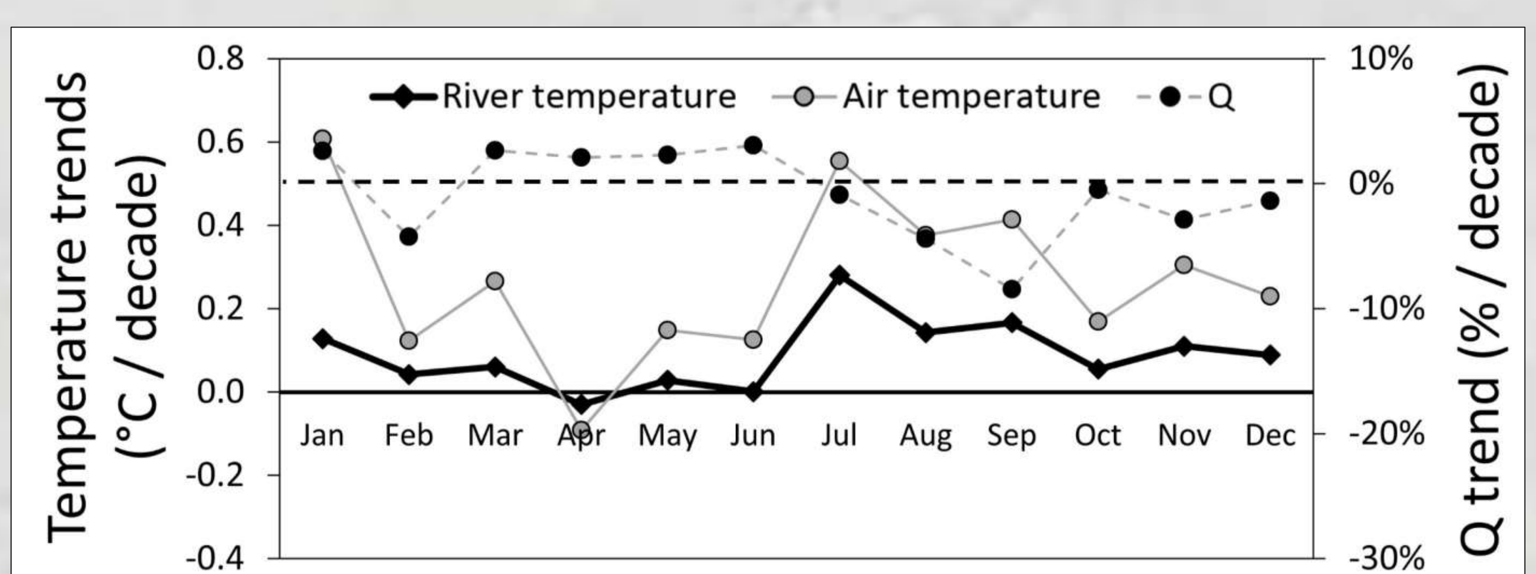
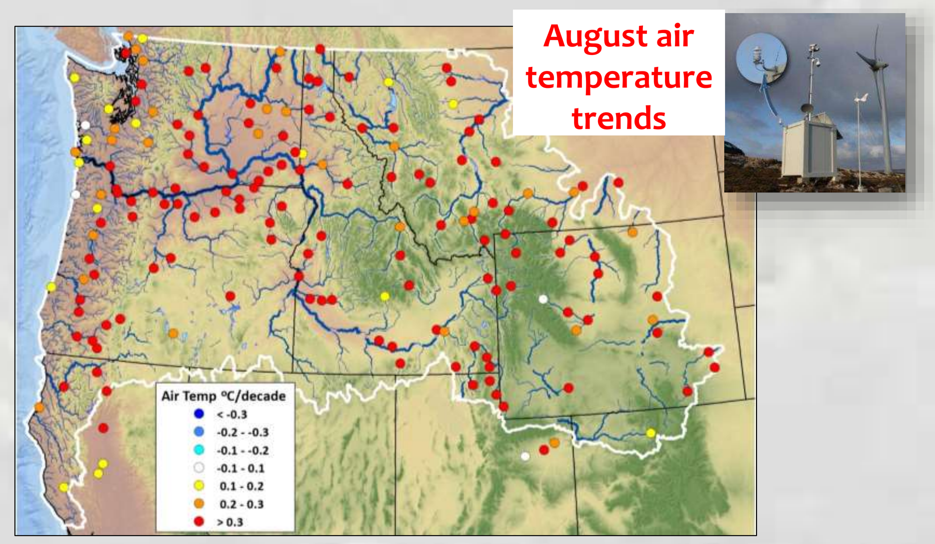
