Sensitivity of Idaho Fishes to Climate Change

Christopher Caudill[1,3], Jonathan Masingale[1], Travis Seaborn[1], Dona Hora[2], and Daniel Isaak[2]

[1] Department of Fish and Wildlife Sciences
College of Natural Resources
University of Idaho
875 Perimeter Drive MS 1136
Moscow, ID 83844-1136

[2] USFS Rocky Mountain Research Station
322 East Front Street, Suite 401
Boise, ID 83702

[3]Corresponding author: caudill@uidaho.edu

Recommended citation: Caudill, C., Masingale, J., Seaborn, T., Hora, D., Isaak, D. 2021. Sensitivity of Idaho Fishes to Climate Change. *Idaho Climate-Economy Impacts Assessment*. James A. & Louise McClure Center for Public Policy Research, University of Idaho. Boise, ID.

Key Messages

- Climate change is predicted to produce “winners” and “losers” among Idaho’s native fishes in terms of kilometers of stream habitat.
- Habitat quality is predicted to decline in large rivers that support the highest quality fisheries for native natural-origin salmon and trout.
- Warming is predicted to expand the distributions of three key non-native species (brown trout, brook trout, and smallmouth bass), but expansions may only benefit smallmouth bass anglers in rivers; expansions of trout species will occur in small headwater streams that are rarely fished.
- The changing climate will affect habitats and species interactions in complex ways beyond the effects of temperature alone.
- Predictions for anadromous fish species are further complicated by migratory life cycles.
- Economic impacts will depend on changes in fish distribution; fish traits, such as size and abundance; angler access and activity; feedback patterns between climate effects; changes in socio-ecological drivers; climate mitigation actions (e.g., riparian management, instream flow regulation); and economic costs and benefits of conservation and management action, including Endangered Species Act (ESA) listings.

Introduction

Introduction to Idaho Fishes

Currently, waters in Idaho support over ninety species of native and non-native fishes that are both resident to freshwater and anadromous (sea-going in juvenile stages). A majority are introduced from outside the state (1). Idaho supports fishes falling into two broad categories based on thermal tolerance: “coldwater fishes,” including salmon, trout, sculpins, and whitefishes and “warmwater fishes,” such as bass and catfish. Overall, the warmwater fishes of Idaho are found at lower elevations and in larger water bodies; a greater proportion of warmwater fishes are non-native.

Salmon, steelhead, and trout species in Idaho all belong to the family Salmonidae, along with whitefishes, char (including bull trout and brook trout), and grayling. All salmonids are classified as “coldwater fishes” because of relatively low maximum upper thermal tolerance temperatures. Anadromous salmon and steelhead are famous for their ability to home to their natal streams to spawn, which leads to rapid adaptation to local environmental conditions and genetic divergence among populations (2). In many cases, the genetic and ecological differences among populations within species of salmon and trout are large enough that populations are provided species-level protection under the ESA as “evolutionary significant units” (ESUs) or “distinct population segments” (DPSs) (3).

Salmon are also famous for their anadromous life history–traveling to the ocean for growth prior to spawning in freshwater. Consequently, viable salmon populations require suitable conditions in 1) freshwater for upstream migration, spawning, early rearing, and juvenile downstream migration and 2) estuaries and the ocean for growth and survival. Pacific lamprey is an ancestral fish species distantly related to salmon, but with a similar anadromous life history and is a species with cultural and ecological importance (4,5). While Pacific lamprey were once common in salmon habitats of Idaho, including in southern and central Idaho, many populations have been extirpated by fish barriers and overall abundance has declined dramatically in recent decades.

Climate Controls and Idaho’s Aquatic Habitats

Temperature is a key factor affecting the ability of ectothermic organisms like fishes to maintain physiological equilibrium and thus the “thermal niche" of a species is a primary control on distributions (6). Climate, geology, and land use all affect the “thermal regime” of a waterbody–the pattern of temperatures through space and time. The thermal regime, in combination with the thermal niche and other environmental and biological factors, determines whether a species can occur in a specific location ((6), Figure 1). Stream temperatures generally increase downstream and are affected by local climate and geography (i.e., air temperature, precipitation, aspect);

factors, such as groundwater exchange; land use in upstream areas; and vegetation and shading in nearby riparian zone areas. Areas of riparian shading and especially groundwater exchange may provide local cold-water anomalies or "pockets" that act as thermal refuges for fishes (7,8), allowing coldwater species to 'behaviorally thermoregulate' and survive in warmer streams than would be expected based on average temperatures (9). Temperatures in lakes are determined primarily by local climate and lake morphology. Large deep lakes may have a wide range of thermal conditions during summer periods, allowing persistence of a broader array of both warm and coldwater fishes compared to nearby streams. Shallow lakes and reservoirs have less thermal variation and thus host a more narrow range of species (10).

