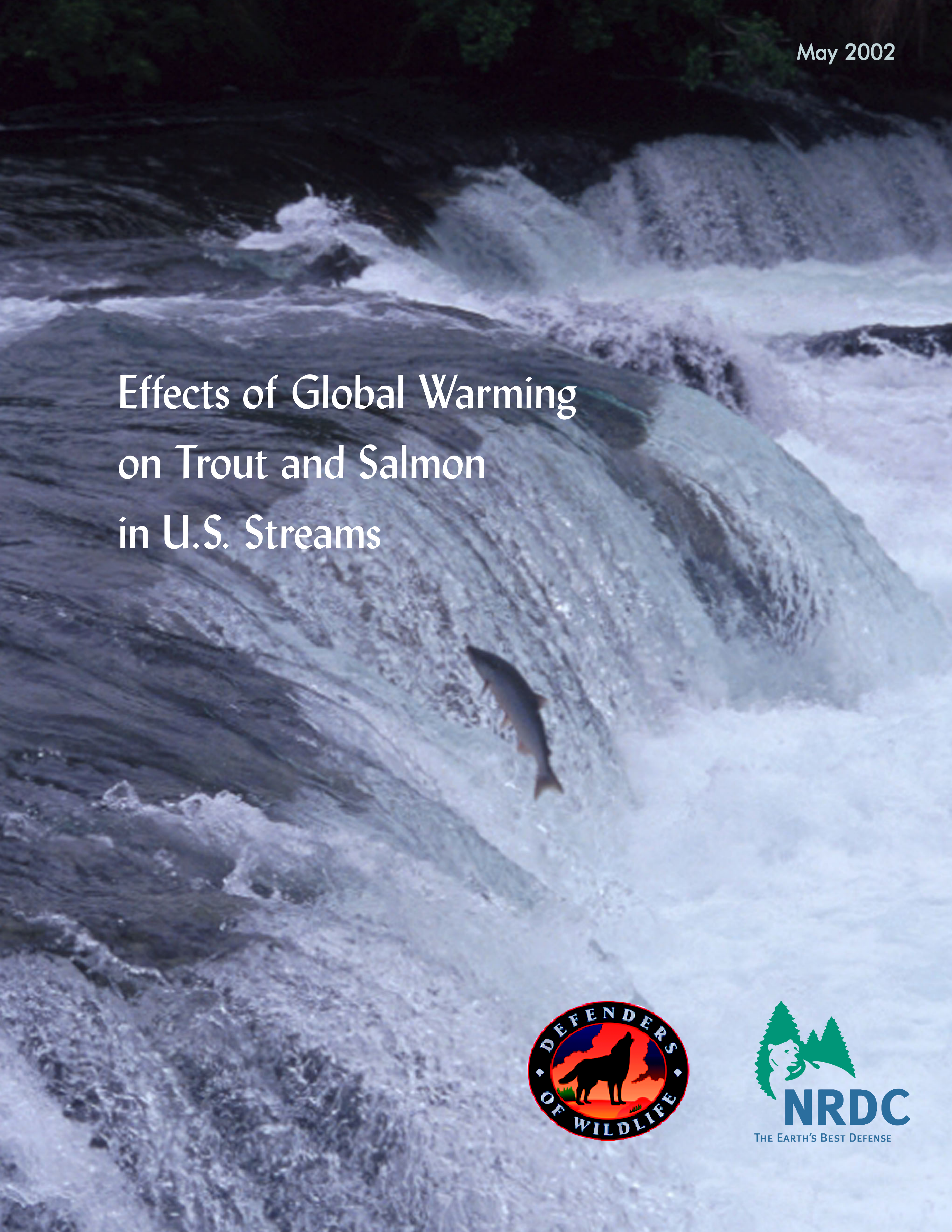

May 2002

Effects of Global Warming on Trout and Salmon in U.S. Streams

DEFENDERS OF WILDLIFE

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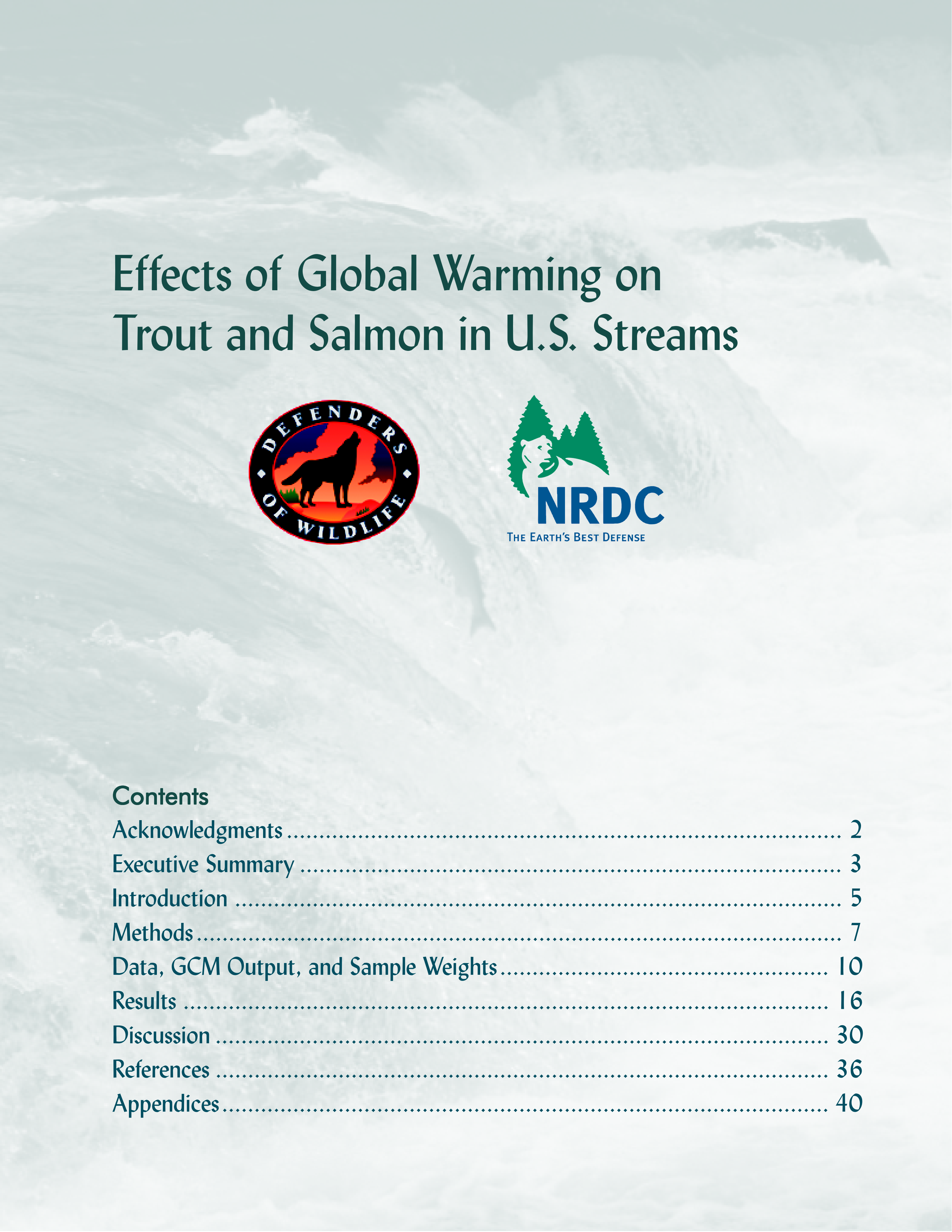

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Defenders of Wildlife is a leading conservation organization recognized as one of the nation's most progressive advocates for wildlife and its habitat. Known for its effective leadership on endangered species issues, particularly wolves and other predators, Defenders is also a proponent of new approaches to wildlife conservation that protect species before they become endangered. Defenders was founded in 1947 and is a nonprofit 501(c)(3)organization with more than 450,000 members and supporters. For more information: Defenders of Wildlife, 1101 Fourteenth Street, NW, Suite 1400, Washington, D.C. 20005; 202-682-9400; www.defenders.org

The Natural Resources Defense Council is a national nonprofit environmental organization with more than 500,000 members. Since 1970, our lawyers, scientists, and other environmental specialists have been working to protect the world's natural resources and improve the quality of the human environment. NRDC has offices in New York City, Washington, D.C., Los Angeles, and San Francisco. Visit NRDC online at www.nrdc.org.

The shared goals and complementary strengths of the Natural Resources Defense Council and Defenders of Wildlife have lead to several natural partnerships on key policy issues of mutual interest. In addition to working together on this report examining one of the many threats to wildlife posed by global warming, Defenders and NRDC recently released a report on the anti-environmental activities of the American Legislative Exchange Council (ALEC) and established the State Environmental Resource Center to develop and promote responsible environmental legislation in state legislatures nationwide.

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Executive Summary

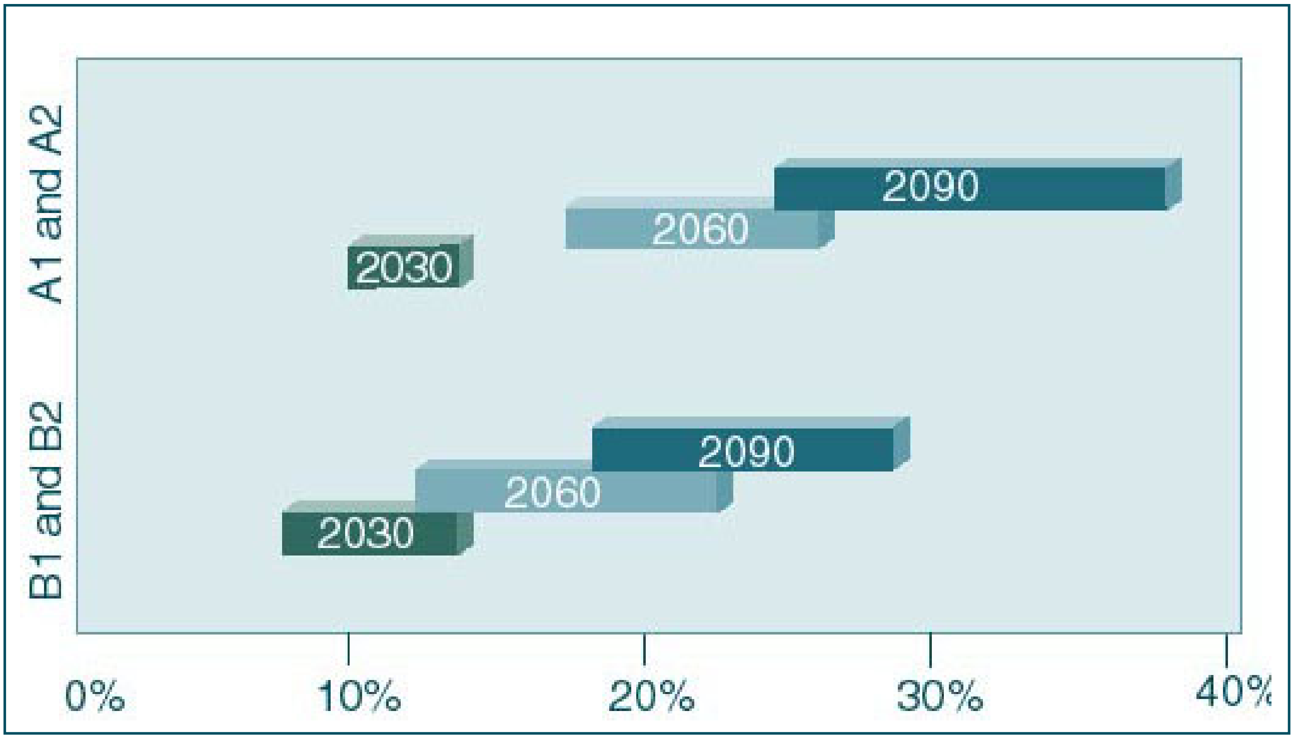
Trout and salmon thrive in the cold, clear streams found in many mountainous and northern regions of the United States. Americans devote more than 100 million person-days per year to angling in streams or lakes for these fish, which are highly valued for their contribution to the economy and culture of the United States. However, dams, water diversions, pollution, and development threaten trout and salmon, which have already disappeared from many of the streams they once inhabited. Climatic warming poses an additional, potentially severe threat to their survival.

