Chapter 4
Effects of Climate Change on Cold-Water Fish in the Northern Rockies

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Abstract Decreased snowpack with climate warming will shift the timing of peak streamflows, decrease summer low flows, and in combination with higher air temperature, increase stream temperatures, all of which will reduce the vigor of cold-water fish species. Abundance and distribution of cutthroat trout and especially bull trout will be greatly reduced, although effects will differ by location as a function of both stream temperature and competition from non-native fish species. Increased wildfire will add sediment to streams, increase peak flows and channel scouring, and raise stream temperature by removing vegetation.

Primary strategies to address climate change threats to cold-water fish species include maintaining or restoring functionality of channels and floodplains to retain (cool) water and buffer against future changes, decreasing fragmentation of stream networks so aquatic organisms can access similar habitats, and developing wildfire use plans that address sediment inputs and road failures. Adaptation tactics include using watershed analysis to develop integrated actions for vegetation and hydrology, protecting groundwater and springs, restoring riparian areas and American beaver populations to maintain summer baseflows, reconnecting and increasing off-channel habitat and refugia, identifying and improving stream crossings that impede fish movement, decreasing road connectivity, and revegetating burned areas

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to store sediment and maintain channel geomorphology. Removing non-native fish species and reducing their access to cold-water habitat reduces competition with native fish species.

Keywords Bull trout • Cutthroat trout • Occupancy modeling • Refugia • Water temperature

4.1 Introduction

Climate change is expected to alter aquatic ecosystems throughout the Northern Rocky Mountains. Prominent *direct changes* will include warmer stream temperatures, lower snowpack, earlier peak flows, reduced and more protracted summer baseflows, greater flow intermittence (Chap. 3), and downhill shifts in perennial channel initiation. In addition, *indirect changes* may be caused by the altered frequency and magnitude of natural disturbances. Because the fish, amphibians, crayfish, mussels, and aquatic macroinvertebrates inhabiting freshwater environments are ectotherms, water temperature dictates their metabolic rates and most aspects of their life history, including growth, migration, reproduction, and mortality. The changes in water temperature and other hydrologic characteristics associated with climate change are expected to have profound effects on their abundance and distribution.

The effects of climate change on aquatic species have been reviewed for the Pacific Northwest (Mote et al. 2003; ISAB 2007; Mantua et al. 2010; Rieman and Isaak 2010; Isaak et al. 2012a, b; Mantua and Raymond 2014) and elsewhere in the western United States (Poff et al. 2002; Ficke et al. 2007; Schindler et al. 2008 Furniss et al. 2010, 2013; Luce et al. 2012). However, empirically based, spatially explicit, and accurate projections of climate change effects on aquatic organisms are needed for scientific assessments and applications across broad geographic regions.

We developed high-resolution scenarios for stream temperature and streamflow, translating outputs from global climate models (GCMs) to habitat factors for stream reaches (Isaak et al. 2015). Scenarios were coupled with species distribution data crowd-sourced from the peer-reviewed literature and agency reports to develop species distribution models for current relationships between climate and fish species. The models were used to project probability of species habitat occupancy in streams throughout the Northern Rockies region.

We focused on climate vulnerabilities, current distribution, and projected distribution of two native salmonid species, bull trout (*Salvelinus confluentus*) and cutthroat trout (*Oncorhynchus clarkii*), which have ecological and cultural value to society and are sensitive to warm stream temperature (Eby et al. 2014). Inferences emphasized suitable habitat for juveniles of each species, because they are more thermally constrained than adults. We also evaluated the effects of nonnative species—brook trout (*S. fontinalis*), brown trout (*Salmo trutta*), and rainbow trout (*Oncorhynchus mykiss*) (the latter native to a portion of the analysis area)—on current and future habitats for native species. Isaak et al. (2015) and the Climate Shield website (http://www.fs.fed.us/rm/boise/AWAE/projects/ClimateShield.html) contain additional details on the context, framework, and databases used in this assessment.

4.2 Analytical Approach

4.2.1 Assessment Area

The assessment includes streams in national forests and national parks encompassed by the U.S. Forest Service (USFS) Northern Region (see Chap. 1). Geospatial data for the 1:100,000-scale National Hydrography Dataset (NHD)-Plus were downloaded from the Horizons Systems website (http://www.horizon-systems.com/NHDPlus/index.php, Cooter et al. 2010) to delineate a stream network, then filtered by minimum flow and maximum stream slope criteria. Summer flow values projected by the Variable Infiltration Capacity hydrologic model (VIC; Wenger et al. 2010) were obtained from the Western United States Flow Metrics website (http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml) and linked to individual stream reaches.

Stream reaches with summer flows <0.0057 m^3s^{-1}, approximating a wetted width of 1 m (Peterson et al. 2013b), or with slopes >15%, were removed because they are unoccupied or support low numbers of fish (Isaak et al. 2015). Steep slopes occur at the top of drainage networks where fish populations are more vulnerable to disturbances (e.g., debris flows after wildfire) that can cause extirpations (Bozek and Young 1994; Miller et al. 2003). Thus, the 183,036-km stream network used as baseline habitat probably overestimates potential habitat, but the current resolution of analytical tools and data prevent further refinement.

4.2.2 Climate Change Scenarios

The following average summer streamflows were available from the flow metrics website: baseline period (1970–1999, hereafter 1980s) and two future periods (2030–2059, hereafter 2040s; 2070–2099, hereafter 2080s) associated with the A1B (moderate) emission scenario. An ensemble of 10 GCMs that best represented historical trends in air temperatures and precipitation for the northwestern United States during the twentieth century was used for future projections (Table 4.1). The A1B scenario used here is similar to the RCP 6.0 scenario from Coupled Model Intercomparison Project 5 simulations (see Chap. 2).