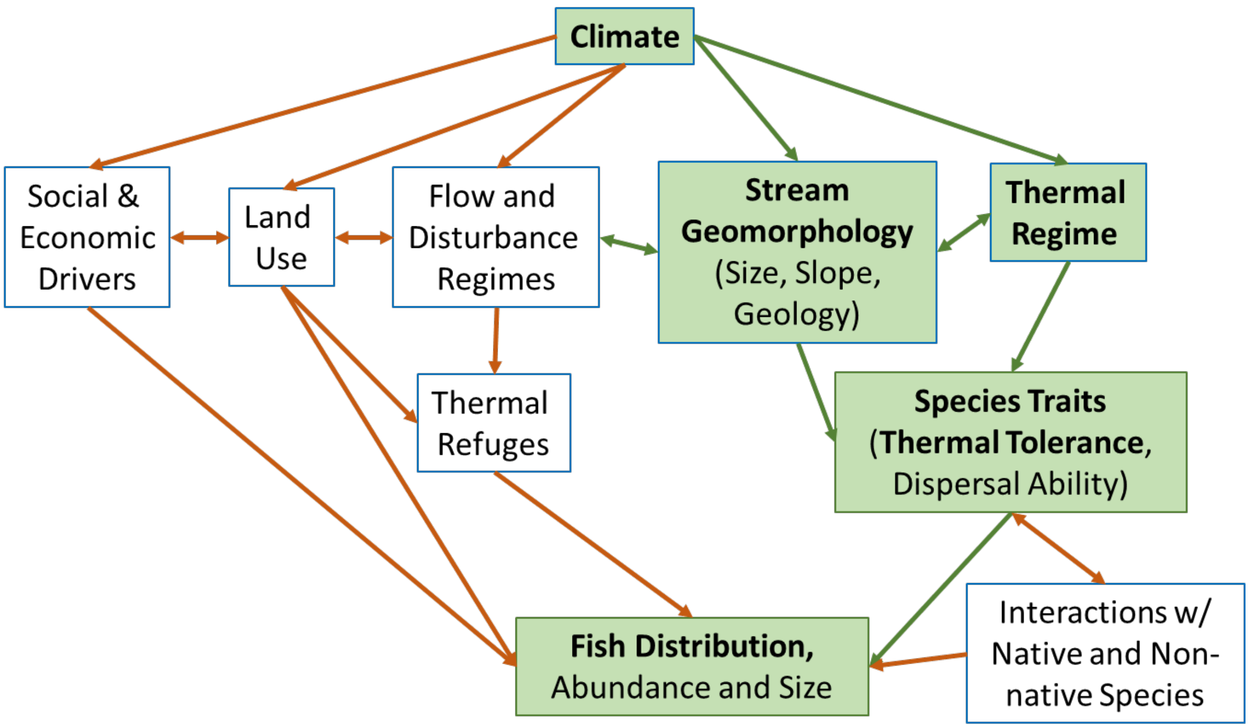

Figure 1: Simplified conceptual model of major factors affecting the distribution, abundance, and size of fishes in a waterbody. The assessment presented here considered factors in bold and linkages in green. Factors known to affect fish but not explicitly considered by the species distribution models are not bolded and connected with orange arrows.

Distribution Modeling Methods and Climate Assessment

The requirements of individual fish species (i.e., the species' niche) can be combined with spatial models of environmental factors to predict the distribution of individual fish species. Modelling efforts of fishes in the western United States have focused on statistical models for streams that attempt to identify suitable habitat using a large number of location records from agency monitoring surveys, a large stream temperature dataset (6), and other geospatial information (i.e., digital elevation maps and other GIS layers; see Appendix 1 for a full description of distribution models and their assumptions). These statistical models have been used to both refine estimates of the thermal niche and predict fish distribution, given maps of predicted stream temperatures during August, the period of highest stream temperatures in the region. Models for individual fish species are then paired with scenarios of future stream temperature to predict species distributions under climate change (see example maps in Figure 2). This report summarizes predictions of thermally suitable habitat for fish species in Idaho rivers and streams based on NorWeST scenarios of current and future summer stream temperatures.[1] The NorWeST scenarios are based on water temperature measurements from >13,000 locations across Idaho that were contributed by more than a dozen state, federal, tribal, and private organizations (6,11).

Suitable habitat was estimated as stream and river kilometers for each species. Suitable habitats were categorized into suboptimal cold, optimal, and suboptimal warm temperatures based on the thermal niches of individual species. Optimal thermal conditions are those associated with highest rates of growth and survival. These results were then filtered to remove stream reaches that were too steep for occupancy by some species. For example, smallmouth bass never occur in reaches with gradients >3% (12), whereas trout species often occupy stream reaches with gradients up to 15-20% (6). The final set of filtered reaches was summarized by river and stream size using stream order and the following classes because fisheries and uses differ by river size: “Headwaters” (1st-2nd order), “Small Rivers” (3rd-4th), “Large Rivers” (5th-6th), and “Lower Mainstem Rivers” (7th-8th = Kootenai, Clark Fork, and lower Clearwater, Salmon, and Snake rivers). We note the metric of suitable stream and river kilometers does not capture differences in total habitat area between size classes. For example, a one-kilometer decrease in suitable habitat in a headwater stream represents much less habitat loss than a one-kilometer decline in a large river. The selected species represent those with the best available data and those of economic and cultural importance and include both native and invasive species. We note that the assessments are restricted to stream habitats and that assessments for some culturally and ecologically important species within the state, such as Pacific lamprey and white sturgeon, are not currently available. Comprehensive predictions for fishes in lakes of Idaho are not available at this time. However, thermal conditions in lakes of Idaho are expected to follow patterns of lakes in similar regions, resulting in invasion by warmwater species and potential reduction or loss of coldwater species (e.g., (13)). Populations of species include some hatchery influence within Idaho. However, the models used here apply to habitat requirements of naturally breeding “wild” populations and do not consider the demographic or genetic effects of hatcheries.