The earth has warmed significantly during the last 50 years, and most of the observed warming is believed to have been caused by increased concentrations of carbon dioxide (CO_2) and other heat-trapping gases. This warming is expected to accelerate over the decades ahead if emissions of these gases continue to increase. Because trout and salmon are known to be intolerant of warm water, their distribution and/or abundance could be threatened if future climate change warms the streams they inhabit.

This report presents results from a new simulation study of how climate change might affect the existing habitat for four species of trout (brook, cutthroat, rainbow, and brown) and four species of salmon (chum, pink, coho and chinook) in streams throughout the contiguous United States. The simulation uses a new, more accurate method to estimate how stream temperatures will respond to the changes in air temperatures projected by global climate (general circulation) models.

We find that trout and salmon habitat is indeed vulnerable to the effects of global warming. Based on emissions scenarios A1 and A2 from the Intergovernmental Panel on Climate Change (IPCC), we estimate that individual species of trout and salmon could lose 5-17% of their existing habitat by the year 2030, 14-34% by 2060, and 21-42% by 2090, depending on the species considered and model used (Figure ES-1). Projected effects on trout and salmon are lower for IPCC scenarios B1 and B2, which assume that global CO_2 emissions are reduced for reasons unrelated to global warming. For these scenarios, we estimate habitat losses of 4-20% by 2030, 7-31% by 2060, and 14-36% by 2090, depending on fish species and model. Of particular note is the number of stream locations that become unsuitable

Figure ES-1: Locations Losing All Cold Water Species by Emissions Scenario

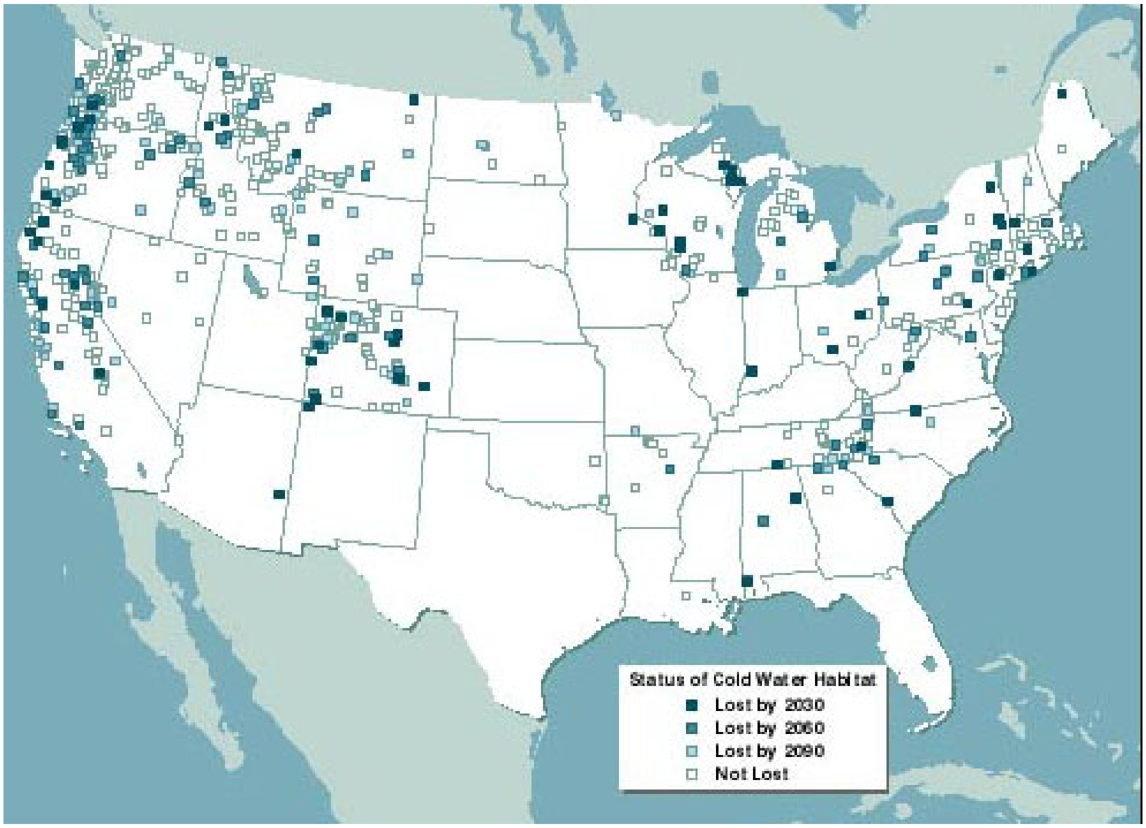


for *all* modeled species. By the year 2090, for example, 18-38% of those locations currently suitable for cold water fish become too warm to provide suitable habitat.

Loss of trout habitat in the South, Southwest, and Northeast could be particularly severe, although substantial losses are also expected in other regions. For salmon, significant losses are projected throughout the current geographic range, with greatest losses expected for California. The number of locations expected to become unsuitable for both trout and salmon expands steadily over time, if emissions of heat-trapping gases continue to increase (e.g., Figure ES-2 for the A2 emissions scenario).

These results are robust with respect to key model specifications and assumptions. For a given emissions scenario, the greatest uncertainty is caused by differences among global climate models. Results also differ according to scenarios for future emissions of heat-trapping gases, even though none of the scenarios examined assumes that policies are adopted specifically to address global warming. Regardless of the emissions scenario selected, our results are likely to understate expected losses of habitat, because of the dimensions of climate change and potential effects on habitat that were beyond the scope of this modeling effort. These include potential changes to stream flows, changes to the temperature of groundwater discharge, and changes to ocean conditions. Moreover, other present and future threats to fish habitat are likely to add to the temperature-related losses estimated in this report. To succeed, future strategies to protect trout and salmon will need to address the potential effects of global warming.

Figure ES-2: Future Status of Cold Water Fish Habitat (CSIRO-Mk2 Model with A2 Emissions)



Introduction

An estimated nine million anglers devoted 94 million person-days to trout fishing in the U.S. in 1996, and more than a million anglers spent 12 million person-days fishing for salmon (U.S. Department of the Interior and U.S. Department of Commerce, 1997)[1]. Depending on the regions studied and methods used, estimates for the economic value of recreational fishing for trout range from $9-147 per fishing day; estimates for salmon range from $33-59 per fishing day, suggesting a total economic value of $1.3-14 billion per year[2].

In addition, these species have long contributed to regional and local cultures of the United States. Salmon are integral to the culture and heritage of the Pacific Northwest, where they have been harvested by Native Americans for centuries, and provided an estimated 60,000 jobs in 1992 (Oregon Rivers Council, 1992). Trout hold a similar position of importance in the Rocky Mountain and Appalachian Mountain regions (*e.g.*, Beers, 2001; Idaho Dept. of Fish and Game, 2001). Americans recognize an "existence" value for these species as wildlife: even those who do not participate in recreational fishing are willing to pay to protect the diversity and ecological stability of wild salmon and trout populations (Olsen *et al.*, 1991). Over $1.3 billion was spent between 1981 and 1991, for example, to improve salmon runs in the Columbia River basin alone (Pulwarty and Redmond, 1997).

Despite their recognized value, trout and salmon fisheries in the United States are being compromised by a range of anthropogenic factors, including habitat degradation, increasing levels of erosion and nutrient mobilization caused by logging and changing land use, hydropower dams and diversions, competition from hatchery-reared fish, and introduction of non-native species (Hauer *et al.*, 1997; Pulwarty and Redmond, 1997; Sanz *et al.*, 2000; Tschaplinski, 2000). Wild Pacific salmon have disappeared from almost 40% of their historic range in the Pacific Northwest, and salmon populations in the Columbia River system have declined by 91-98% compared to their numbers prior to European visitation (Pulwarty and Redmond, 1997). Within the states of California, Oregon, Washington, and Idaho, Nehlsen *et al.* (1991) identified 160 native, naturally spawning stocks of salmon or anadromous trout at high or moderate risk of extinction, and classified seventeen of those stocks as possibly already extinct. Chinook salmon have been listed under the Endangered Species Act (Pulwarty and Redmond, 1997), and populations of coho salmon are listed as threatened (Shea and Mangel, 2001). Cutthroat trout, which are native to the western United States, have been reduced to less than 5% of their original range; of the 14 recognized subspecies, three are listed as threatened under the Endangered Species Act, and conservation plans have been developed for most others (Harig and Fausch, 2002). Acidification has been identified as a serious threat to brook trout in western Virginia, where about half of all otherwise available trout streams have been rendered unsuitable by acidic deposition (Bulger *et al.*, 2000).

Climate change could exacerbate the damage to trout and salmon caused by existing stressors. The earth's atmosphere has warmed significantly over the last 50 years, and most of the observed warming is believed to have been caused by increased concentrations of carbon dioxide (CO_2) and other heat-trapping gases (Albritton *et al.*, 2001; Cicerone *et al.*, 2001). As concentrations of these gases continue to increase, further warming is expected (Cubasch *et al.*, 2001). This warming could in turn raise the temperature of water in streams, thus altering the habitat of freshwater fish (*e.g.,* Stefan and Preud'homme, 1993; Meisner *et al.*, 1988). Trout and salmon, known to require cold water habitat for growth and successful inter-species competition, are characterized as belonging to the "cold water thermal guild" (Magnuson *et al.*, 1979). Increased stream temperatures could benefit cold water species in some circumstances, but are more generally expected to eliminate viable habitat.