Geospatial data for August mean stream temperature were downloaded for the same A1B trajectory and climate periods from the NorWeST website and linked to the stream hydrology layer (www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html).

Table 4.1 Projected changes in mean August air temperature, stream temperature, and streamflow for major river basins in the Northern Rockies

NorWeST unit [a]	2040s (2030–2059)			2080s (2070–2099)		
	Air temperature change (°C)[b]	Stream flow change (%)[b]	Stream temperature change (°C)[c]	Air temperature change (°C)	Stream flow change (%)	Stream temperature change (°C)
Yellowstone	2.81	−4.1	1.01	5.08	−5.4	1.81
Clearwater	3.17	−23.9	1.62	5.45	−34.2	2.78
Spokoot	3.05	−20.1	1.27	5.33	−31.5	2.19
Upper Missouri	3.25	−14.9	1.17	5.47	−21.3	1.94
Marias-Missouri	2.91	−10.0	0.75	5.30	−18.7	1.37

Projections are based on output from an ensemble of 10 global climate models for the A1B emission scenario. See text for more details on modeling and data sources (Isaak et al. 2010; Mote and Salathé 2010; Wenger et al. 2010; Hamlet et al. 2013; Luce et al. 2014)

[a]Unit boundaries described at the NorWeST website

[b]Changes in air temperature and streamflow expressed relative to 1980s (1970–1999) baseline climate period

[c]Stream temperature change accounts for differential sensitivity to climate forcing within and among river basins (Luce et al. 2014; NorWeST website)

Then, the NorWeST scenarios were developed using spatial statistical network models (Ver Hoef et al. 2006; Isaak et al. 2010) applied to 11,703 summers of monitoring data at 5461 stream sites monitored with digital sensors from 1993 to 2011. Additional rationale and criteria associated with climate scenarios and stream temperature modeling are discussed in Isaak et al. (2015).

4.2.3 Fish Species

Bull trout in the Northern Rockies are largely from an inland lineage (Ardren et al. 2011), and may express migratory or resident life histories. Migratory fish travel long distances as subadults to more productive habitats, achieving larger sizes and greater fecundity as adults before returning to natal habitats to spawn. Resident fish remain in natal habitats and mature at smaller sizes, although often at the same age as migratory adults. Adults spawn and juveniles rear almost exclusively in streams with average summer water temperature <12 °C and flow >0.034 m^3s^{-1} (Rieman et al. 2007; Isaak et al. 2010). This species has declined substantially compared to its historical distribution because of water development and habitat degradation (leading to higher water temperatures and lower habitat complexity), human-created migration barriers, harvest by anglers, and interactions with nonnative fishes (Rieman et al. 1997). Nonnative brook trout, brown trout, and lake trout (*Salvelinus namaycush*) compete with or prey on bull trout (Martinez et al. 2009; Al-Chokhachy et al. 2016), or cause wasted reproductive opportunities (Kanda et al. 2002). Bull trout are listed as threatened under the U.S. Endangered Species Act (ESA) (USFWS 2015).

Cutthroat trout were represented by two subspecies. Westslope cutthroat trout (*O. c. lewisi*) have a complicated phylogenetic history, with a northern/eastern lineage that occupied and colonized river basins influenced by glaciation, and a suite of southern/western lineages in basins never influenced by glaciation (M. Young, unpublished data). These fish also exhibit resident and migratory life histories, and may spawn and rear in smaller (<70 cm wide) and warmer (up to 14 °C) streams than do bull trout (Peterson et al. 2013a, b; Isaak et al. 2015). Yellowstone cutthroat trout (*O. c. bouvieri*) has an unresolved distribution because of its complex geohydrologic history associated with the Bonneville Basin. Life histories and spawning and juvenile habitats are presumed to be the same as for westslope cutthroat trout.

Distributions of both subspecies have declined >50% in response to the same stressors affecting bull trout (Shepard et al. 2005; Gresswell 2011), although cutthroat trout appears to occupy a larger proportion of its historical habitat than bull trout. Both subspecies of cutthroat trout have been petitioned under the ESA, but found not warranted for listing. Brook trout have replaced cutthroat trout in many areas, especially in the upper Missouri River basin (Shepard et al. 1997), facilitated by the distribution of low-gradient alluvial valleys (Benjamin et al. 2007; Wenger et al. 2011a). Where rainbow trout have been introduced outside their native range, introgressive hybridization occurs with cutthroat at lower elevations and in warmer waters (Rasmussen et al. 2012; McKelvey et al. 2016b). Yellowstone cutthroat trout have been widely stocked throughout the historical range of westslope cutthroat trout (Gresswell and Varley 1988), resulting in hybridization (McKelvey et al. 2016b). Lake trout predation greatly reduced Yellowstone cutthroat populations in Yellowstone Lake in the early twenty-first century, but cutthroat trout populations have rebounded somewhat following predator control (Syslo et al. 2011).

4.2.4 Trout Distribution Models

Species distribution models were developed to predict occurrence probabilities of juvenile bull trout and cutthroat trout; juvenile presence is indicative of natal habitat and a locally reproducing population (Rieman and McIntyre 1995; Dunham et al. 2002). Juvenile distributions are more restricted than those of adults, especially with respect to temperature (Elliott 1994). Juvenile bull trout are rarely found where mean summer temperatures exceed 12 °C (Dunham et al. 2003; Isaak et al. 2010), whereas some adult bull trout occupy habitats as much as 5–10 °C warmer (Howell et al. 2010). Similar patterns exist for cutthroat trout (Schrank et al. 2003; Peterson et al. 2013a), so a thermal criterion was also used to define suitable habitat for juvenile cutthroat.