[1] https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

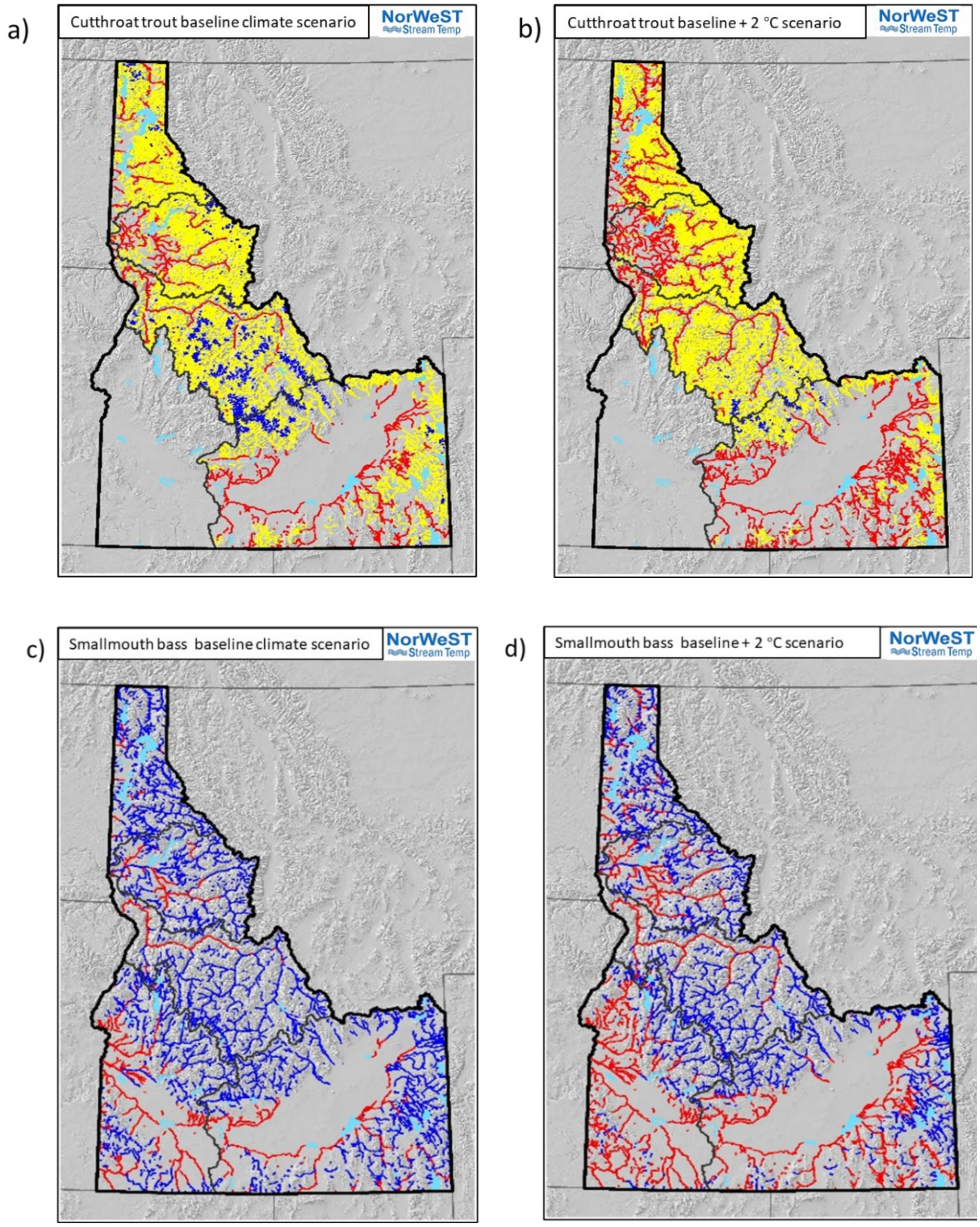

Figure 2: Representative maps of predicted thermal habitat conditions for coldwater and warmwater species. Figure 2a-b: Maps for a native coldwater species (cutthroat trout, *Oncorhynchus clarkii*) within its historical Idaho range under (a) current conditions and (b) +2°C warming. Blue indicates stream segments below 8°C (suboptimal cold), yellow indicated segments 8-16°C (optimal), and red indicates segments >16°C (suboptimal warm). Temperature suitability zones shift upstream in concert as future temperatures increase. Figure 2c-d: Current and future predicted distributions for a non-native warmwater species (smallmouth bass, *Micropterus dolomieu*) under (c) current and (d) +2°C increase in mean August stream temperature. Red stream segments denote those which are >17.5 °C and warm enough to be invaded by smallmouth bass. Suboptimal cold areas shift to optimal in lower elevation reaches as temperatures increase, with a net increase in potentially occupied stream segments.

Status and Predicted Futures for Idaho Fishes

Recognizing the caveats and cautions of the distribution models for assessed species, these models clearly suggest some species will be “winners” and others will be “losers” (i.e., some species are predicted to expand in some areas but decline in others). Overall, the models predict declines in native and non-native salmonids in all habitats except headwater streams and increases in non-native smallmouth bass across all stream types in Idaho (Figures 2 & 3). Notably, for some species, such as rainbow trout, net losses in larger rivers are offset by expansion into habitats that are currently too cold for optimum growth in headwater streams, resulting in a net overall *increase* in stream habitat kilometers with ‘optimum’ thermal habitat. However, we note that losses in the larger rivers are those areas that support larger fish generally most valued by anglers and total area of stream (rather than length) of habitat lost in larger rivers may exceed gains in headwaters where gains occur. Moreover, two key resident native trout are predicted to experience declines in optimum habitat across stream types: the Idaho state fish, cutthroat trout (31,005 river kilometers [rkm] to 27,502 rkm with 2°C warming; ~11.3% decline), and an ESA-listed species, bull trout (19,614 rkm to 10,542 rkm, ~46.3% decline). Conversely, optimum habitat for smallmouth bass, a predator of juvenile salmonids, is predicted to expand from 5,523 rkm to 10,543 rkm (~191% increase).