Previous efforts to quantify expected effects of climate change on cold water fish have for the most part focused on limited geographic regions and a small number of fish species. Several such studies have concluded that local or regional effects could be severe. In his pioneering

[1] Excludes fishing in the Great Lakes, but includes fishing in other lakes.

[2] Boyle *et al.* (1996) used contingent valuation to estimate a net economic value of $9 per fishing day for trout (averaged over the two regions with reported estimates for trout only). Duffield *et al.* (1987) used reported travel cost to estimate a consumer surplus of $147 per day of trout fishing in Montana streams. Cameron and James (1987) estimated a value of $33 per day of sport fishing for salmon, based on contingent valuation. Olsen *et al.* (1991) also used contingent valuation to estimate a value of $59. All values have been adjusted to 2001 dollars.

Photograph provided by Art Today (www.arttoday.com)

investigation, for example, Meisner (1990a) estimated that 30-42% of available habitat for brook trout could be lost from two streams in southern Ontario as a consequence of a 4.1ºC (7.4ºF) increase in July and August temperatures. Flebbe *et al.* (1993) used the methods of Meisner (1990b) to estimate that 82-89% of brook trout could be lost from North Carolina and Virginia as a result of a climate change scenario in which average air temperatures increased by 3.8ºC (6.8ºF). Keleher and Rahel (1996) tested 1-5ºC (1.8-9ºF) increases in July temperatures with a Geographical Information System (GIS)-based model to project a loss of 17-72% of the area in the Rocky Mountain region that supports habitat for brook trout, cutthroat trout, rainbow trout and brown trout. Similarly, Clark *et al.* (2000) used a GIS-based model to project that brook trout could lose 24% and rainbow trout 16% of available habitat in the southern Appalachians. Rahel *et al.* (1996) estimated 7-76% losses of brook, brown, and rainbow trout habitat in the North Platte River drainage of the Rocky Mountains.

To date, only two studies have prepared national assessments of the expected effects of climate change on freshwater fish habitat: U.S. EPA (1995) and Eaton and Scheller (1996). Both simulated changes in water temperatures at numerous stream locations throughout the contiguous United States, and applied those estimated changes to determine likely effects on habitat for several dozen species of freshwater fish. In addition, U.S. EPA (1995) estimated likely effects on recreational fishing activity and associated changes in economic value, by linking projected changes in fish habitat to an economic model of recreational fishing behavior.

Like its two predecessors, this study encompasses the entire contiguous U.S. It refines the methods used in U.S. EPA (1995) and Eaton and Scheller (1996), but is limited to eight species of cold water fish: brook trout (*Salvelinas fontinalis*), cutthroat trout (*Oncorhynchus clarki*), steelhead[3] and rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), chum salmon (*Orcorhynchus keta*), pink salmon (*Oncorhynchus gorbuscha*), coho salmon (*Oncorhynchus kisutch*), and chinook salmon (*Oncorhynchus tshawytscha*). It is important to note that this study considers direct *thermal* effects only, and does not assess potential impacts from future changes to precipitation, evapotranspiration, and stream flow regimes. It also excludes the impacts of climate change on marine environments (in which salmon and anadromous trout spend part of their lives before returning to spawn in freshwater). Possible interactions between climate change, water quality, and food availability due to ecosystem changes; fragmentation of species populations due to thermal constraints; increases in predation; and changes in species interactions and competition within aquatic ecosystems are also excluded. Finally, it excludes future changes in other anthropogenic stresses on fish habitat, like increasing water withdrawals or changing land use. These trends pose additional risks to cold water fish populations, and could compound the effects of climate change reported in this study.

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[3] A steelhead is a rainbow trout that has spent part of its life in the ocean.

Methods

The methods used in this study are similar to those of the two previous national assessments (U.S. EPA, 1995; Eaton and Scheller, 1996). For a sample of sites within the lower 48 states, we first determined existing, or "baseline" water temperatures, and whether the geographic location and water temperatures at each site provided suitable habitat for each of the eight species included in this study. Second, we determined how air temperatures at each site are expected to change over time, and how those changes would in turn affect water temperatures. Third, we used projected water temperatures to identify locations that would become intolerably warm to species for which temperatures are now suitable. Only in the second of those three steps do the methods used in this study differ appreciably from those used in U.S. EPA (1995) and Eaton and Scheller (1996).

Baseline Stream Temperatures and Suitability of Habitat

Our sample of sites was necessarily limited to streams for which available water temperature data were adequate. For each site, we used maximum weekly averages as the appropriate measure of water temperatures. Using historical records of daily average water temperatures for each site, we calculated average water temperatures for each week of the year (with the first week of each year beginning on January 1 and the last containing either eight or nine days) for each year of recorded data. We next identified the highest average across all years of available data for each of the 52 weeks, and stored the resulting value for later use. Finally, for each site we took the highest of those 52 maximum values as the "maximum weekly average temperature" under present climate conditions.

Photograph by Jim Yuskavitch

Data on fish presence have not been collected for most of these sites, so we determined current or "baseline" suitability of habitat for each fish species according to two considerations: (1) whether each location was within the reported geographic range of the species' current habitat, and (2) whether the maximum weekly average water temperatures at the site exceeded the "upper thermal tolerances" established for that species (Eaton *et al.*, 1995; Eaton and Scheller, 1996). The fact that these two conditions are met for a stream at a particular gaging station does not necessarily mean that a particular fish species will be present at that location, however. Reasons the species might be absent include lack of access (including access to and from oceans for anadromous species), winter kill, predators and competitors, lack of adequate food sources, and unsuitable conditions for reproduction (Sinokrot *et al.*, 1995). Without data for actual fish presence, however, we are forced to rely on these two conditions as our best indicator of whether a stream at a particular gaging station provides suitable habitat for each fish species.

Changes in Air and Stream Temperatures

To quantify expected changes in air temperatures, we used results from general circulation models (GCMs), computer models that simulate air temperatures and other components of climate over multi-decadal periods. Recent, "coupled" versions of GCMs (including those used in this study) combine three-dimensional representations of the Earth's oceans with three-dimensional representations of its atmosphere. Model output for each projected climate variable is typically condensed into monthly averaged values for each of about 3,500-7,000 grid cells covering the entire Earth's surface, for years beginning in the mid-1900s and ending in 2099 or 2100.

To determine how these projected changes in air temperatures would affect the temperatures of streams within our sample, we estimated the existing relationship between weekly average air and water temperatures at each site. Here our methods departed from those of the earlier national studies, which assumed identical air/water temperature relationships for all sites. Eaton and Scheller (1996), for example, assumed each 1° increase in average summer air temperatures would raise maximum weekly average water temperatures by 0.9° for all affected streams. Because relationships between air and water temperatures are likely to vary by location, however, we instead estimated them separately for each site.

Two relatively simple statistical methods have been advanced for quantifying the relationship between water and air temperatures for a given stream location. The first is a linear model (Stefan and Preud'homme, 1993):

Equation 1

$$Tw(t) = A + B \cdot Ta(t)$$

where *Tw(t)* is the average water temperature for week *t*, *Ta(t)* is the average air temperature for week *t*, and *A* and *B* are parameters to be estimated by linear regression.

With this method, Stefan and Preud'homme estimated that for each 1° of incremental increase to air temperatures, surface waters in the 11 streams they studied increased from 0.67-1.03 degrees, with a mean of 0.86. This latter value provided the slope of 0.9 generalized by Eaton and Scheller (1996) for use in their national study. Similarly, Pilgrim *et al.* (1998) regressed weekly average water temperatures against weekly average air temperatures for each of 37 streams in Minnesota and found regression coefficients ranging from 0.71 to 1.1, with an average of 0.99. In our own regression analysis of more than 2,000 stations we found an average *B* of 0.80, and (like Pilgrim *et al.*) observed that the average of coefficients was 0.99 for the 34 sites in Minnesota, which had the fourth highest average of all states in the contiguous U.S.

More recently Mohseni and Stefan (1999) have argued that relationships between air and water temperatures are better characterized as non-linear, and that assuming a linear relationship is likely to overstate the expected response of stream temperatures to climate change. They note that at higher temperatures, evaporative cooling increases, and water temperatures become less responsive to further increases in air temperatures, ultimately approaching an upper bound at which further increases in air temperatures are without effect (Mohseni *et al.*, 2002). As an alternative to the linear model, Mohseni *et al.* (1998) have proposed a logistic relationship:

Equation 2

$$Tw(t) = \mu + \frac{\alpha - \mu}{1 + e^{\gamma\,[\beta - Ta(t)]}}$$

where the model parameters $\alpha, \beta, \gamma,$ and μ must be estimated for each location. Equation (2) describes a sigmoidal, or S-shaped relationship between air and water temperatures, in which the slope of the air/water relationship flattens both at low air temperatures (where *Tw* approaches its theoretical minimum μ), and at high air temperatures (where *Tw* approaches its theoretical maximum α). As illustrated in Figure 1, the parameter β describes air temperature at the point of inflection where the slope of the curve stops increasing and starts decreasing, and γ is a function of the curve's slope (θ) at that point:

Equation 3

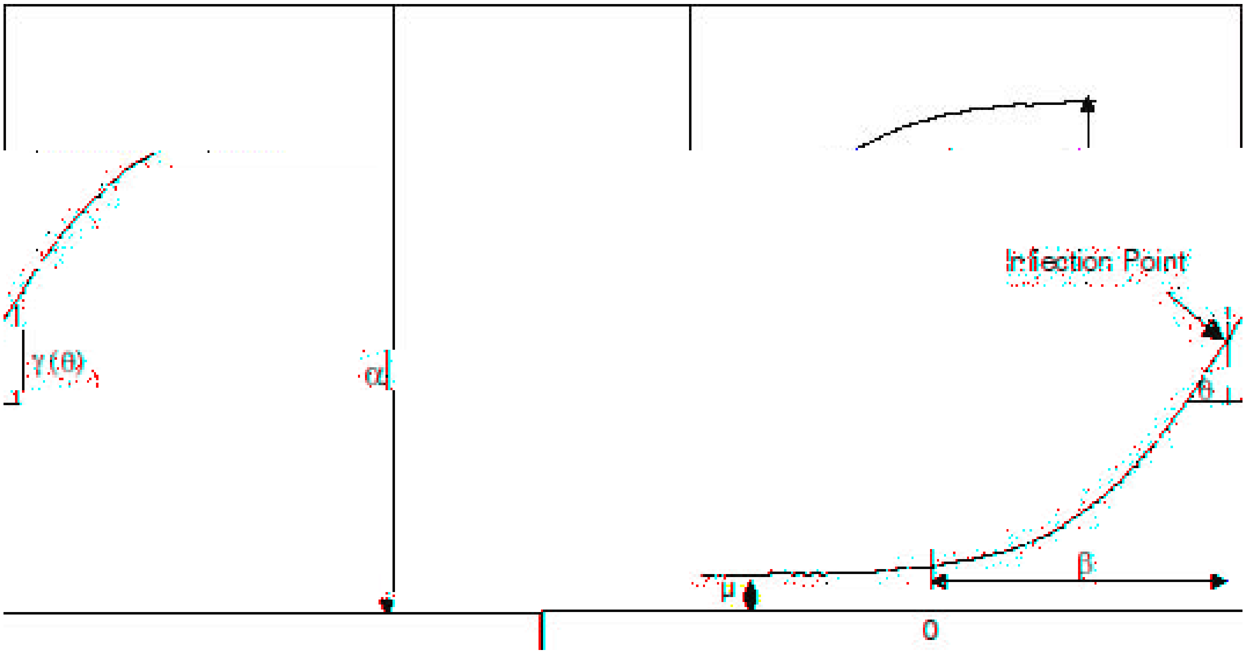
$$\gamma = \frac{4 \tan \theta}{\alpha - \mu}$$

Typically, values for μ will be near 0°C (32°F) for undisturbed streams, as ice cover appearing at that temperature tends to reduce the stream's response to further decreases in air temperatures. Values for μ may be higher at locations where releases from upstream reservoirs raise stream temperatures in winter. Values for α typically fall between 20-33°C, or 68-91°F (Mohseni *et al.*, 1998).