A mean August stream temperature of 11 °C was chosen as the temperature criterion after cross-referencing thousands of species occurrence observations in Montana, Idaho, and Wyoming against temperature estimates from the NorWeST baseline scenario. Fish data were contributed by state and federal agencies (Isaak et al. 2015). Most native juvenile trout (90% of bull trout observations, 75% of cutthroat trout observations) occurred at sites less than 11 °C, whereas most nonnative species were rare at those sites. The thermal niche of brook trout overlapped that of the native species, but peaked at a slightly warmer temperature. Very cold temperatures reduced rainbow trout incursions and limited their introgression with cutthroat trout, particularly below 9 °C (Rasmussen et al. 2012; Young et al. 2016).

Spatially contiguous 1-km reaches of streams with temperature <11 °C were aggregated into discrete cold-water habitats (CWHs), and the fish survey data were used to assign occupancy (present, absent) by native trout juveniles and brook trout. Logistic regressions modeled the probability of native trout occupancy as a function of CWH size, stream slope, brook trout prevalence, and stream temperature. For each CWH, habitat size was represented as channel length, stream slope as the average value across all reaches, and brook trout prevalence as percentage of sample sites where they occurred.

Classification accuracy of the models at a 50% occupancy threshold was 78.1% for bull trout and 84.6% for cutthroat trout. The final logistic regression models included the four main predictor variables and some interactions among the variables. Habitat occupancy for both native trout was positively related to CWH size, but bull trout required habitats five times larger than cutthroat trout to achieve comparable probabilities of occupancy. Bull trout occupancy declined as minimum temperature warmed, whereas cutthroat trout occupancy was positively related to mean temperature. Stream slope and co-occurrence with brook trout negatively affected both species, especially in small streams. The presence of brook trout masked the apparent preference of cutthroat trout for habitats with low slopes.

The logistic regression models were applied to the full set of CWHs within the historical range of each native species in the Northern Rockies. Occupancy probabilities were calculated for a no-brook-trout scenario and a scenario in which brook trout were present at 50% of sites within each CWH. We did not include a scenario in which brook trout were present at all sites, because their prevalence rarely exceeded 50% in the large CWHs, and because not all locations were suitable for brook trout (Wenger et al. 2011a).

Species probability maps were cross-referenced with land administrative status using geospatial data from the U.S. Geological Survey Gap Analysis Program (Gergely and McKerrow 2013). The total length and percentage of CWHs and stream temperatures were summarized by jurisdiction for different climate periods. CWHs with occupancy probabilities exceeding 90% were considered potential climate refugia for native trout.

4.3 Vulnerability of Native Trout to Climate Change

4.3.1 Stream Temperature

A high level of thermal heterogeneity exists across the complex topography and elevation range of Northern Rockies streams (Fig. 4.1). Of the 183,036 km of stream habitat within the analysis area, 38% had a mean August temperature <11 °C. Most of those CWHs (86%) were in publicly administered lands, primarily (69%) in national forests. Areas with concentrations of cold streams were generally