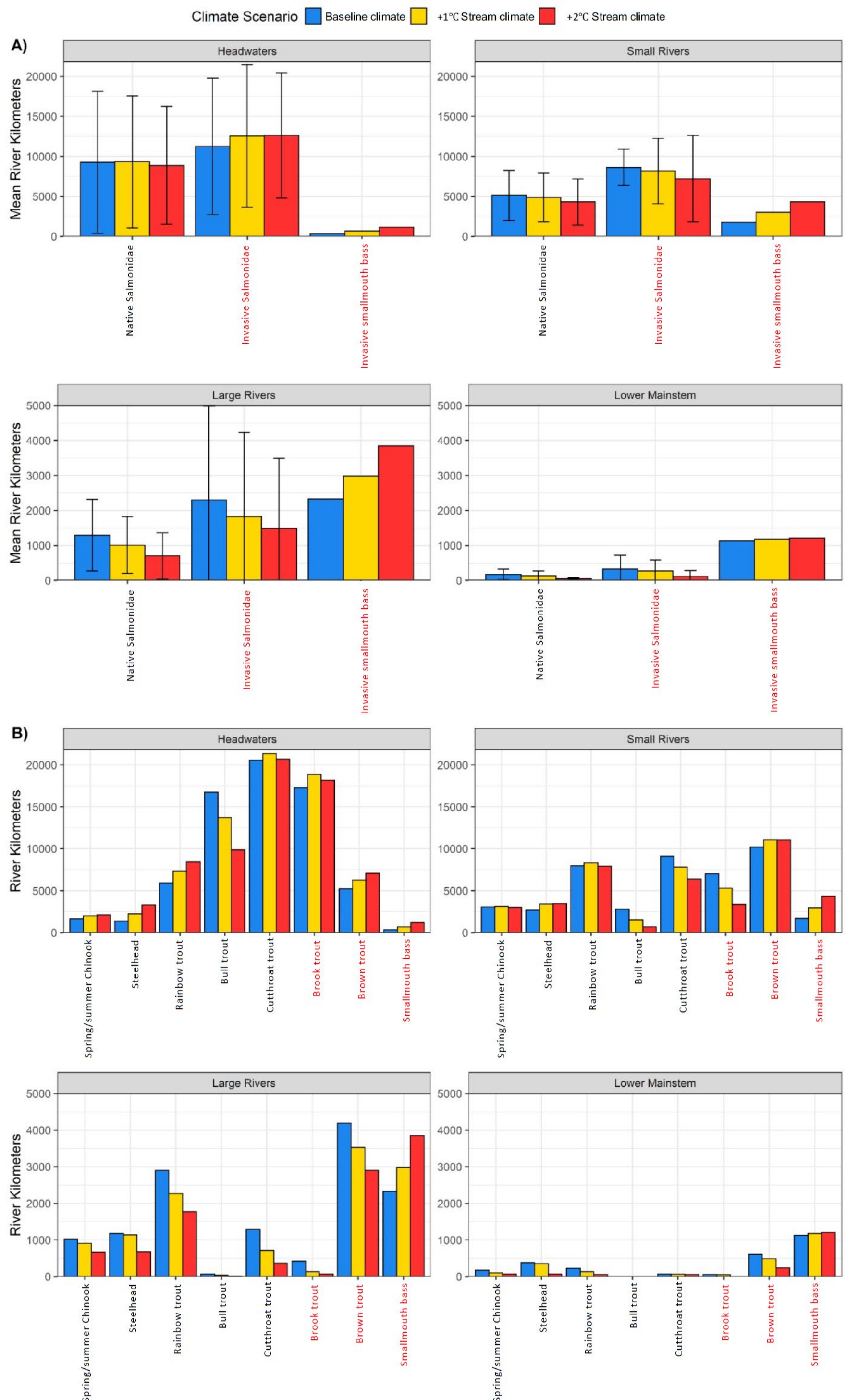

Figure 3: Predicted size of optimal habitat for fish species by river size and climate scenario. Number of river kilometers providing optimal habitat for A) species group and B) individual species under three climate scenarios by stream size. Baseline period was 1993-2011. Labels in red indicate non-native species; +/- 1 standard deviation (SD) provided for groups with more than one species.

Individual Species Accounts

Native Resident Fishes

Redband Rainbow Trout (*Oncorhynchus mykiss gairdneri*)
Redband rainbow trout is a native subspecies in Idaho, which is resident to freshwater. Importantly, the taxonomy and conservation status of populations across the species is complicated because of a complex evolutionary history and introductions of non-native genetic strains through stocking by fisheries managers (1). Sea-going steelhead populations further complicate classifications of the species and are considered separately in the section on anadromous species.

Resident rainbow trout are ranked as *apparently secure* both in Idaho and globally at the species level. Native interior redband trout populations are known to be genetically distinct, display local adaptations (e.g., (14)), and are of conservation concern for regional land managers because isolated populations may simultaneously represent unique natural heritage and may also be more vulnerable to climate warming (15).