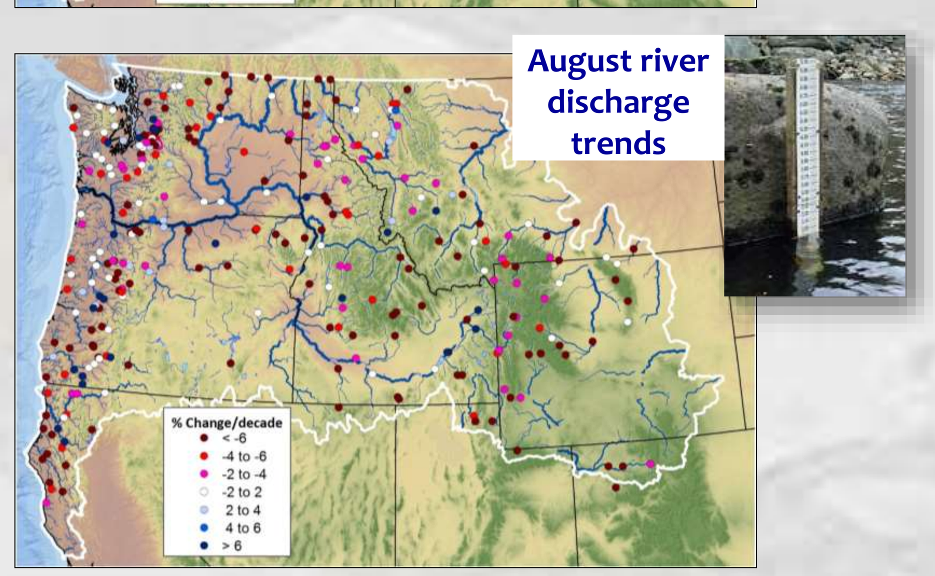