We used a non-linear, least squares regression technique based on Newton's method to fit the logistic model of Equation (2) to each stream in our sample. Data from the weather stations nearest each United States Geological Survey (USGS) gaging station were used to derive weekly average air temperatures, which were matched by year and week to corresponding water temperatures. A minimum of three years of data with 52 available pairs of concurrent weekly average air and water temperatures was required for a site to be included in this study. We assumed the week-long averaging period absorbs much of the expected lag between air and water temperatures (Stefan and Preud'homme, 1993).

Some streams show evidence of appreciable hysteresis in their response to changing air temperatures; *i.e*, the relationship between air and water temperatures differs according to whether waters are warming or cooling. Temperatures in such streams, for example, might be lowered in the spring by the cooling influence of snow-melt, and then show a different relationship to air temperatures in the autumn. Alternatively, water temperatures could be affected by seasonal patterns of reservoir releases. For each stream, we first fit a single logistic function (Equation 2) to the complete set of annual data, and then fit separate functions to the rising (before the yearly maximum) and falling (after the yearly maximum) limbs of the site's annual temperature cycle. Following the procedure described by Mohseni *et al.* (1998), we used the separately-fit functions to describe the stream if the combined R^2 for the two functions fit separately exceeded by more than 0.01 that of the function fit to the complete data. Finally, the regression was considered

Figure 1: Schematic Representation of Logistic Function



Source: Mohseni *et al.*, 1998

unsuccessful for the 12% of sites for which the resulting R^2 (for the function or functions used) was lower than 0.7: these sites were excluded from further modeling efforts. The sensitivity of model results to this rule is examined later.

To predict how climate change could affect the temperature of surface waters, we used each site's reported latitude and longitude to identify the appropriate grid cell in each GCM's output data. For each of the 52 maximum weekly average water temperatures identified earlier, we evaluated Equation (2) at the corresponding air temperature both before and after the warming predicted by the GCM, and added the projected increment in water temperature to the observed maximum for that week. For streams with hysteresis, we used separate versions of Equation (2) for the weeks preceding and following the present maximum weekly average temperature. At the week of maximum weekly average temperatures for streams with hysteresis, we averaged the values of β and γ estimated for the rising and falling limbs, used the maximum of the two values for α, and used the minimum for μ (a practice adopted from Mohseni *et al.*, 1998). For streams without appreciable hysteresis, all weeks were evaluated with the single equation derived from complete annual data.

Changes in Availability of Suitable Habitat

We next identified the highest value of the resulting array of adjusted weekly average water temperatures, which represented the expected maximum weekly average water temperature for that site after climate change. Finally, we compared that result to each species' upper thermal tolerance and geographical range to determine the suitability of habitat for that species after climate change. It should be noted that because GCMs predict different increases (or occasionally decreases) to air temperatures for different months of the year, the timing of simulated maximum water temperatures sometimes changes as a result of these steps. For those streams in which the timing of the modeled maximum weekly average temperature is altered by climate change, simply adjusting the previous maximum by its calculated increment would have underestimated the new maximum.

Limitations of Scope

This study provides a broad and somewhat coarse simulation of available coldwater fish habitat on a national scale. Because of limitations in available data, the selections of stream locations modeled cannot fully represent U.S. streams or the diversity of habitat presently available to each of the modeled species. Further, because of its exclusive focus on maximum weekly average stream temperatures as a determining factor in habitat for cold water species, this study does not consider several other possible direct and indirect mechanisms by which climate change could affect cold water habitat. Implications of these omissions are discussed later in this report.

Data, GCM Output, and Sample Weights

Simulating effects of climate change on habitat for freshwater fish requires data for the upper thermal tolerance of each species, (*i.e.*, each species' tolerance for warm water temperatures), the current geographic range for each species, current water temperatures, and current air temperatures. These data must then be combined with outputs from general circulation models. Furthermore, for a national study such as this one, the sample locations used in the analysis must be weighted appropriately. Sources for the data, GCM output, and sample weights are described below.

Thermal Tolerances: Fish Temperature Data Matching System (FTDMS)

Table 1 lists upper thermal tolerances for each of the eight species of cold water fish included in this study. These values are taken from Eaton and Scheller (1996), who updated and supplemented values from the Fish Temperature Data Matching System (FTDMS) developed by the U.S. EPA (Eaton *et al.,* 1995). FTDMS links the observed presence of each fish species with maximum weekly average water temperatures in streams, based on quality-assured data from 173 stream stations with matching fishery and daily or weekly water temperature records (Hokanson *et al.*, 1995). Upper thermal tolerances in Table 1 represent the estimated 95th percentile of maximum weekly average water temperatures encountered for streams inhabited by each species. The sensitivity of model results to these estimates is examined later.

Geographic Ranges of Habitat: Atlas of North American Fishes and National Audubon Society Field Guide

The Atlas of North American Fishes (Lee *et al.*, 1980) and the *National Audubon Society Field Guide to North American Fishes, Whales and Dolphins* (Boshung *et al.*, 1983) provide maps of habitat ranges for hundreds of species of freshwater fishes, including those in the present study. For cutthroat trout and all four species of salmon, we interpreted maps from the *Atlas* and the *Field Guide* to estimate the geographic ranges for each species at the state level. In general, whenever native or introduced populations were depicted as present in streams within a state, the entire state was assumed inhabitable. We modeled habitat for cutthroat trout as present for suitable sites in Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. Baseline habitat for chum and pink salmon was assumed to be limited to


Photograph provided by Art Today (www.arttoday.com)

California, Oregon and Washington, whereas coho and chinook salmon were also modeled as potentially present in Idaho. Although coho salmon have been extirpated from the Snake River system in Idaho, there are pressures to reintroduce them, so inclusion of Idaho within the baseline distribution for coho salmon seemed justified.

In addition, coho and chinook salmon have been introduced into tributaries of the Great Lakes. Unfortunately, such tributaries are not well represented within the sample of USGS gaging stations available for this study. With the exception of those in Michigan, the majority of available USGS gaging stations within the eight states bordering the Great Lakes (and having suitably cold stream temperatures) are located outside the Lakes' drainage area. It therefore seemed inappropriate to extend the practice of state-level assignments of baseline habitat to this region for these species. Instead, we have modeled coho and chinook salmon using all the sample stations in Michigan, supplemented by those few stations with suitable temperatures that are located on streams that drain to the Great Lakes from each of the other seven bordering states. The sensitivity of modeling results to this decision is examined later.

We used a different method for brook trout, brown trout, and rainbow trout, which have been widely introduced outside their native ranges. We assumed that habitat for these species is limited only by thermal conditions, so that they could be present wherever summer water temperatures are sufficiently low (Eaton and Scheller, 1996).

Baseline Water Temperatures: USGS Daily Values File

This study is based on water temperature data from the U.S. Geological Survey (EarthInfo, 1998a), which include daily minimum, maximum, and average measurements of stream flow and other parameters for 4,649 stations in the contiguous United States. Water temperatures are reported for 2,954 of these locations, covering periods ranging from 1 to 46 years. For stations failing to report daily average

Table 1: Upper Thermal Tolerance by Fish Species

Species	Latin Name	Upper Thermal Tolerance
Brook trout	*Salvelinus fontinalis*	22.4°C (72.3°F)
Cutthroat trout	*Oncorhynchus clarki*	23.3°C (73.9°F)
Rainbow trout	*Oncorhynchus mykiss*	24.0°C (75.2°F)
Brown trout	*Salmo trutta*	24.1°C (75.4°F)
Chum salmon	*Orcorhynchus keta*	19.8°C (67.6°F)
Pink salmon	*Oncorhynchus gorbuscha*	21.0°C (69.8°F)
Coho salmon	*Oncorhynchus kisutch*	23.4°C (74.1°F)
Chinook salmon	*Oncorhynchus tshawytscha*	24.0°C (75.2°F)

Source: Eaton and Scheller (1996).

water temperatures, we began by approximating daily averages as the arithmetic mean of daily minimum and maximum values. Next, we combined these daily values into weekly averages for each week, year, and site. The total quantity of resulting data varied greatly by location, from as little as one average for a single week at some locations to more than 2,100 weekly averages at others; on average, 316 weekly averages were available per site (representing about six years of data).

We screened the data for obvious errors, eliminating implausible data (either at the observation, year, or site level) whenever detected. Whenever a single year of data for a particular site contained more than one rejected value, the entire year was rejected. After these tests, individual sites were tested further and rejected if data were insufficient for reliably determining maximum weekly average water temperatures. Finally, sites were included in the analysis only if three years of record with 52 weeks of satisfactory data were available for regression. Of the original 2,954 sites with water temperature data, 2,335 (79%) passed all tests, with a total of 871,028 pairs of matched air and water temperatures (an average of 373 per site) available for regression analyses. An additional 285 sites were dropped because of unsatisfactory fitting of the logistic function (R^2<0.7), leaving 2,050 sites for inclusion in the model.

Baseline Air Temperatures: Daily Hydroclimatological Data Set

For temporally matched air temperatures near to each sample site, we used the Daily Hydroclimatological Data Set for the Continental United States (Wallis *et al.*, 1990). This source provides daily values for maximum and minimum air temperatures for 41 years at 1,036 locations in the contiguous United States. Wallis *et al.* have checked and cleaned these data, and filled missing values where appropriate with values from nearby stations. One limitation, however, is that their coverage ends with the year 1988. Because more than 15% of available water temperature measurements were for years after 1988, we supplemented the Wallis *et al.* data with National Climatic Data Center (NCDC) air temperature records for the same stations for the years 1989 to 1996 (Earthinfo, 1998b). For data from both sources, we approximated daily average air temperatures as the mean of daily maxima and minima. We then combined the resulting daily values into arithmetic averages for each week.