Rainbow trout have the highest thermal tolerances among the resident native salmonids (optimal temperatures 12-20°C). Consequently, more stream kilometers in higher elevation streams are predicted to support rainbow trout under warming, potentially increasing overall range and abundance. However, the expansion may exacerbate hybridization with cutthroat trout, especially in warmer, lower elevation areas with introduced (i.e., stocked) rainbow trout (e.g., (16,17)). Further, the kilometers of optimal habitat in large rivers are expected to decline by approximately one-third with +2°C warming (Figure 3B), potentially affecting higher quality fisheries.

Bull Char (a.k.a. Bull Trout) *(Salvelinus confluentus)*
Bull trout are listed as *threatened* under the ESA and are currently listed as *apparently secure, but cause for long-term concern* at both state and range-wide levels.[2] Bull trout are among the most migratory of "resident fishes," with a proportion of some populations moving between headwater streams for spawning and large rivers or lakes for foraging. Bull trout have the coldest and narrowest thermal niche of species modeled here. The narrow thermal niche and migratory nature of the species contributed to listing under the ESA.

Optimal bull trout habitat for all stream types is predicted to decline approximately 25% per degree Celsius warming for +1° C and +2°C warming scenarios. Despite the predicted decline in distribution, a subset of particularly cold streams in central Idaho is predicted to provide bull trout populations with climate refuges that could allow the species to persist (14,18). However,

[2] https://idfg.idaho.gov/species/taxa/19737

these high elevation refuges will be isolated from other such populations, potentially affecting metapopulation dynamics and increasing risk of extinction as populations are restricted to smaller ranges (19,20). Further, warming temperatures may increase the area of overlap and interaction between bull trout and a non-native competitor species, brook trout, which may exacerbate declines of bull trout beyond the effects of temperature alone through competitive interactions (21,22) and/or hybridization with brook trout (e.g., (23)).

Cutthroat Trout (*Oncorhynchus clarkii*)
Three native cutthroat trout subspecies currently persist in Idaho: Yellowstone cutthroat trout (*O. c. bouvieri; imperiled* in Idaho), westslope cutthroat trout (*O. c. lewisi, vulnerable*), and Bonneville cutthroat trout (*O. c. utah, vulnerable*). This assessment was conducted at the species level.

Cutthroat trout optimal habitat is predicted to remain relatively constant in headwaters as populations shift upstream into areas that are currently unsuitably cold, but decline in larger, lower elevation rivers. The length of large rivers classified as optimal for cutthroat trout is predicted to decline by more than one-third with +1°C warming (1,286 rkm current to 714 rkm [+1°C]) and to decline to less than 30% the baseline river length with +2 °C warming.

Similar to bull trout, the species is predicted to persist in particularly cold headwater streams that act as climate refuges (18). However, the large decline in optimum large river habitat will likely impact the quality of "trophy" native fisheries. In addition, hybridization with *O. mykiss* noted above (and not accounted for in this assessment) may further impact cutthroat trout, although headwater populations are likely to remain genetically pure (24,25).

Native Anadromous Fishes

Spring/Summer Chinook Salmon *(Oncorhynchus tshawytscha)*
The Snake River spring/summer-run Chinook salmon ESU return to freshwater in spring or early summer, migrate ("run") upstream, and hold in freshwater until spawning in headwater streams and rivers in late summer or early fall. The long period in freshwater (spring to late summer/early fall) increases the potential for negative thermal exposure and is expected to increase mortality during migration and prespawn mortality on spawning grounds with future warming (26). Juveniles are typically in freshwater for more than a year. In Idaho, the ESU includes spring/summer Chinook salmon spawning in the mainstem Snake and Salmon rivers. The ESU also includes hatchery salmon from 13 programs in Idaho, Oregon, and Washington.

Thermal habitat modeling suggests a slight increase and then decrease in thermally optimal rearing habitat from baseline conditions to +1°C to +2°C scenarios, with an increase in habitat in headwater streams in both warming scenarios and losses in larger, lower elevation reaches, such as sections of the Salmon River (Figure 3B). We note the species is vulnerable to mortality during upstream migration and on spawning grounds because these populations hold in freshwater near spawning sites during summer for weeks to months in between adult migration and spawning in fall (26). Overall, impacts in freshwater habitats that are partially accounted for using the thermal niche models, combined with observed and predicted effects of warming on migration corridors and marine habitats, imply spring/summer-run Chinook salmon in Idaho are particularly vulnerable to warming climate (27,28).

Fall-run Chinook Salmon *(Oncorhynchus tshawytscha)*
The Snake River fall-run Chinook salmon ESU is distinguished by return of adults to freshwater in late summer and fall just prior to spawning in mainstem/lower elevation locations (2,3). Juveniles hatch the following spring and rapidly migrate to the ocean as sub-yearlings. The Snake River fall-run Chinook ESU is listed as *threatened* and includes populations in Idaho spawning in the mainstem Snake River below Hells Canyon Dam, the Salmon and Clearwater rivers, and four hatchery programs (3). Because adults arrive in the modeled area as water temperatures are cooling (i.e., after August) and juveniles typically outmigrate prior to peak summer temperatures in August, estimates of thermal habitat were not attempted. Since the timing of upstream migration, spawning, and juvenile outmigration are all outside the warmest period of the year, fall-run Chinook salmon may be the least sensitive of Idaho's anadromous fishes to climate warming.