FIGURE 2. Regional average trends in mean monthly river temperatures, air temperatures, and discharge (Q) for each of 12 months during the 40-year period of 1976–2015. River temperatures largely paralleled air temperatures, albeit at reduced rates. The average annual rate of river temperature warming during this period was 0.084 °C/decade but rates where 2–3 fold greater (0.14–0.27 °C/decade) during the summer and early fall months when rivers were at baseflow and most sensitive to climate forcing.

Maps to the right show trends in mean August air temperature at 168 stations (top) and river discharge at 299 gages (bottom) during 1976–2015, the same period as the river temperature trends shown in Figure 1.





Long-term climate-induced warming of rivers in the Northwest will affect several species of salmon and trout and hundreds of individual populations. To illustrate the biological consequences later this century of river warming, two examples are provided. In the first example, the thermal exposure of adult sockeye salmon migrating to four inland and coastal population areas (lettered in Figure 1) was calculated for baseline river temperature conditions and scenarios representing +1–3 ºC temperature increases. Thermal exposure was quantified as degree-days by multiplying the length of each river path by it's average temperature during the number of days that adult salmon required to swim from the ocean to the natal area. Travel rates of 25 km/day and 50 km/day were used based on previous biotelemetry studies and whether river reaches occurred within run-of-the-river reservoirs along the Columbia/Snake rivers or were free-flowing (results shown in Figure 3).