Gaging stations with adequate water temperature data are concentrated in the eastern U.S., the Rocky Mountain region, and the West Coast. Weather stations in the Wallis *et al.* data set are more evenly distributed, but are also concentrated somewhat in the eastern U.S. (Figure 2). Distances between matched USGS gaging stations and weather stations averaged 23 km (14 miles) for sites used in this study, with a maximum of 122 km (76 miles). Ninety-nine percent of distances were less than 63 km (39 miles); ninety percent were less than 42 km (26 miles). For those stations with available data, elevations of gaging stations averaged 515m (1,690 ft) compared to 482m (1,582 ft.) for weather stations.

Climate Change: Output from General Circulation Models

Output data from three general circulation models (GCMs) were used in this study. The three GCMs were: the CGCM2 model of the Canadian Center for Climate Modelling and Analysis (Flato and Boer, 2001), the CSIRO-Mk2 coupled GCM from the Commonwealth Scientific and Industrial Research Organization of Australia (Gordon and O'Farrell, 1997), and the HadCm3 model of the Hadley Centre for Climate Prediction and Research (HCCPR) of the United Kingdom (Gordon *et al.*, 2000; Hadley Centre, 1998). All data for these GCMs were obtained online from the Data Distribution Center of the Intergovernmental Panel on Climate Change (IPCC, 2002).

These models require assumptions about future emissions of greenhouse gases as well as the formation of anthropogenic sulfate aerosols, which have a cooling effect on climate. In 1996 the IPCC Plenary decided to develop a new set of emissions scenarios to represent the range of driving forces and emissions described in current scenario literature. The resulting 40 emissions scenarios developed by the IPCC describe futures *without* policies for reducing greenhouse gas emissions. They are grouped into families defined by four different narrative storylines (A1, A2, B1 and B2) to describe plausible future courses for the complex mix of demographic, socio-economic, and technological forces that drive emissions. Unlike the preceding set of IPCC emissions scenarios (known as IS92) used in the Second Assessment Report (Leggett *et al.*, 1992), these newer scenarios project eventual decreases in anthropogenic sulfate aerosols over the next century as a result of efforts to reduce air pollution.

According to the Special Report on Emissions Scenarios or "SRES" (Nakicenovic *et al.*, 2000), the A1 storyline describes "a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies." The A2 storyline describes "a very heterogeneous world" in which "the underlying theme is self-reliance and preservation of local identities, and per capita economic growth and technological change are more fragmented and slower than in other storylines." The B1 storyline describes "a convergent world with the same global population as A1 but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies." Finally, the B2 storyline describes a world "with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines."

In 1998, the IPCC Bureau decided to release draft scenarios to climate modelers for their input into the Third Assessment Report: one "marker" scenario was chosen from each of the four scenario groups based on storylines A1, A2, B1 and B2. Model output based on these four marker scenarios is now available through the IPCC Data Distribution Center, and provides the basis for modeling results presented in this report. None of the four marker scenarios is to be considered more likely than the others.

At the time this study was prepared, results based on SRES emissions scenarios A2 and B2 were obtainable through the IPCC Data Distribution Center (IPCC, 2002) for all three GCMs, but results for A1 and B1 were provided for CSIRO-Mk2 only. We used results from all eight available combinations of GCM and draft marker emissions scenario. Figure 3 summarizes predicted increases in surface air temperatures, averaged over all grid cells for each combination. These 10-year moving averages show the amount of warming each model predicts over the entire earth relative to a "baseline" period centered on the year 2000. For the first half of this century, projections of warming are more sensitive to choice of GCM than to choice of emissions scenario. For the second half, projected warming is more sensitive to emissions scenario.

The suitability of habitat for cold water fish in the U.S. is most sensitive to summer temperatures, which drive the maximum weekly average water temperatures we compare to each species' thermal tolerance. Figure 4 describes projected warming of June, July, and August air temperatures for the rectangle of each model's grid cells covering the lower 48 states. As with global averages, predicted warming based on A2 and A1 scenarios typically exceeds that based on B2 and B1 in the latter half of this century, but warming is less sensitive to choice of emissions scenario in the earlier years. Of the three GCMs tested, HadCM3 predicts the greatest warming of summer temperatures for the U.S., culminating in increases as high as 5.6°C (10.0°F) for July temperatures by the year 2090. This result is notable because the same model predicts the least warming of yearly global average temperatures for the same period.

Figure 2: Location of Weather and Stream Stations

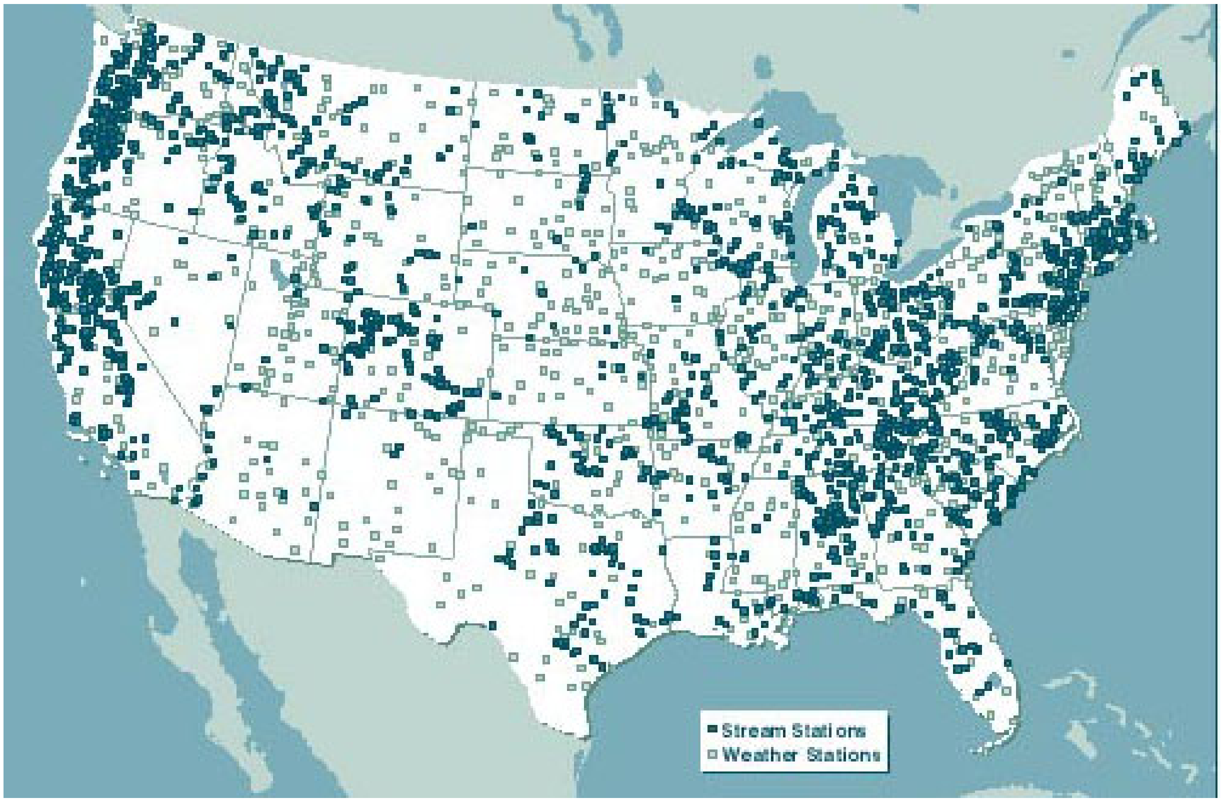


Figure 3: Average Global Warming by GCM and Emissions Scenario

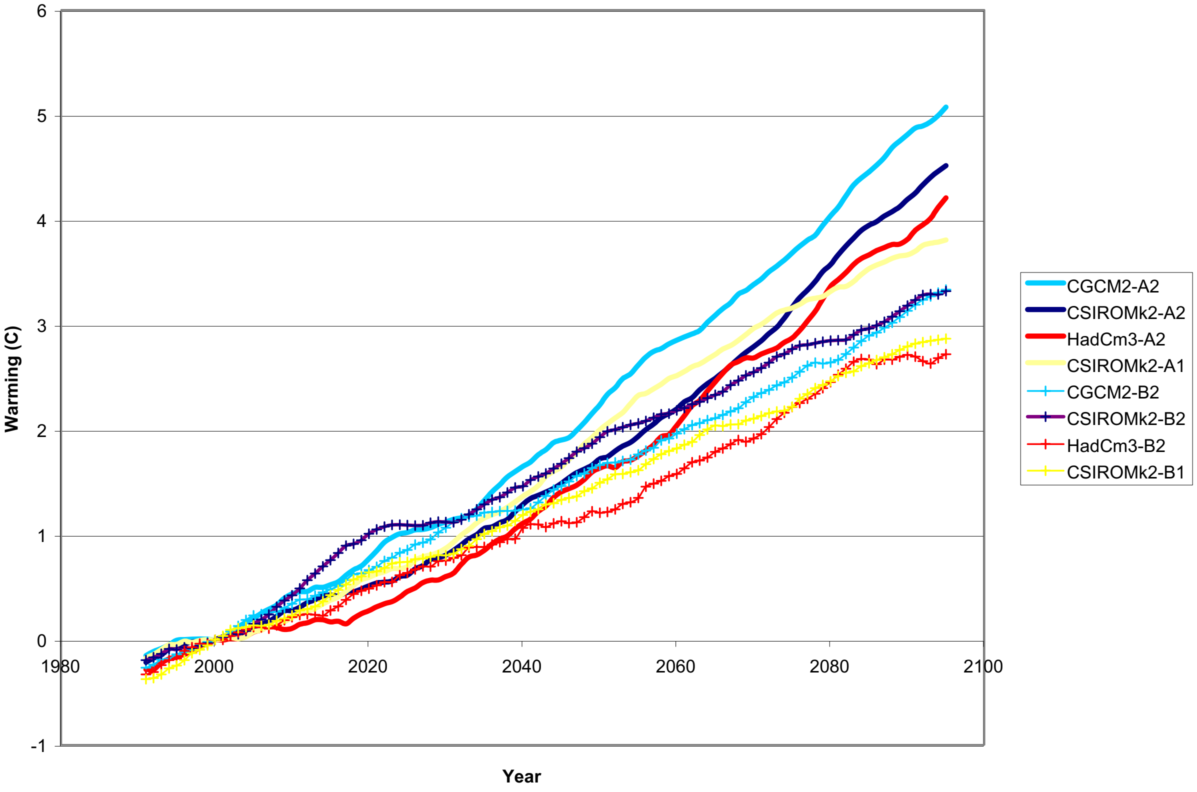
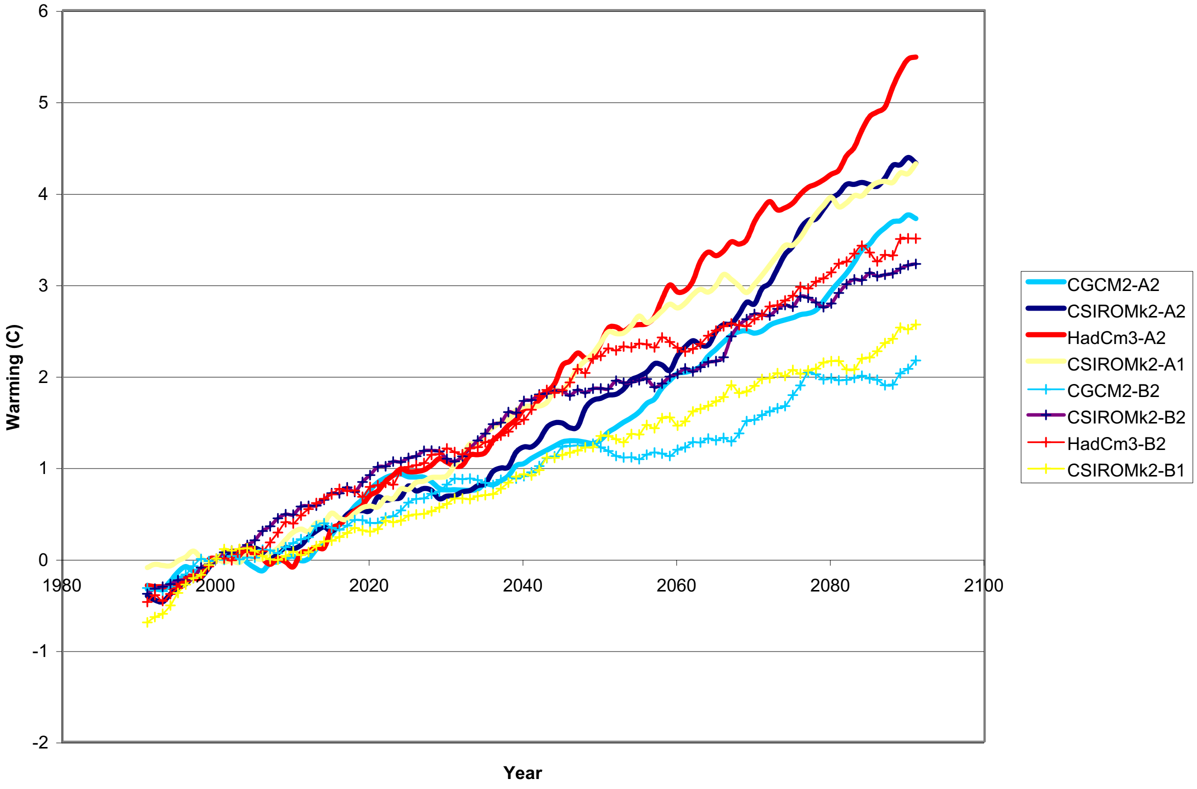