Sockeye Salmon *(Oncorhynchus nerka)*
The Snake River sockeye salmon ESU is considered one of the most critically imperiled populations of fishes. The ESU includes all naturally spawning sockeye salmon within the Snake River. Spawning is limited to Redfish Lake in the Sawtooth Mountains and is reliant on the Redfish Lake Captive Broodstock program (29,30). The ESU was listed as *endangered* under the ESA because of the restricted range of the species. In addition to small population size and geographic range, sockeye salmon in Idaho share several traits with spring/summer-run Chinook salmon–early summer upstream migration, long freshwater holding, and fall spawning–and thus the population is subject to high en route mortality in years with high summer temperatures (27,31) and is vulnerable to prespawn mortality. Consequently, the species will likely require direct management intervention to persist, through hatchery supplementation and trap-and-haul collection during years with high water temperatures. The latter has been implemented in 2021.[3]

Steelhead (anadromous redband rainbow trout; *Oncorhynchus mykiss gairdneri)*
Range-wide, steelhead rainbow trout display the widest variety of life histories of any salmonid, including the populations in Idaho (e.g., (32)). Snake River steelhead is listed as *threatened* under the ESA (3) and the ESU includes all naturally produced anadromous rainbow trout below natural and artificial barriers in the Snake River Basin in Idaho, Oregon, and Washington, along

[3] https://idfg.idaho.gov/press/low-flows-high-temperatures-impact-fisheries-and-hatchery-operations-statewide

with steelhead from six hatchery programs. Important Idaho populations include those in the Clearwater and Salmon river basins.

All steelhead returning to Idaho are "summer" steelhead, meaning they return to freshwater in late summer and early fall coincident with fall-run Chinook salmon. Unlike fall-run Chinook, steelhead overwinter in spawning tributaries or mainstem habitats prior to spawning the following spring and remain in freshwater for 1-3 years prior to smolting (2,33). Unlike Pacific salmon species, many steelhead attempt post-spawn migration to the ocean and additional spawning events, though rates of successful repeat spawning are low (<3%) because of the high costs of long-distance migration and long freshwater holding period (32,34). Some populations are fully anadromous, others are partially anadromous with individuals that remain in freshwater, and some populations are associated with resident populations restricted to areas above fish passage barriers (e.g. (35)). The thermal niche models presented here assessed the Clearwater and Salmon river basins as anadromous.

The thermal niche models predict an increase in optimal steelhead habitat in headwaters and small rivers, but declines in large rivers and lower mainstem areas, with an overall increase in kilometers of optimal habitat of 26.8 % (+1°C) and 33.3% (+2°C; Figure 3B) over baseline conditions. All else being constant, the increase in total suitable thermal habitat could result in increased smolt production and adult steelhead returns. Thus, despite a reduction in large river habitats with optimal thermal conditions, the +1 and +2°C increase scenarios could functionally increase adult steelhead in all river classes because mainstem and large river reaches serve as migration corridors for steelhead, which are the location of key fisheries activity (e.g., (36)). However, this conclusion is contingent on the assumptions that 1) smolt production per kilometer is similar in small and large rivers, 2) other ecological conditions besides temperature are not limiting in freshwater, 3) steelhead migration corridors remain suitable and/or that migration timing can track changing conditions, and 4) warming conditions do not negatively affect marine stages. We caution that simple projection of stream kilometers to future steelhead population sizes is not warranted because it is unlikely all four assumptions will be met under future climate warming scenarios.

Coho Salmon *(Oncorhynchus kisutch)*
Coho salmon were native to the Clearwater River and possibly lower Snake River in Idaho, but the populations eventually were extirpated in the 1980s following construction of the Washington Water Power Dam (a.k.a. Lewiston Dam) in 1927. A reintroduction program by the Nez Perce Tribal Fisheries Division has established spawning populations in the lower Clearwater Basin and reestablishment of a fishery in 2014 (1). Coho salmon will likely continue to expand their distribution within Idaho and were not formally assessed here because their current distribution is likely limited by recent dispersal and reintroduction, rather than the thermal niche of the species.

Non-Native Species: Coldwater

Brown Trout *(Salmo trutta)*
Native to Europe and western Asia, brown trout are believed to have been introduced in the U.S. in 1883. Brown trout occur in the Pend Oreille, Spokane River, and Priest Lake drainages in northern Idaho and in the Snake River drainage and its tributaries in southern Idaho. Brown trout (and other non-native species) are not ranked for conservation status. Brown trout are an important sport fish where they occur, including in many trophy wild trout fisheries in the western U.S. They are generally thought to be more tolerant of warmer or degraded ecological conditions, but are a conservation concern because large adults prey on other fishes, including native trout and competition occurs with native trout species at all sizes where distributions overlap (1,37,38).

Brown trout have similar thermal tolerances to rainbow trout (identical threshold values for temperature were used in this analysis). Consequently, the pattern of predicted habitat gains in headwaters and losses in large rivers and lower mainstem habitats parallel the predictions for rainbow trout (Figure 3B). Increases in headwaters could impact native salmonids through competition or predation, whereas declines in larger streams could negatively impact recreational fisheries.