In the second example, the effect of river temperature increases on the distribution and extent of thermally suitable habitats for resident brown trout and rainbow trout populations was assessed using the same baseline scenario and +1–3 ºC river temperature scenarios used in the salmon example. River reach temperatures throughout the Northwest were classified as sub-optimally cold (<12 ºC), optimal (12–18 ºC), or sub-optimally warm (>18–21 ºC) and results are mapped in Figure 4. Suitability categories were derived from previously published thermal response curves that were developed by combining 23,000 biological surveys with a NorWeST scenario of mean August temperatures for the baseline period of 1993-2011 (Isaak et al. 2017b).

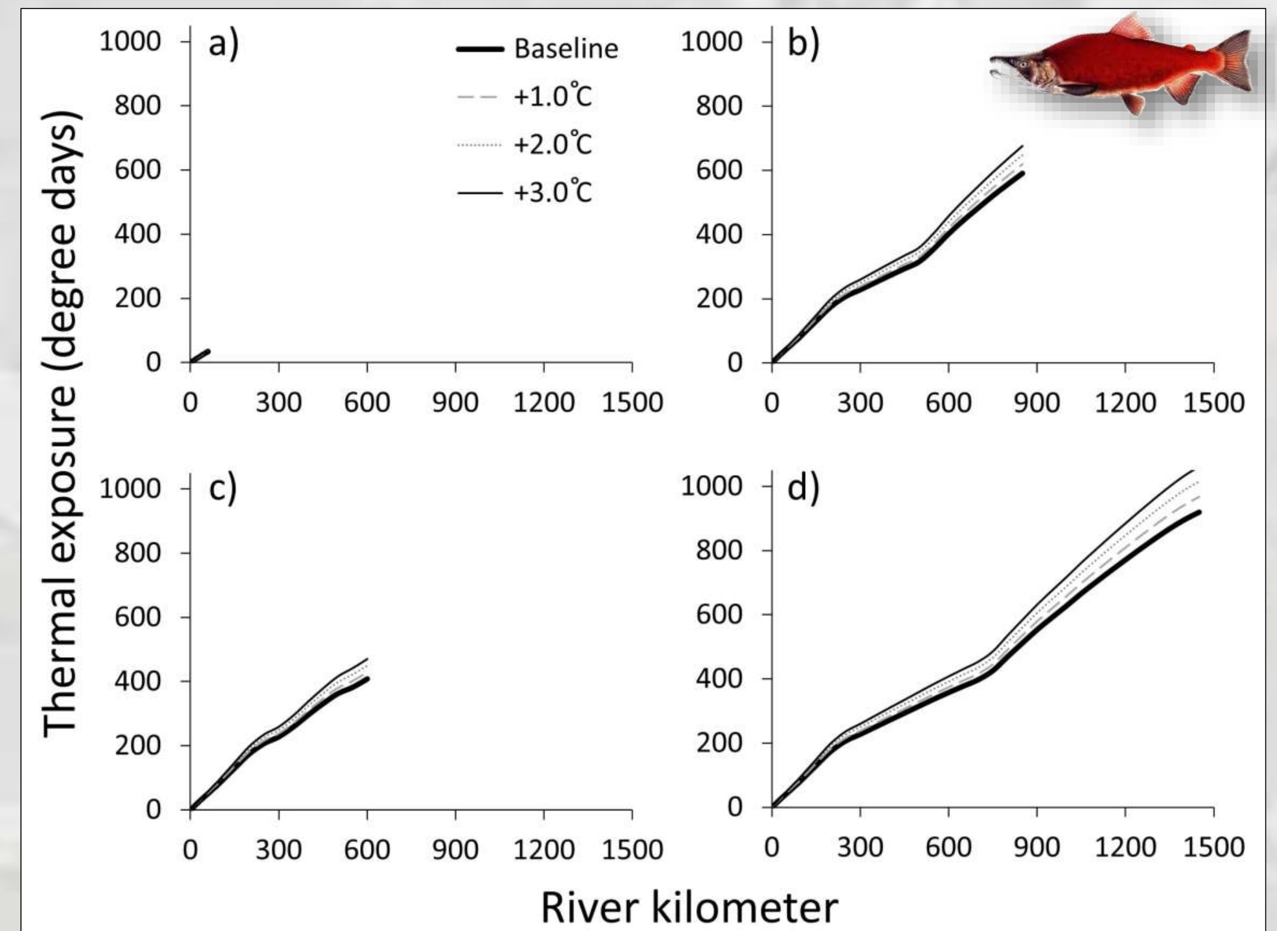


FIGURE 3. Thermal exposure for four sockeye salmon populations under baseline summer temperature conditions varied almost 30-fold, from 34 degree-days along a short migration path in a relatively cool river for Lake Quinault fish (population a) to 920 degree-days along the long migration path to Redfish Lake in Idaho (population d). Future temperature increases of 1–3 ºC increased the cumulative thermal exposure along the four population river paths by 5–16%, which translated to an additional 3–47 degree-days in the 1.0 °C scenario and 7–143 degree-days in the 3.0 °C scenario. Exposure increases were proportional to the length of the river path, so populations with longer migrations incurred larger absolute degree-day increases. Compounding the bioenergetic difficulties that future temperature increases may present for migrating sockeye salmon will be increases in short-term maximum temperatures that more frequently exceed lethal levels. During 2015, for example, record high temperatures during an extended period of 3–4 weeks caused catastrophic mortalities of adult sockeye salmon in the warm portions of the Columbia River immediately upstream of Bonneville Dam. An earlier study my Mantua et al. (2010) predicted that the number of weeks with lethal temperatures exceeding 21 °C could increase 10-fold in this river reach by the end of the 21st century. If that occurs, the extreme thermal conditions observed in 2015 may become "average" in the future and the tempo of what summer-migrating salmon experience as extreme events could threaten the persistence of some stocks.