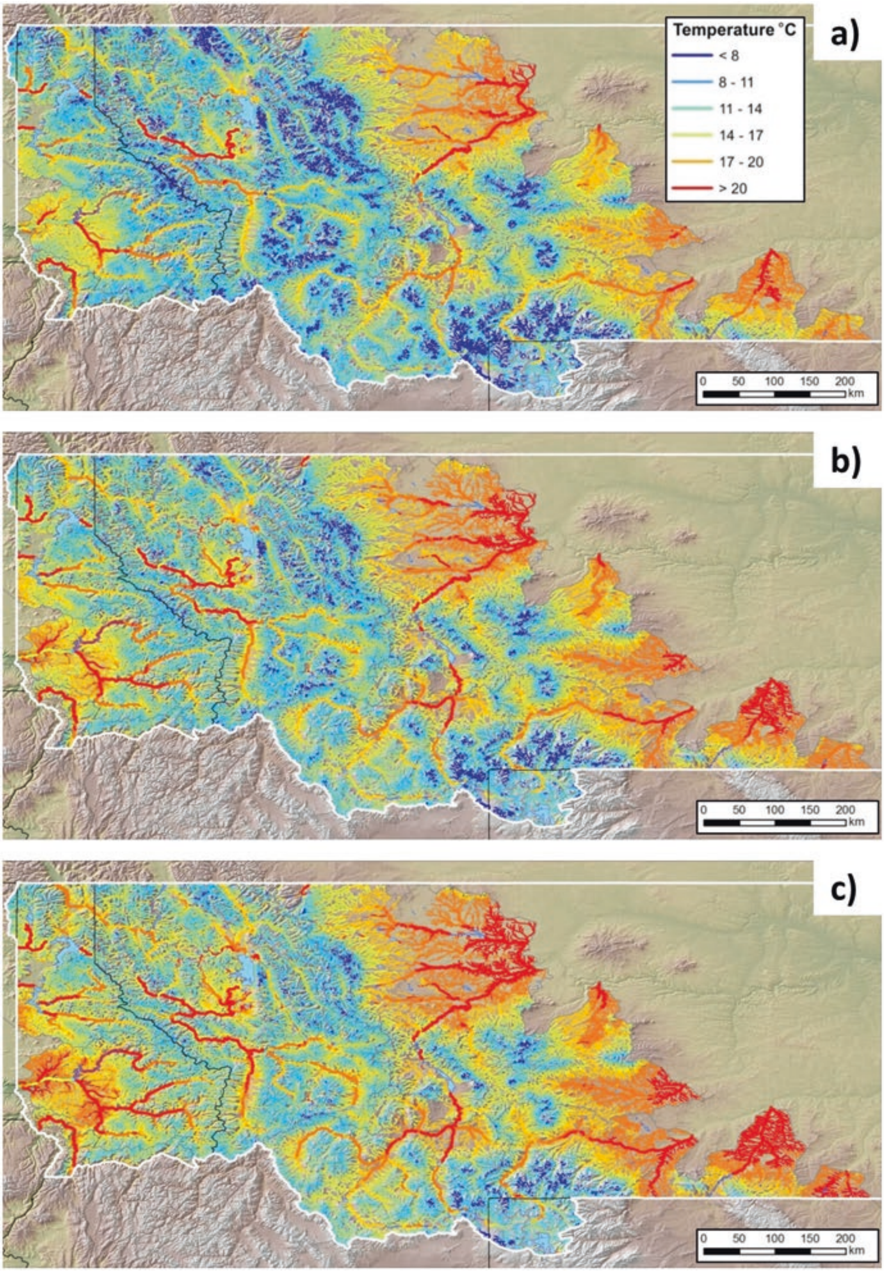

Fig. 4.1 NorWeST August mean stream temperature maps interpolated from 11,703 summers of monitoring data at 5461 unique stream sites across 183,500 km of streams in the Northern Rockies. Map panels show conditions during baseline (**a**, 1980s), moderate (**b**, 2040s), and extreme change scenarios (**c**, 2080s). See text for details on analytical methods and data sources

Table 4.2 Lengths of streams (km) in the Northern Rockies categorized by mean August stream temperature during the baseline and two future climate periods, and by land administrative status

Land status	<8 °C	8–11 °C	11–14 °C	14–17 °C	17–20 °C	>20 °C	Totals
Forest Service lands							
1980s[a]	11,416 (17.4)	36,717 (56.0)	15,034 (22.9)	1957 (3.0)	393 (0.6)	27 (0)	65,544
2040s[b]	4030 (6.3)	28,739 (44.7)	25,607 (39.8)	4976 (7.7)	716 (1.1)	194 (0.3)	64,262
2080s[b]	1547 (2.4)	20,441 (32.3)	30,660 (48.5)	8891 (14.1)	1345 (2.1)	381 (0.6)	63,265
Non-Forest Service lands							
1980s	2501 (2.1)	19,290 (16.4)	41,272 (35.1)	34,215 (29.1)	17,644 (15.0)	2571 (2.2)	117,493
2040s	915 (0.8)	9593 (8.4)	33,764 (29.5)	39,303 (34.3)	24,838 (21.7)	6148 (5.4)	114,561
2080s	407 (0.4)	5549 (4.9)	26,395 (23.3)	40,440 (35.7)	29,628 (26.1)	10,941 (9.7)	113,360

Values in parentheses are percentages of the total in the last column
[a]Stream reaches with slope <15% and VIC summer flows >0.0057 m^3s^{-1}
[b]Reduced network extent results from projected decreases in summer flows per Table 4.1

associated with high-elevation, steep mountain ranges in Montana, whereas such concentrations were absent from most of northern Idaho.

Mean August stream temperature was projected to increase across the Northern Rockies by an average of 1.2 °C in the 2040s and 2.0 °C in the 2080s (Table 4.1, Fig. 4.1). Increases will be disproportionately higher in the warmest streams at low elevations, and lower for the coldest streams. Differential warming occurs because cold streams are often buffered by influxes of groundwater (Luce et al. 2014). Averaged across all streams, future projections imply faster rates of warming (0.2–0.3 °C per decade) than were observed recently (0.1–0.2 °C per decade; Isaak et al. 2012a).

Based on these projections, the length of streams with temperatures <14 °C will decrease to 43,277 km in the 2040s and 27,944 km in the 2080s (Table 4.2). In both scenarios, >75% of the cold streams are in national forests. Very cold streams likely to provide habitat for bull trout and cutthroat trout originate along the Continental Divide in northern Montana, several smaller mountain ranges scattered throughout central Montana, and along the northern flank of the Beartooth Plateau (Fig. 4.1). Persistent CWHs are more isolated elsewhere.

Table 4.3 Number and length of cold-water habitats for juvenile cutthroat trout by probability of occurrence during three climate periods and two brook trout invasion scenarios across the Northern Rockies

Metric and brook trout prevalence	Period	Probability of occurrence (%)					
		<25	25–50	50–75	75–90	>90	Total
Cold-water habitat number							
0% brook trout prevalence	1980s	71	392	1314	1817	1739	5333
	2040s	41	328	1405	1505	1148	4427
	2080s	86	659	949	977	770	3441
50% brook trout prevalence	1980s	73	501	2790	1384	581	5329
	2040s	41	382	2571	1065	367	4426
	2080s	86	684	1837	673	161	3441
Cold-water habitat length (km)							
0% brook trout prevalence	1980s	432	1278	4068	7730	32,646	46,154
	2040s	126	898	3832	6034	17,964	28,856
	2080s	229	1659	2938	4151	10,459	19,436
50% brook trout prevalence	1980s	387	2344	10,320	13,201	19,348	45,602
	2040s	126	1376	8174	8772	10,306	28,756
	2080s	228	1992	6327	6289	4598	19,436

4.3.2 Cutthroat Trout

The historical range of cutthroat trout includes most of the Northern Rockies. The number of discrete CWHs for cutthroat trout in the baseline climate period was estimated to exceed 5000, encompassing over 45,000 km of streams (Table 4.3, Fig. 4.2). Over 90% of CWHs had occupancy probabilities exceeding 50%, because cutthroat require relatively small stream networks (10 km is associated with an occupancy probability of 90%; also see Peterson et al. 2013a). The largest CWHs contained a disproportionate amount of habitat most likely to be occupied; 32.6% were climate refugia, which accounted for 70.7% of the length of CWHs.

In future scenarios, the number and extent of CWHs decreased 20–60%, but even under the extreme scenario nearly 3500 potential CWHs (>19,000 km) were projected to remain. And in a few basins currently too cold for cutthroat trout (e.g., Teton River basin along the Rocky Mountain Front, streams in northern Yellowstone National Park), future warming is expected to increase their suitability. Although the presence of brook trout did not alter the number of CWHs, it did decrease the probability of cutthroat trout occupancy (Table 4.3). Sensitivity of streams to brook trout varied with local conditions, with the greatest reductions in small streams with relatively shallow slopes.