Brook Char (a.k.a. Brook Trout) *(Salvelinus fontinalis)*
Brook trout are native to eastern North America and are believed to have been introduced in Idaho around 1908. Currently, except for the southwestern corner of Idaho, brook trout are found in all major watersheds of the state, including high mountain lakes and streams. Past studies have demonstrated or implicated negative effects of brook trout on native salmonids through competition (e.g. (39), but see (40)) and/or hybridization (e.g., (23)). Brook trout rarely achieve large size and thus are typically less valued as sport fish than other trout species in Idaho (1).

Like bull trout, brook trout prefer low summer temperatures. Consequently, the thermal niche model predicts brook trout habitat in rivers and lower mainstem habitats will decline by half or more (Figure 3B). However, under both warming scenarios, the total length of optimal habitat in headwater streams is predicted to increase (Figure 3B) where interactions may impact native species (bull trout, cutthroat trout, and Chinook salmon). Across river sizes, the models predict an overall decline of ~12.4% in stream miles classified as optimal (24,746 rkm baseline to 21,620 rkm with +2°C warming).

Non-Native Species: Warmwater

Smallmouth Bass *(Micropterus dolomieu)*
Smallmouth bass are one of the most important sport fishes in North America, but are not native to Idaho. Within the state, they are widespread and expanding in lakes, reservoirs, and lower elevation rivers, where populations support active recreational fisheries. They are classified as a gamefish and were intentionally introduced to many waterbodies in the state, including Hayden Lake as late as 1983. Recent illegal introductions have also contributed to the species' expansion (1). Adults prey on invertebrates and larval and juvenile fishes and can have negative impacts on both resident and anadromous native salmonids and other fishes, such as native minnows (41,42). For instance, it is estimated that smallmouth bass may consume nearly a million juvenile fall-run Chinook salmon spawned in Idaho, potentially causing a 3.9-16% reduction in adult returns (43).

Smallmouth bass are predicted to have the largest increase in distribution among the species examined. Smallmouth bass are expected to expand from 5,523 rkm (baseline) to 10,543 rkm (+2°C; ~191% increase), with the largest gains in small and large rivers at lower elevations (Figures 2 & 3). Gains in lower mainstem rivers are proportionally smaller, primarily because those reaches are already largely classified as optimal (mean August temperature > 17.5°C) under current baseline conditions. A species distribution model that was refined using Environmental DNA (eDNA) surveys estimated an expansion from ~18,000 river kilometers (current) to ~30,000 rkm in 2080 across the Columbia River Basin (nearly all of Idaho was included in the survey (12)). Thus, smallmouth bass are expected to expand in range within Idaho in coming decades, with impacts on native salmonids and simultaneous expansion of bass sport fisheries, likely exacerbating tension between conservation and angling opportunity goals (42).

Discussion

The summaries here used information about species' thermal tolerances and maps of current and future predicted August stream temperatures throughout Idaho to estimate available habitat for focal fish species. The summaries also accounted for barriers to fish passage and upstream dispersal, additional key factors controlling fish distribution (Figure 1). This work builds on past studies (6,11) by parsing predicted habitat condition across river sizes from small headwater streams to the largest rivers in Idaho.

Most modeling results were intuitive–most species will expand in distribution upstream as temperatures increase and lose habitat in downstream areas where temperatures will exceed tolerances. Less intuitive are the findings that some species of coldwater fish may experience net gains in stream kilometers as areas that are currently too cool become suitable or optimal habitat with warming. In that regard, our findings mirror other studies (e.g. (12)) demonstrating the potential for non-native species, such as smallmouth bass, to expand as temperature increases. Such expansions will likely increase interactions with native species, which were not modeled here (Figure 1). The increased interactions may have negative impacts on native fishes beyond the effects of temperature alone through competition, predation, hybridization, or disease dynamics, potentially causing declines in abundance and/or occupied habitat not captured in the thermal niche modeling results. Beyond these major patterns, the most relevant findings in the context of this climate assessment may be the general loss of habitat in larger rivers for salmonids because these habitats support more fish per kilometer and likely hold the greatest fisheries-related economic value within the state of Idaho (44).

The model results also highlight that there may be complex patterns that emerge with climate warming, particularly for anadromous populations. For instance, at face value, steelhead are predicted to experience net gains in optimal habitat, primarily in headwater streams, which could increase overall productivity and abundance, including adult returns to fisheries in Idaho's large rivers. However, we reiterate these gains may be offset by the reduced habitat area in smaller headwater streams, increased mortality costs during migration to the ocean (e.g., (34)), and/or degraded conditions in marine habitats with warming. Similarly, several important factors potentially affecting Chinook salmon and other anadromous species are not fully captured with the thermal modeling approach used here. The long period of prespawn holding for spring-summer Chinook salmon and sockeye salmon, in combination with potential exposure to warm temperatures during migration, is thought to contribute to 'prespawn mortality' after upstream migration, but before spawning (26,27). A recent extensive analysis of Salmon River spring/summer-run Chinook salmon indicates that poor survival in freshwater, marine, and migration habitats all contributed to recent declines; that declines may continue under climate warming; and that increasing freshwater habitat carrying capacity could provide improvements (28). Thus, while the relatively simple results presented here indicate potential increases in Chinook salmon habitat within Idaho, those increases will be tempered by increased costs of migration for juveniles and adults, along with other impacts that could cause population decline or extinction.