Figure 4: Average Summer Warming in the U.S. by GCM and Emissions Scenario



Because the distribution of predicted increases in air temperatures at the regional level differs substantially among different GCMs and emissions scenarios (all to be considered equally plausible), no single model or scenario can definitively predict regional patterns of warming and hence effects on fish habitat. For this reason, we have reported results based on multiple models and emissions scenarios. For each combination of GCM and emissions scenario, we averaged monthly temperatures projected for each grid cell over the years 1986-2015, 2016-2045, 2046-2075, and 2080-2099[4] to represent projected surface air temperatures for the years 2000, 2030, 2060 and 2090, respectively[5]. We then subtracted the averages calculated for 2000 from the averages for each of the three later periods to calculate the increase in monthly averaged air temperatures projected to occur between 2000 and the years 2030, 2060 and 2090.

Sample Weights: River Miles Per State

Sample sites used for this study were chosen solely on the basis of the quality and quantity of their reported water temperature data. Unfortunately, the sites are not distributed among states in proportion to each states' share of existing rivers or streams. To compensate for this imbalance, we computed sample weights as the ratio of the total number of river miles reported for each state (U.S. EPA, 2000) to the number of sample sites within that state. All estimates of national-level effects in this report have been computed using these weights.

Although this practice of state-level weighting is intended to compensate for the disproportionate distribution of USGS gaging stations among states, it does not address the extent to which sampled stream reaches might fail to represent the distribution of stream sizes or elevations within individual states or the U.S. generally. Nor does it address the fact that larger streams can offer more potential habitat space per unit length than smaller streams (and would thus deserve greater weighting for estimates of total available habitat). Because of these limitations, numerical results presented in this report should not be interpreted as literally reflecting either "stream miles", or "total habitat." Throughout this report, we use the term "stations" to refer to counts or percentages of USGS gaging stations within our sample, and "locations" to refer to aggregated, multi-state counts of stations that have been weighted by each state's contribution to total U.S. stream miles. Despite the limitations of these measures, we feel they provide a reasonable index of fish distributions and potential effects of climate change.

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[4] All GCM integrations used in this study end in the year 2099 or 2100, requiring a shorter averaging period to represent 2090.

[5] The use of 30-year or 20-year averaging periods reduces the influence of higher frequency "noise" (*i.e.*, year-to-year or short-term variability) inherent in monthly GCM output.

Results

Maximum Weekly Average Water Temperatures for Baseline

Current maximum weekly average water temperatures for sample stations in this study range from 9.6-39.9°C (49-104°F), with a mean of 25.8°C (78°F) and a median of 26.4°C (80°F). On average, coldest streams are found in Colorado, Idaho, Montana and Washington; warmest are found in Louisiana, Mississippi, Oklahoma, and Texas (Figure 5). We estimate that 34% of locations in the U.S. (represented by 791 out of 2,050, or 39% of sample stations) have maximum weekly average temperatures sufficiently cold to support at least one of the species of cold water fish considered in this study. Only 17% of locations are cold enough to support all eight species.

Baseline Habitat

Table 2 shows the number of sample sites (and the corresponding weighted percentage of national locations) modeled as currently providing suitable habitat for each of the eight fish species in this study. Brown trout are assigned the highest thermal tolerance, and are not assumed to be restricted by geographical limits. They are therefore modeled as present at any site for which habitat is suitable for any of the trout or salmon species in this study. Conversely, if waters warm beyond the upper thermal tolerance for brown trout, none of the eight species is modeled as remaining.

As mentioned earlier, baseline habitat for chum and pink salmon is assumed to be limited to California, Oregon, and Washington, whereas coho and chinook salmon are assumed present in those states, as well as Idaho, Michigan, and selected streams in the Great Lakes' drainage. These constraints, together with the lower value of upper thermal tolerances assigned to chum and pink salmon, restrict their available habitat to about 25-45% of that of the other two salmon species.

Photograph provided by Art Today (www.arttoday.com)

Relationship between Air and Water Temperatures

Our examination of air and water temperature data for U.S. streams confirms the observation by Mohseni *et al.* (1998) that the relationship is best characterized as non-linear, with a diminishing response typically observed at higher air temperatures. For example, we found that *B* coefficients of linear regression relationships (Equation 1) fit to the upper 30 percent of each site's air temperatures were on average 22% lower than those fit to the entire ice-free data set; coefficients fit to the highest 20% were 29% lower, and those fit to the highest 10% were 38% lower. Similarly, slopes calculated for Equation (2) at the maximum weekly average air temperature for each site were on average 34% lower than linear regression coefficients obtained for each site's combined data.

Statistics for our estimates of model parameters α, β, γ, and μ are listed in Table 3. We detected hysteresis at 51% of the sites evaluated. Separately modeling the rising and falling limbs of the annual temperature cycle improved the coefficient of determination (R^2) by an average of 0.05 for affected streams. An improvement of more than 0.10 was achieved for 105 streams. For example, fitting Equation (2) to all available data for USGS station number 12473520 near Richland, Washington yields an R^2 of only 0.72, whereas the combined R^2 for the rising and falling limbs fitted with separate functions is 0.95 (Figure 6).

Following the example of Mohseni *et al.* (1998), we considered the model specification unsuccessful for those 285 sites with final R^2 values lower than 0.7, and excluded those sites from the modeling of fish habitat. R^2 values for the remaining 2,050 sites averaged 0.92, with a median of 0.94 and standard deviation of 0.05. Regression for 90% of

Table 2: Baseline Suitability of Habitat for Trout and Salmon

Species	Number of Sample Sites	Weighted Percent of National Locations
Brook trout [1]	574	24%
Cutthroat trout [2]	514	22%
Rainbow trout [1]	782	33%
Brown trout [1]	791	34%
Chum salmon [3]	151	3%
Pink salmon [3]	207	5%
Coho salmon [4]	389	11%
Chinook salmon [4]	424	12%
Any coldwater	791	34%

[1] Habitat restricted by thermal tolerance only.
[2] Habitat restricted to Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Washington.
[3] Habitat restricted to California, Oregon, and Washington.
[4] Habitat restricted to California, Idaho, Oregon, Washington, Michigan, and selected sites in Great Lakes drainage.