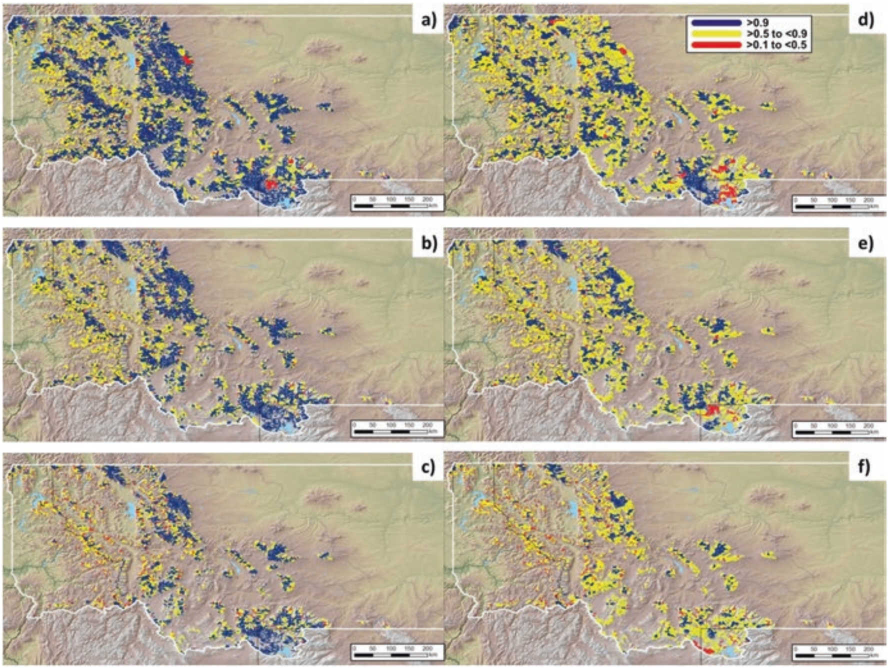

Fig. 4.2 Distribution of cold-water habitats with occupancy probabilities >0.1 for juvenile cutthroat trout during baseline (**a** & **d**, 1980s), moderate-change (**b** & **e**, 2040s), and extreme-change scenarios (**c** & **f**, 2080s). Panels **a**–**c** illustrate occupancy when brook trout are absent; panels **d**–**f** illustrate occupancy when brook trout prevalence is 50%. See text for details on analytical methods and data sources

4.3.3 Bull Trout

The number of discrete CWHs for bull trout during the baseline climate period exceeded 1800, encompassing >23,000 km (Table 4.4, Fig. 4.3). Occupancy probabilities for most bull trout CWHs were <50% because of the large stream networks required by this species (50 km is associated with occupancy probability of 90%). Only 6% of CWHs were considered climate refugia, but they were 30% of the total length of CWH. This requirement for large CWHs caused projected decreases in the number and extent of bull trout CWHs to be much higher (38–71%) than for cutthroat trout, particularly for CWHs with the highest occupancy probabilities. More than 800 CWHs representing over 7000 km were projected to remain, even in the extreme scenario.

Brook trout invasions reduced bull trout occupancy rates. These declines were more pronounced for bull trout than cutthroat trout, especially in CWHs most likely to be occupied (those with >50% occupancy probability). Fewer than 10 climate refugia for bull trout are projected to remain under any warming scenario if brook trout occupy half of each CWH. However, many large CWHs for bull trout appear

Table 4.4 Number and length of cold-water habitats for juvenile bull trout by probability of occurrence during three climate periods and two brook trout invasion scenarios across the Northern Rockies

Metric and brook trout prevalence	Period	Probability of occurrence (%)					
		<25	25–50	50–75	75–90	>90	Total
Cold-water habitat number							
0% brook trout prevalence	1980s	875	534	248	92	106	1855
	2040s	664	314	98	41	32	1149
	2080s	474	274	81	24	13	866
50% brook trout prevalence	1980s	995	484	181	65	28	1753
	2040s	697	270	63	17	5	1052
	2080s	535	260	49	5	3	852
Cold-water habitat length (km)							
0% brook trout prevalence	1980s	4677	5099	4128	2601	7495	24,002
	2040s	3583	3112	1817	1237	2157	11,906
	2080s	2109	2130	1243	622	932	7035
50% brook trout prevalence	1980s	6309	6055	4365	3043	3783	23,554
	2040s	4390	3553	1916	948	656	11,462
	2080s	2525	2647	1133	246	428	6980

less susceptible to brook trout invasions (Isaak et al. 2015). CWHs with the highest bull trout occupancy probabilities during all climate periods and brook trout invasion scenarios were associated with river networks with a high number of cold streams (e.g., Whitefish River, North Fork Blackfoot River, and headwater portions of the North and Middle Forks of the Flathead River) (Figs. 4.1 and 4.3). Because of the lower elevations and warmer streams in northern Idaho, few or no climate refugia were projected to remain under either warming scenario.

4.3.4 Additional Fish Species

Native fish species other than bull trout and cutthroat trout occupy streams throughout the Northern Rockies, but were not considered priorities for this assessment because they are not expected to be as sensitive to warming temperatures as cold-water salmonids. Prairie fish in the Grassland subregion are a geographically discrete group of species that are tolerant of warm water but may be sensitive to other climate-related stressors (e.g., low water levels) (Box 4.1). Additional fish species in the Northern Rockies can be considered as candidates for the habitat occupancy-climate vulnerability approach described here.