An additional caveat is that the thermal approach summarized here does not account for all aspects of climate change. Altered flow regimes, with shifts in winter precipitation from snow to rain, are expected to affect scouring of redds and habitat quality during spawning and rearing (45,46). Summer flow magnitudes are also declining, as snowpack decreases and runoff occurs earlier each decade (47,48). Estimates suggest summer flows decreased by 25-30% across Idaho in the latter half of the 20^{th} century and are projected to continue declining in future decades (48,49). Salmonids are "disturbance adapted," inhabiting landscapes with a long history of forest fire, landslides, and periodic drought (2). However, altered 'disturbance regimes' through more frequent or intense fires, low flow periods, and/or heat waves will affect fishes through mechanisms not accounted for using predictions from average conditions. For example, flow regime and geomorphology are expected to interact to alter salmon spawning distributions in the future (50). Climate-related changes in water withdrawal, hydro-operations, and potential interactions with an increasing number of introduced species will present further challenges. Moreover, the thermal habitat shifts associated with a 1°C water temperature increase are currently projected to occur over 30 to 50 years, but this assumes recent historical warming rates of 0.2-0.3°C/decade for Idaho streams remain constant (11,44). These rates could increase, however, if future radiative forcing accelerates or as snowpack continues to decrease and the sensitivity of headwater streams increases (48,51). In the event of one or both of those changes, warming rates of streams may increase and the projected changes will happen sooner.

We note that the scale of thermal mapping and metrics for thermal tolerance may not capture processes important to fish distribution and the management of stream habitats. For example, within-reach variation in stream temperatures, changes in riparian vegetation, and the influence of beaver impoundment are all known to affect the thermal ecology of fishes, but are currently difficult to account for at broad scales. Salmon and trout seek and use areas of cooler water emerging from groundwater upwelling zones or at tributary junctions when available during summer high temperature periods (9,52). Variation in geomorphology and groundwater inputs can create thermal refuges not captured by stream temperature models (e.g., (53,54)) and these refuges may buffer populations locally from the effects of warming. Similarly, riparian vegetation affects stream temperature through shading (e.g., (55)) and recent studies suggest regrowth of riparian vegetation where it has been seriously degraded could have substantial effects on stream temperatures (56,57). Finally, beaver are recolonizing many streams in the western U.S. and beaver dams are known to alter both the flow regime and thermal regime of streams (58), including improving fish habitat by decreasing intermittency of streams and buffering thermal regimes in semi-arid landscapes (59). The installation of beaver dam analogs (BDAs) has been implemented in several locations in an attempt to achieve these same ecosystem services (e.g., (60)). Identification of thermal refuges, management of riparian vegetation, and beaver restoration and/or BDA installation may be important components of climate adaptation for Idaho fishes.

Appendix 1: Expanded Distribution Modelling Information

Distribution Modelling Methods

Efforts to model fishes of the western U.S. have focused primarily on using a large number of known presences and absences for various species and pairing that data with an array of stream characteristics and a large stream temperature dataset (6,11). These types of distribution models are called ecological niche models and come in forms of varying complexity (61). In the simplest models, the environment is measured, often through remote-sensing satellites or geospatial information systems and compared to locations where the species is present and absent. The maximum and minimum thresholds of the environment relating to temperatures, stream sizes, and reach gradients are then used to develop an "envelope" of appropriate conditions, which can be mapped on to the landscape, including in unsurveyed areas or under future climate scenarios. Although factors like land cover and human impact can also be included in the model and improve performance (62), they are often absent in distribution modelling efforts focused on future predictions because of the difficulty of predicting these variables into the future. Recently, advances have been made for modelling the relationship between known locations of the species and the environment, such as machine-learning approaches (e.g. Maxent, (63,64)).

To statistically quantify the relationship of stream characteristics to species occurrence data, multiple logistic regressions are used. These regression models allow thermal response curves to be created and then used to map the probability of presence across the landscape. These methods are often paired with estimates of future stream temperature scenarios and other variables to understand changes in the probability of presence for each individual fish species (11). Warming trends can also be estimated at individual sites and extrapolated to the future. For some salmon and trout species, some river reaches may become too warm (44). These basic methods and models were used to prepare the summaries in this report.

Distribution Modelling Assumptions and Caveats

There are several assumptions that need to be considered. A model only focused on climatic tolerances may be inaccurate in cases when dispersal or biotic interactions may be important (65). For example, it is important to simulate individuals moving and their ability to colonize new areas because open suitable habitat may not be filled and changes in distribution will be overestimated without considering dispersal limitations (66). Similarly, the presence of other species and biotic interactions may increase or decrease range expansion or contraction. Because of this, a community-level approach may be more appropriate (67). For instance, an increase in smallmouth bass distribution may negatively affect salmon and steelhead under warming through increased predation on salmonids by smallmouth bass (68). Another assumption is the challenge of determining the most relevant environmental measure of biological thermal tolerance. There is potential for habitat heterogeneity within watersheds not to be captured by the thermal tolerances measured and biological factors, such as seasonal movements or behavioral thermoregulation, can be complex (69). The scale of the climate measurements are also important, with microclimates likely to play an important role for persistence of species on the landscape (6). In fact, the factors above can combine to create "surprises," such as locations where thermal refuges and/or seasonal movements may allow some species to persist in areas predicted to be too warm in the future. Similarly, climate scenarios may not capture the effects of future mitigation efforts, such as riparian management or changes to water use. Lastly, additional assumptions may occur if the scale of the biological/ecological processes and predictions do not fully match the economic scale(s) of the analysis.

Acknowledgements
CCC, JM and TS were supported by the National Science Foundation (NSF) Idaho EPSCoR Program and by the NSF under award number OIA-1757324.

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