Figure 5: Present Maximum Weekly Average Water Temperature

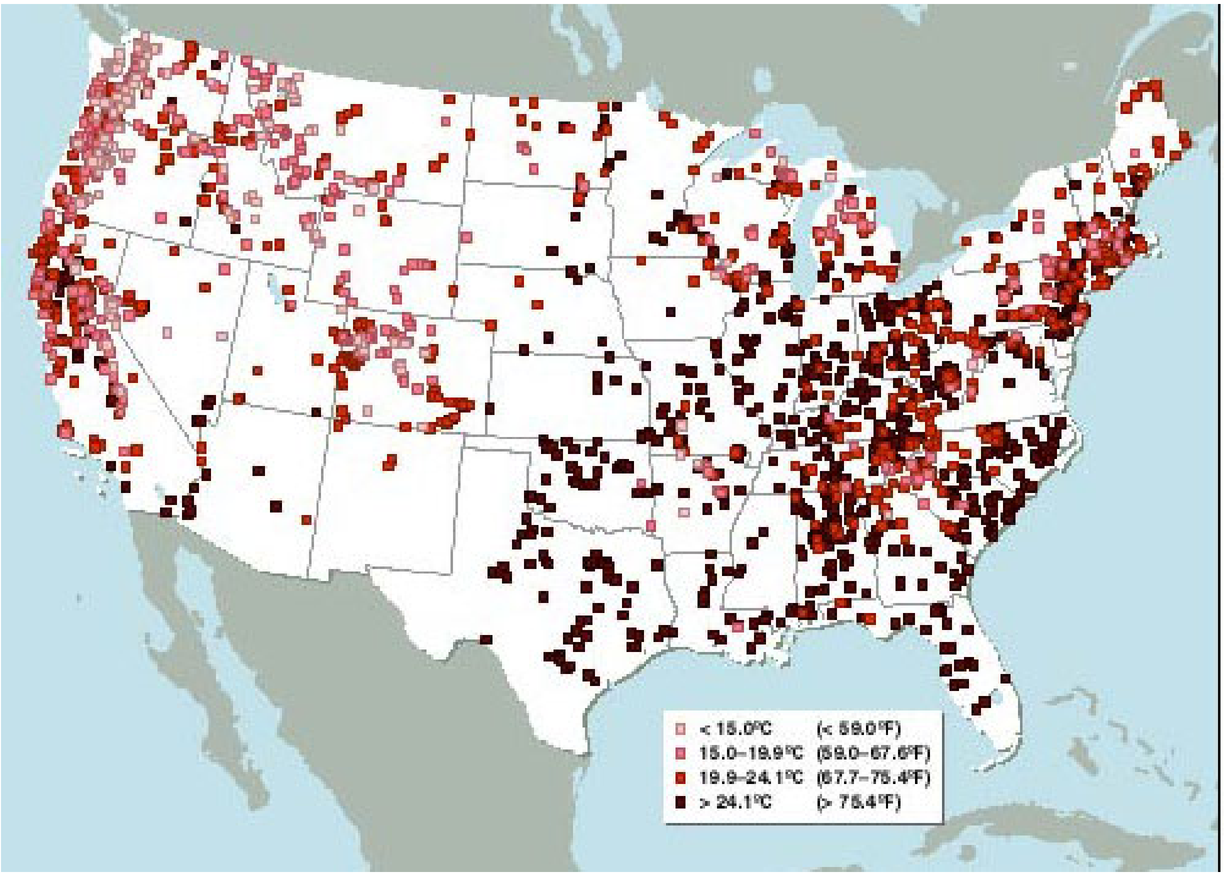


Table 3: Statistics of Model Parameters for the Logistic Model

	α	β	γ	μ
Mean	28.2°C (82.8°F)	14.2°C (57.6°F)	0.20°C^{-1} (0.11°F^{-1})	1.5°C (34.7°F)
Median	27.3°C (81.1°F)	13.6°C (56.5°F)	0.17°C^{-1} (0.09°F^{-1})	0°C^{-1} (32.0°F)
Standard deviation	9.6°C (17.3°F)	4.0°C (7.2°F)	0.57°C^{-1} [a] (0.32°F^{-1})	2.5°C (4.5°F)
Standard error	2.0°C (3.6°F)	1.1°C (2.0°F)	0.022°C (0.012°F)	0.62°C (1.1°F)

[a] Excluding the single outlier estimate of 25.1°C^{-1}, the standard deviation for γ is 0.14°C^{-1}.

Figure 6: Air and Water Temperatures for Site 12473520

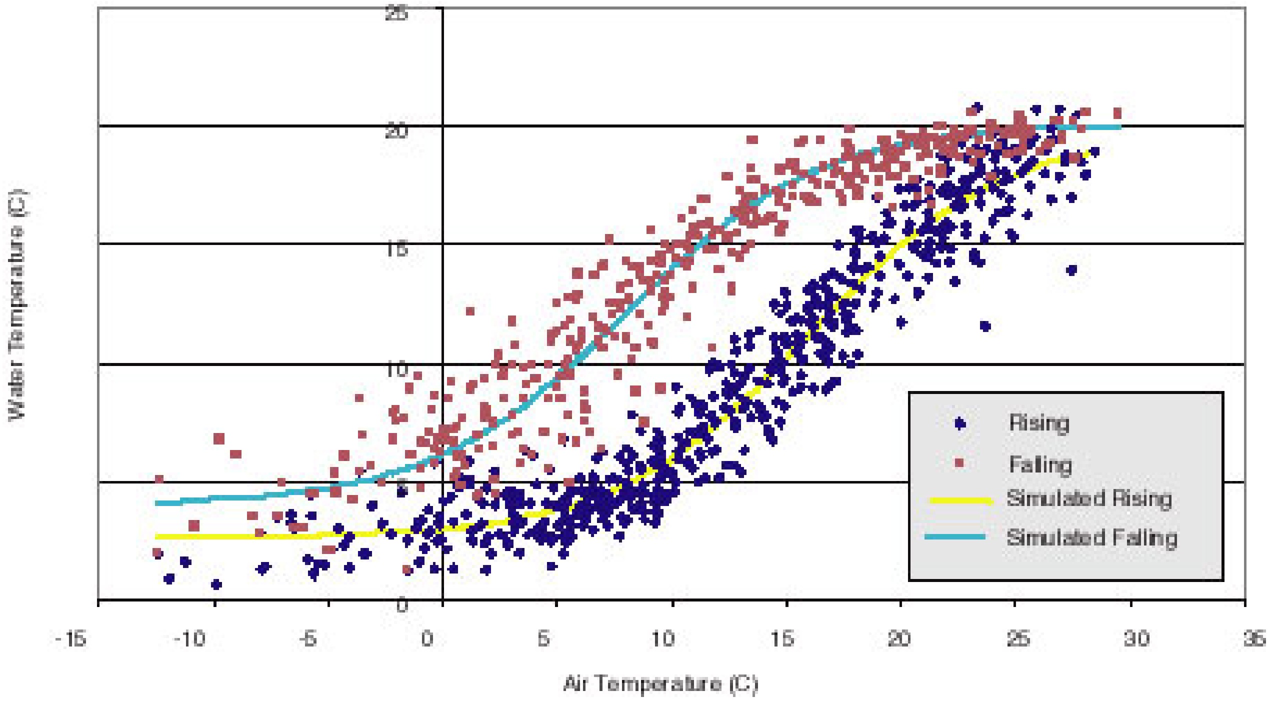
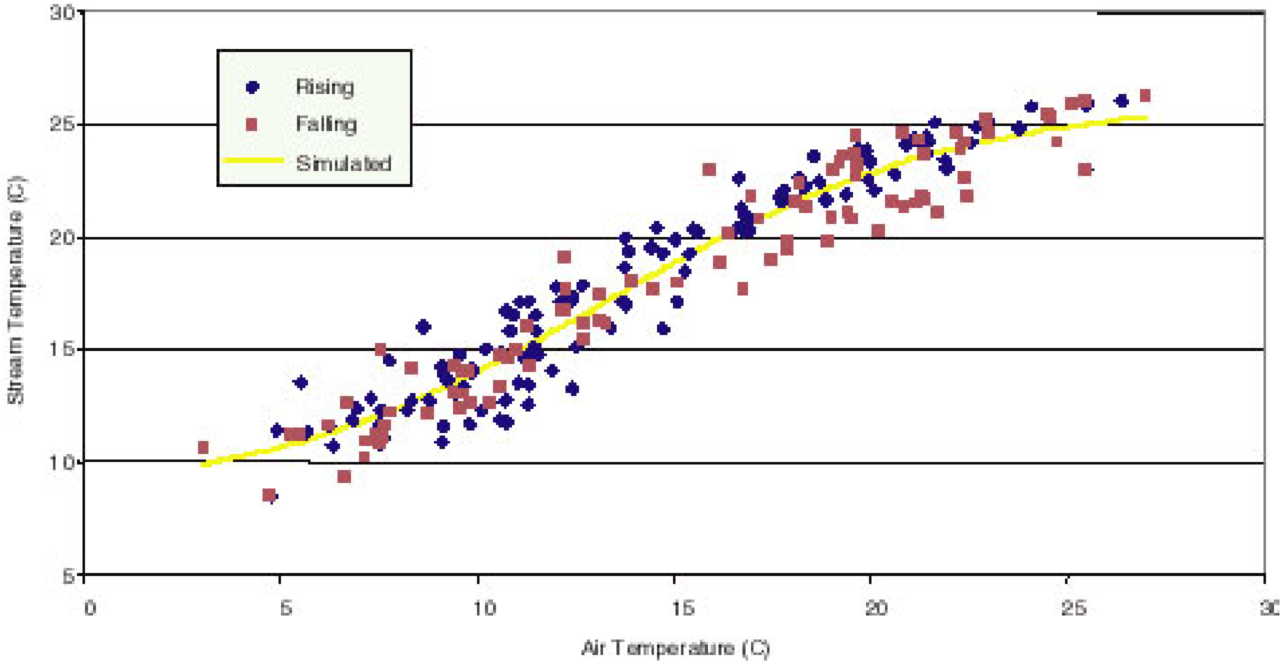


Figure 7: Air and Water Temperatures for Site 11176350



those sites yielded R^2 values higher than 0.85. Figure 7 depicts air and water temperatures for USGS station number 11176350 near Pleasanton, CA, a typical site (R^2=0.92) without detected hysteresis.

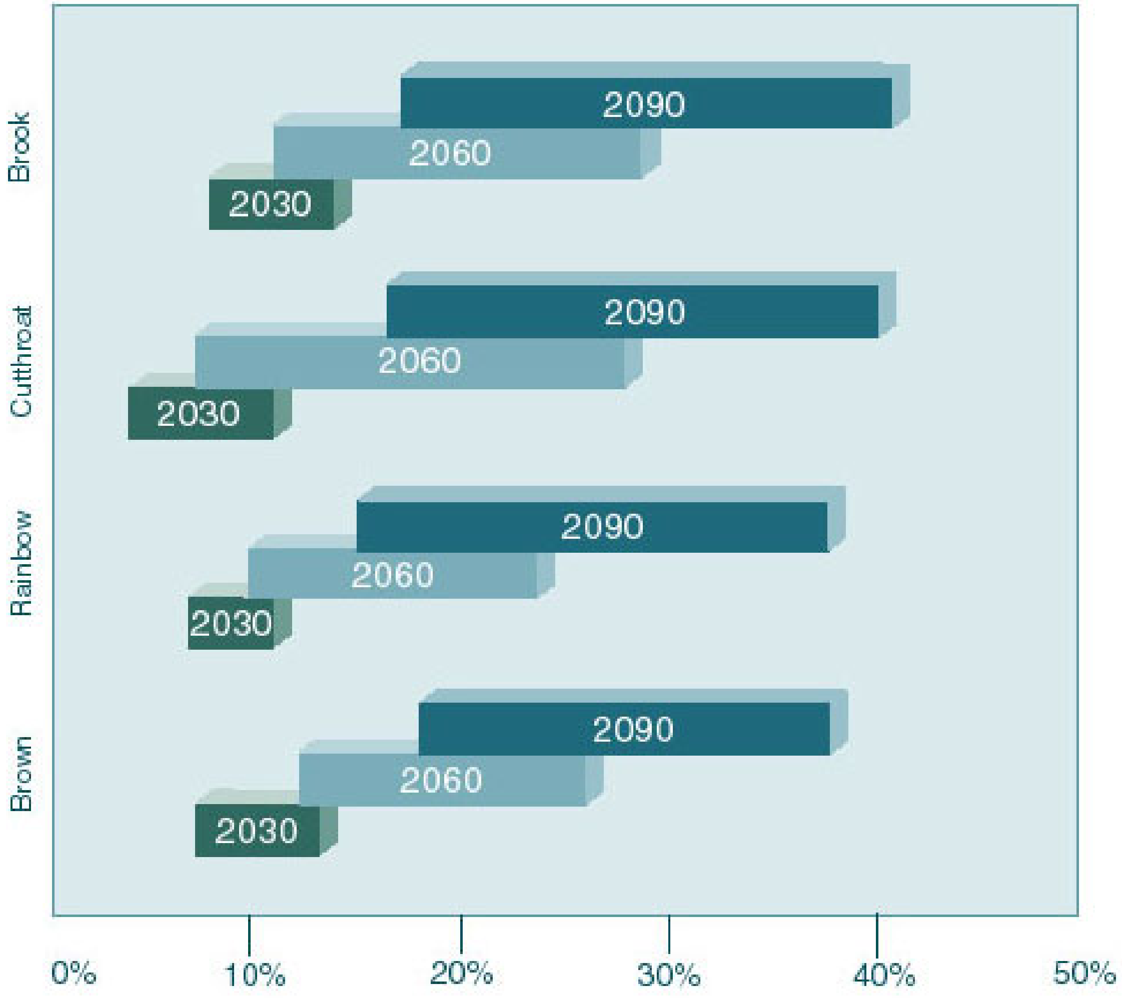
The goodness of fit for these regression relationships was surprisingly independent of the distance between the stream gaging station and the weather station used to provide matched air temperatures. Compared to an average R^2 of 0.92 for all sites, those sites more than 40 or 60 km (25 or 37 miles) from their matched weather station yielded average R^2 values of 0.92 and 0.93, respectively. For the site with the greatest distance to a matched weather station (a Michigan station with a distance of 122 km or 62 miles) the R^2 was 0.91. Similarly, differences in elevation between weather and gaging stations showed no appreciable effect on the goodness of fit of regression relationships.