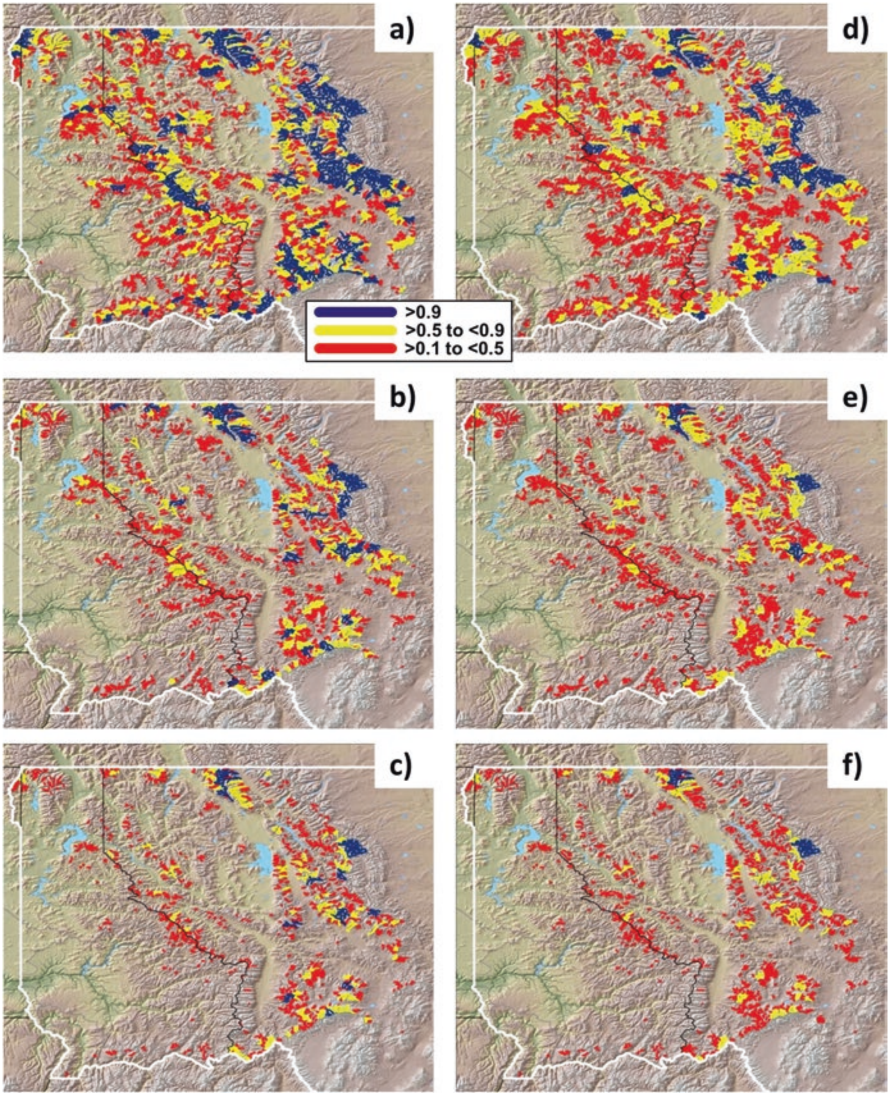

Fig. 4.3 Distribution of cold-water habitats with occupancy probabilities >0.1 for juvenile bull trout during baseline (**a** & **d**, 1980s), moderate-change (**b** & **e**, 2040s), and extreme-change scenarios (**c** & **f**, 2080s). Panels a–c illustrate occupancy when brook trout are absent; panels d–f illustrate occupancy when brook trout prevalence is 50%. See text for details on analytical methods and data sources

Box 4.1 Climate Change Effects on Fish Species in the Grassland Subregion

Several fish species are found in the Grassland subregion of the Northern Rockies. Located in the eastern portions of Custer-Gallatin National Forest and Dakota Prairie Grasslands, these species have received little scientific study and monitoring compared to cold-water salmonids and warm-water sportfish. Most prairie streams have been poorly sampled, making fish populations and aquatic habitat difficult to evaluate. Small streams constitute the majority of fish habitat, providing seasonal habitats for spawning and rearing of species favoring larger streams, rivers, and lakes.

Prairie streams are dynamic, varying between periods of floods and intermittent flows within and between years. Extirpation and recolonization of local habitats by fish species is the norm, with fish species distributed as metapopulations. Although it is typical for prairie streams to be reduced to sets of disconnected pools in some years, this pattern is more prevalent in agricultural landscapes where surface and groundwater withdrawals are common. Climate change is expected to cause greater extremes, including both severe droughts and wet intervals in dryland systems.

Projecting responses of prairie fishes to climate change is complicated by difficulty in identifying habitat preferences, because many species are habitat generalists, and interannual habitat occupancy is difficult to quantify. Prairie fish assemblages include four species guilds—northern headwaters, darter, madtom, and turbid river guilds—that are likely to differ in their vulnerability to climate change. Annual air temperature and various measures of streamflow are strong predictors of presence for the northern headwaters, darter, and madtom guilds.

The northern headwaters guild may be most vulnerable to increasing temperature, as well as to climate-related decreases in groundwater recharge. This guild includes the northern redbelly dace (*Chrosomus eos*), a sensitive species in the USFS Northern Region, which occupies small, relatively cool headwater streams. Accurate mapping of habitat types, species assemblages, and monitoring of habitat conditions will help refine potential climate change effects on habitat and species, as well as suggest appropriate management responses.

Buffering variations in flow extremes (e.g., securing instream flows or facilitating American beaver colonization where suitable habitat exists) and encouraging the presence of riparian vegetation are sound climate change adaptation options where the northern headwaters guild is present. Although

(continued)

Box 4.1 (continued)
other prairie fish guilds seem less vulnerable to changes to temperature, all are influenced by amount and timing of flow, so adaptation strategies for the northern headwater guild should also be appropriate for other guilds. All guilds are currently at risk, and may become more so if flow regimes become more variable. If migration barriers are present, it would be prudent to remove them to facilitate fish movement, while being cognizant of the potential for nonnative fish to become established. Responses of nonnative fish to climate change are uncertain, although some species (e.g., smallmouth bass [*Micropterus dolomieu*]), are expected to expand their distribution.