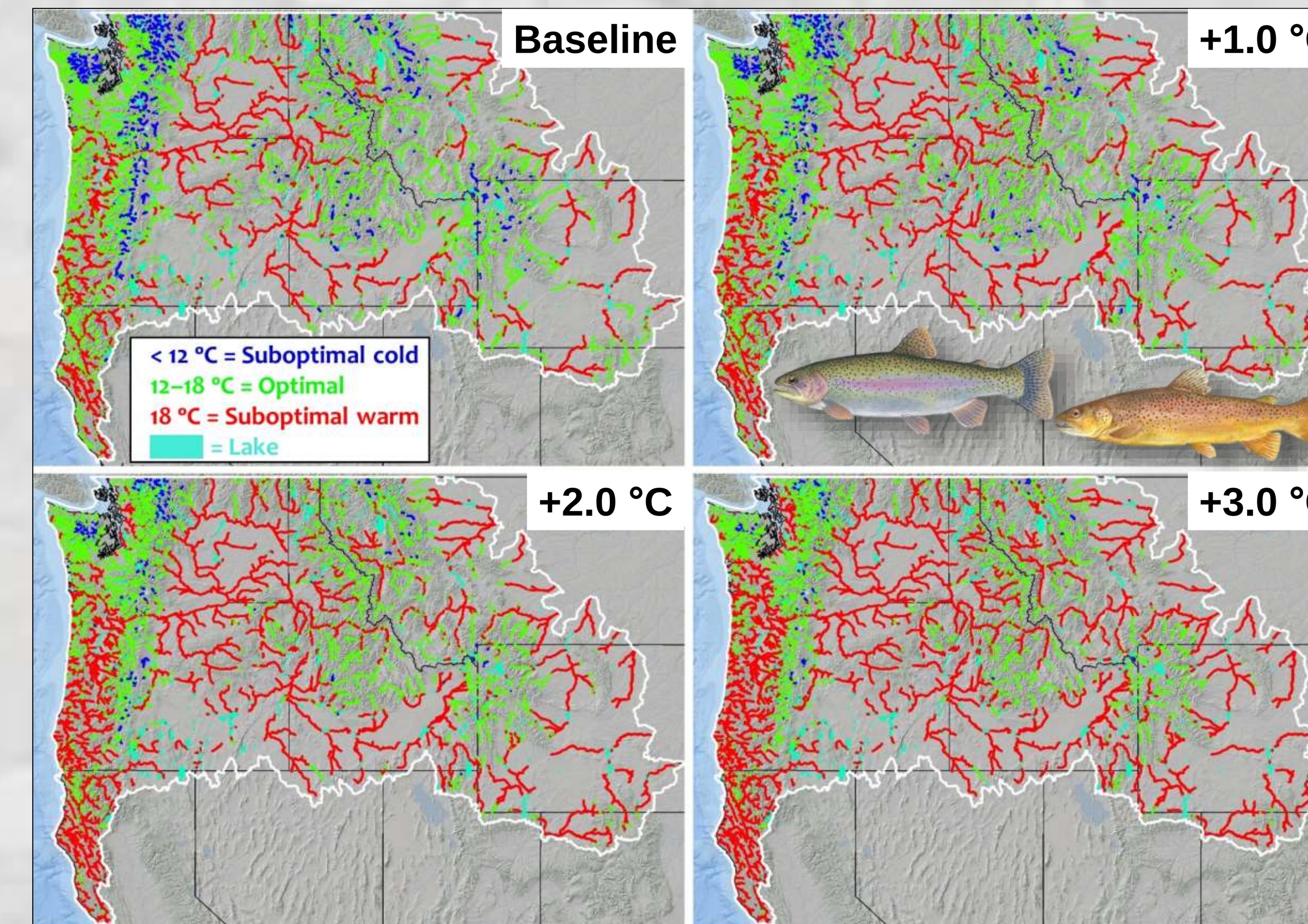


FIGURE 4. Of the 56,500 km of rivers in the Northwest, 50,200 km provided some level of thermal suitability for brown trout and rainbow trout in the baseline summer temperature scenario (panel a). About 4,730 km of those rivers were sub-optimally cold with mean August temperatures < 12 ºC, 30,260 km had optimal temperatures, and 15,220 km were sub-optimally warm. A future river temperature increase of 1.0°C, which would occur by mid-century given historical warming rates, was predicted to cause an 8% decrease in the total length of thermally suitable river reaches and declines of 18%–31% under more extreme warming scenarios (panels b, c, and d). At the statewide scale, relatively small decreases in thermal habitat were predicted for Washington's rivers (-6% to -18%) while larger decreases were predicted for Oregon and northern California (-12% to -47%). Disparities in rates of decline arose due to the interaction between baseline river temperature conditions and their proximity to suitability thresholds. Many rivers in the northern Cascade Range of western Washington, for example, were sub-optimally cold initially but were predicted to move into the optimal range in the future, which would partially offset losses in warmer reaches elsewhere in the state. Even under the extreme warming scenarios of +2–3 ºC, however, some rivers in isolated enclaves and larger sub-regional areas (e.g., the Greater Yellowstone Ecosystem, central Idaho, northern Cascade Range, and northwestern Montana) appeared likely to retain suitably cold temperatures for brown trout and rainbow trout populations.

Discussion

Our results indicate that a broad pattern of warming occurred in Northwest rivers during the last four decades and that temperatures during summer and early fall months now average ~1 ºC warmer. Despite that trend, it is encouraging to note that salmon and trout populations remain widespread in the region—by some measures even increasing, due in part to extensive habitat restoration efforts. Less encouraging is that the Earth is probably in the initial decades of a long-term warming period, and that temperature increases will act synergistically with regional trends in hydrology, non-native species invasions, human population growth and water use, and less favorable ocean conditions to negatively affect cold-water fishes. For some populations or fisheries that are heavily exposed and vulnerable, an additional 1–3 ºC of warming accompanied by those changes may well prove to be a road to ruin. But for the majority of salmon and trout populations, a more apt metaphor is likely to be a path through purgatory as these fish continue adapting by tapping their remarkable stores of diversity and resilience. Current global greenhouse gas emission rates may make their purgatory last much of the 21st century, so concerted, ongoing, and strategic efforts by the conservation and management communities will be needed to assist in that adaptation. Additional details regarding this research are provided in Isaak et al. (2018).

Acknowledgements

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