4.4 Applying the Assessment

The assessment described above provides spatially explicit projections of habitat occupancy in the Northern Rockies by combining ecological understanding of cutthroat trout and bull trout, species distribution data, and high-resolution projections of stream temperature and streamflow. Projections of habitat occupancy in response to anticipated climate change have several implications for future viability of native fish populations in the Northern Rockies and for conservation of these species.

Both native trout species require cold-water habitat, but their response to warmer stream temperatures will differ. Bull trout are adapted to some of the coldest freshwater environments in the Northern Hemisphere (Klemetsen et al. 2003), inhabiting variable environments with strong productivity gradients that favor migration as a life history tactic (Klemetsen 2010). Because bull trout in this region require cold water, are near the southern end of their range, and have inherently low populations in most locations (High et al. 2008), their susceptibility to range contraction in a warmer climate is unsurprising. We anticipate large reductions in their distribution in the Northern Rockies because climate refugia are relatively uncommon and dispersed, but at least some climate refugia will be retained in the future, making it more likely that bull trout will persist. The conditions favoring migratory or resident life histories may change, perhaps in uncertain ways, and it remains to be seen how to accommodate or exploit this transition in conservation practices. Research and monitoring can provide a better understanding of environmental drivers of bull trout life history.

Cutthroat trout can accommodate a broader range of thermal environments, commensurate with their evolutionary history and extensive latitudinal distribution. Their life history strategies are flexible, ranging from migratory populations that use large water bodies for growth and fecundity, to resident populations with low mobility that have been isolated for decades (Northcote 1992; Peterson et al. 2013a). The distribution of cutthroat trout is expected to decrease in the Northern Rockies, but not as much as that of bull trout. In addition, some basins currently too cold to support cutthroat trout may become suitable as the climate warms (Cooney et al. 2005; Coleman and Fausch 2007).

The degree to which nonnative salmonids displace bull trout and cutthroat trout in a warmer climate will have a major impact on long-term population viability and conservation strategies (Wenger et al. 2011a). Tolerance of cold temperature by brook trout is nearly equivalent to that of cutthroat trout, and they are especially competitive in the low-gradient environments preferred by bull trout and cutthroat trout (Wenger et al. 2011a). Large habitats (>100 km long) are less susceptible to incursions by brook trout, at least partially because they face competition from rainbow trout or brown trout (Fausch et al. 2009), species expected to shift upstream in a warmer climate (Wenger et al. 2011b; Isaak and Rieman 2013).

The USFS will play a major role in the conservation of native fish populations because most cold-water habitats in the Northern Rockies are in national forests (Table 4.2). Active management that conserves native fish is an option, because most of the cold-water habitats are outside designated wilderness areas and national parks that restrict management activities. Even under extreme warming, cold-water habitats are expected to persist in some river basins in Montana. Maintenance of these conditions is critical. In locations where climate refugia are unlikely to persist (Clearwater, Spokane, and Kootenai River basins in Idaho), active management—manipulation of habitat, fish populations, or both—may be the only way to ensure long-term persistence of native fish populations. Retaining native trout populations in some areas may require costly conservation investments, so it will be important to prioritize projects where success is likely and where benefits can be gained for other resources (e.g., riparian restoration or improved water quality).

The model projections described above are consistent with trends that have been occurring in the Northern Rockies during the last 50 years: increased air temperature, increased stream temperature, and decreased summer streamflow (Luce and Holden 2009; Isaak et al. 2010, 2012a,b; Leppi et al. 2012). This provides validation that modeled estimates of occupancy probabilities are biologically robust, facilitating a spatially explicit ranking of critical habitats. The Climate Shield fish distribution maps and databases developed in this assessment are easy to understand and access, allowing users to quantify the likely amount, distribution, and persistence of native trout habitats at multiple spatial scales (e.g., stream, river network, national forest, or region).

In general, model output suggests that environmental gradients are the primary drivers of habitat occupancy by juvenile native trout. Model projections can be improved in the future by including more local information on habitat conditions (Peterson et al. 2013a), especially the presence of barriers that influence habitat connectivity (Erős et al. 2012), and by applying spatial network models (Isaak et al. 2014). An ongoing assessment process can reduce uncertainties about distribution of aquatic species and climate change responses. Currently available data were derived from thousands of sites, but additional data would improve existing models and help develop models for additional species. Ongoing assessment and updated modeling can be combined with new surveys, such as those based on rapid and reliable environmental DNA surveys (McKelvey et al. 2016a), to provide a more accurate picture of species distribution at fine spatial scales. Such surveys will also expand our capability of assessing multiple species simultaneously.

4.5 Adapting Fish Species and Fisheries Management to Climate Change

4.5.1 Adaptation Options

Climate change adaptation for fish conservation has been reviewed extensively for western North America, including for the Northern Rockies (ISAB 2007; Rieman and Isaak 2010; Isaak et al. 2012a; Beechie et al. 2013; Luce et al. 2013; Williams et al. 2015), based on a relatively well-established set of climate sensitivities and adaptation options (Rieman et al. 2007; Mantua and Raymond 2014; Isaak et al. 2015). This provides credibility and consistency for sustainable management of fisheries in a warmer climate. This information, combined with the Northern Rockies fisheries assessment, provide the foundation for federal resource specialists to develop strategic (general, overarching) and tactical (specific, on the ground) management responses that improve the resilience of fish populations in a warmer climate.

Climate change sensitivities and adaptation options are similar among the mountainous subregions of the Northern Rockies. An exception occurs in the Eastern Rockies and Grassland subregions, where livestock grazing is a significant stressor. The Grassland subregion has no cold-water fish species and is dominated by warm-water species, many of which are nonnatives. Although some concern exists about aquatic systems in this subregion, no adaptation options were developed for fisheries in the Grassland subregion (but see Box 5.2).

Reduced snowpack is a well-documented effect of warmer temperatures in mountainous regions (Chap. 3), resulting in lower summer streamflows and warmer stream temperatures. Adaptation strategies include maintaining higher summer flows and reducing the negative effects of lower flows. On-the-ground adaptation tactics include pulsing flows from regulated streams when temperature is high, reducing water withdrawals for human uses, and securing water rights for instream flows to control overall water supply.

Increasing cold-water habitat resilience by maintaining and restoring structure and function of streams is another important adaptation strategy. Adaptation tactics include restoring channel and floodplain structure to retain cool water and riparian vegetation, and ensuring that passages for aquatic organisms are effective. These tactics can be leveraged with ongoing habitat restoration activities, especially near roads and where high streamflows are frequent. As a general principle, accelerating riparian restoration will be an effective way to improve hydrologic function and water retention. Maintaining and restoring American beaver (*Castor canadensis*) populations is also an excellent approach for water retention in mountain landscapes. Finally, road removal and relocation from locations near stream channels and floodplains can greatly improve hydrologic function.

Interactions with nonnative fish species are a significant stress for native cold-water fish in the Northern Rockies. Facilitating movement of native fish to locations with suitable stream temperatures is a primary adaptation strategy. Adaptation tactics include increasing the size of suitable habitat, modifying or removing barriers to fish passage, and documenting where groundwater inputs provide cold water. Efficacy of these tactics will be higher if native fish populations are currently healthy and nonnatives are not well established. Another important adaptation strategy is reducing nonnative fish species. Adaptation tactics include increased harvest of nonnative fish (e.g., sport fishing), manual or chemical removal of nonnatives, and excluding nonnatives with migration barriers where feasible.

Livestock grazing can damage vegetation adjacent to streams in grasslands and shrublands, predisposing aquatic systems to further degradation from warmer stream temperatures. One adaptation strategy is managing grazing to reduce damage and restore ecological and hydrologic function of riparian systems. Adaptation tactics include ensuring that standards and guidelines for water quality are adhered to and monitored, making improvements that benefit water quality and riparian shading (e.g., fencing), and reducing the presence of cattle through the retirement of vacant grazing allotments. Locations with high ecological value can be prioritized.

In a warmer climate, it is almost certain that increased wildfire occurrence will contribute to erosion and sediment delivery to streams, thus reducing water quality. Increasing resilience of vegetation to wildfire is an adaptation strategy that can help reduce the severity of fires when they occur. Hazardous fuel treatments that reduce forest stand densities and surface fuels are an adaptation tactic that is already widely used in dry forest ecosystems. Disconnecting roads from stream networks, another tactic already in practice, is especially important, because most sediment delivery following wildfire is derived from roads.

4.5.2 Principles of Climate-Smart Management

Adaptation options summarized here provide a diverse range of management responses to climate change for fisheries managers. In addition to these adaptation options, several overarching principles can help guide implementation:

- *Be strategic* — Prioritize watershed restoration to ensure that the most important work is done in the most important places. For example, climate refugia for native trout in wilderness areas may not require habitat modification to ensure persistence of those populations. Similar refugia outside wilderness can be targeted to improve habitat conditions and reduce nonnative species. Some basins are unlikely to provide suitable habitat for native trout in the future, so direct conservation investments elsewhere.

- *Implement monitoring programs* — Reduce current and future uncertainties for decision-making with strategic monitoring, then revise assessments and adaptation as needed. More data are needed for streamflow (more sites), stream temperature (annual data from sensors), and fish distributions. These data will improve knowledge of status and trends, and contribute to improved models. Monitoring efficiency is being improved with eDNA inventories of aquatic organisms (Carim et al. 2016) and inexpensive temperature and flow sensors (USEPA 2014).
- *Restore and maintain cold stream temperatures* — Many options exist: relocate roads away from streams, limit seasonal grazing, and manage riparian forest to maintain shade. In addition, take advantage of existing restoration programs to improve aquatic habitat for native fish populations.
- *Manage connectivity* — Remove obstacles to fish migration to enhance the success of migratory life history forms of native fish species, but be aware that increased connectivity can also provide access for nonnative fish species (Fausch et al. 2009). Native populations above barriers may be secure if they can adopt resident life histories, but are susceptible to extreme disturbances.
- *Remove nonnative species* — Use chemical treatments or electrofishing to remove nonnative fish species in smaller habitats, thus reducing stress on native fish populations. Control measures can be useful even if all nonnatives cannot be removed, although a migration barrier to prevent reinvasion and periodic additional controls will generally be needed to improve effectiveness.
- *Implement assisted migration* — Move native fish species from one location to another, a historically common activity in fish management, to found populations in previously fishless or formerly occupied waters. Although controversial for most taxa, assisted migration (or managed relocation) may be useful where basins are currently fishless (or contain only nonnative species in limited numbers) because of natural barriers, with the potential to be climate refugia in the future. Repeated introductions of native species may be appropriate when natural refounding is not an option, such as when populations are isolated and susceptible to periodic population crashes (Dunham et al. 2011).

Fisheries managers require a portfolio of strategic and tactical adaptation options, as described here, to address the many biogeographic circumstances they will encounter in the future. Stream habitats are already dynamic and will be even more variable in a warmer climate, undergoing both gradual and episodic changes over time. Many fish populations will adapt successfully, but others will be extirpated. Although it may not be possible to preserve all populations of all fish species in their current location, new data can inform adaptive management that targets conservation where it is most likely to succeed.

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