Effect of Climate Change on Average Air and Water Temperatures

Depending on the GCM and emissions scenario selected, average summer air temperatures at sample locations are projected to increase by 0.9-1.5°C (1.6-2.7°F) for 2030, 1.4-3.7°C (2.5-6.7°F) for 2060, and 2.5-6.2°C (4.5-11°F) for 2090. These values are higher than estimates of globally-averaged warming predicted by these same models for the same time periods, consistent with the expectation that warming will be greater over land and at higher latitudes (Cubasch *et al.*, 2001).

As expected, simulated maximum weekly average stream temperatures increase less, rising on average 0.4-0.8°C (0.7-1.4°F), 0.7-1.8°C (1.3-3.2°F), and 1.2-2.7°C (2.2-4.9°F) by the year 2030, 2060, and 2090, respectively. Not only do water temperatures change, but the timing of the

Figure 8: Locations Losing Suitable Habitat for Trout



summer maximum also changes in some cases. By 2090, the week in which maximum water temperature occurs is projected to change at 29-48% of sample sites, becoming earlier at 15-27% of sites and later at 12-23% of sites. The week of maximum temperature changes by more than four weeks at 6-16% of sites. Advances and delays of the maximum's timing occur with approximately equal frequency, yielding average changes across all sites and emissions scenarios of about +0.6, -0.8, and –2 days for the CGCM2, HadCM3, and CSIRO-Mk2 models, respectively.

Changes in Available Habitat for Trout and Salmon Species

The three GCMs and four emissions scenarios generate a range of expected losses of locations with suitable habitat for each trout and salmon species (Figures 8 and 9), where losses are calculated as the change in the weighted number of stations at which habitat is suitable after climate change, divided by the weighted number of stations at which it is suitable under baseline conditions. Losses are comparable across all species, but appear slightly higher on average for pink salmon. Greatest losses are projected in most cases by the Hadley HadCM3 model, based on the B2 emissions scenario for 2030, and on the A2 scenario for 2060 and 2090. Least losses are predicted for all three periods by the CGCM2 model with the B2 emissions scenario.

For the A1 and A2 emissions scenarios, individual species of trout and salmon could lose 5-17%, 14-34%, and 21-42% of locations with available habitat by 2030, 2060, and 2090, respectively. For the B1 and B2 emissions scenarios (which assume lower emissions for reasons independent of climate change policy) the corresponding estimates are reduced to 4-20%, 7-31%, and 14-34%. For additional detail, the interested reader is referred to Appendix Tables A1-A3.

Figures 10 and 11 show the number of trout or salmon species for which habitat is modeled as suitable at each site providing cold water habitat under baseline conditions. Sites

Figure 9: Locations Losing Suitable Habitat for Salmon

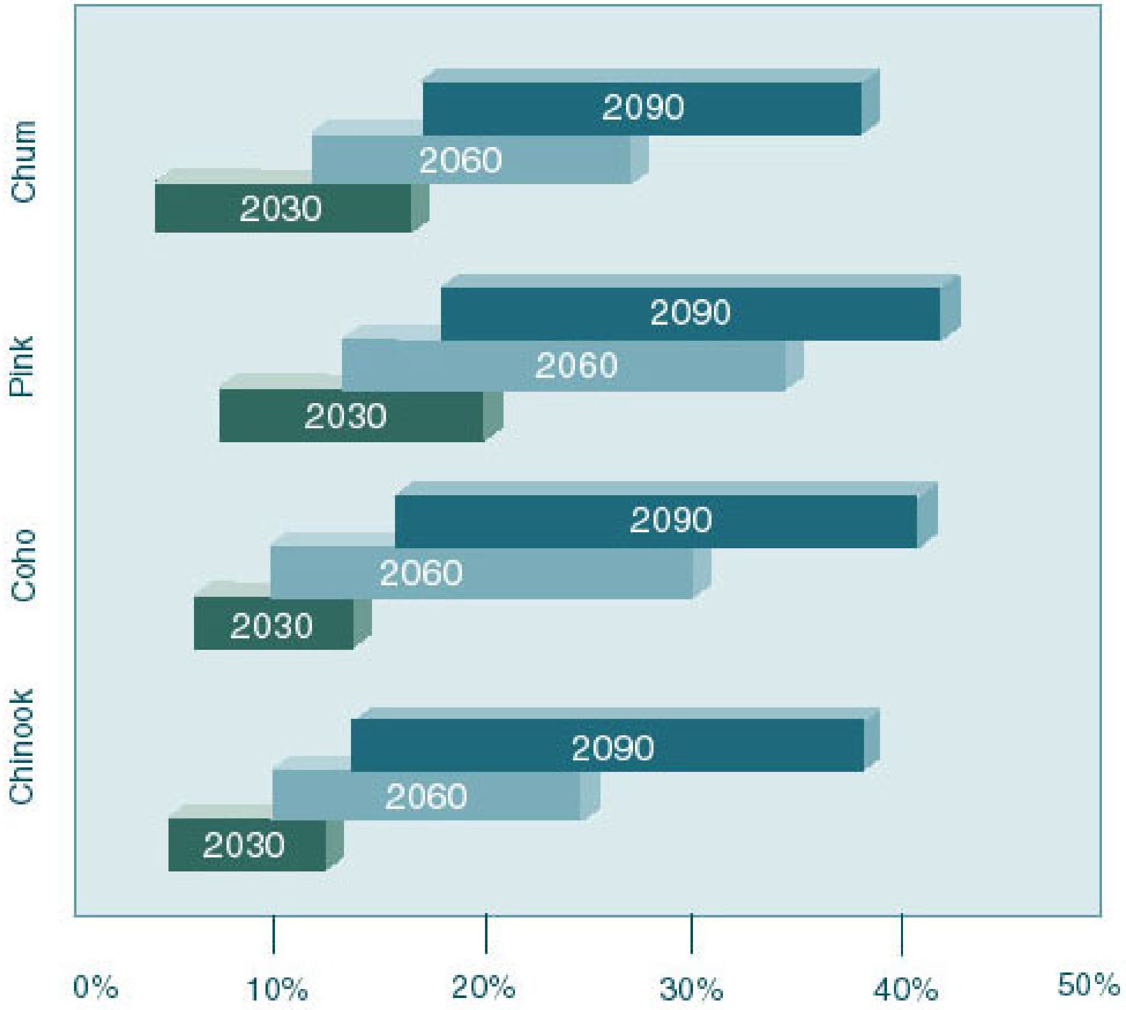


Figure 10: Modeled Suitability of Habitat for Trout Species (Baseline)

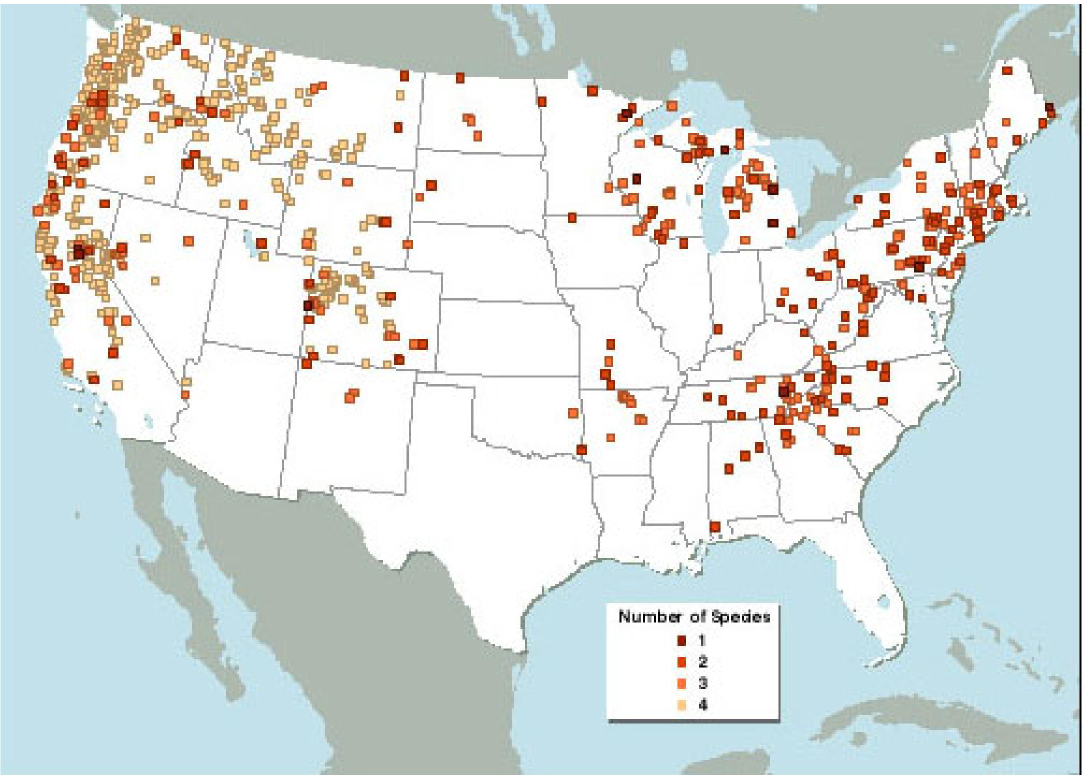
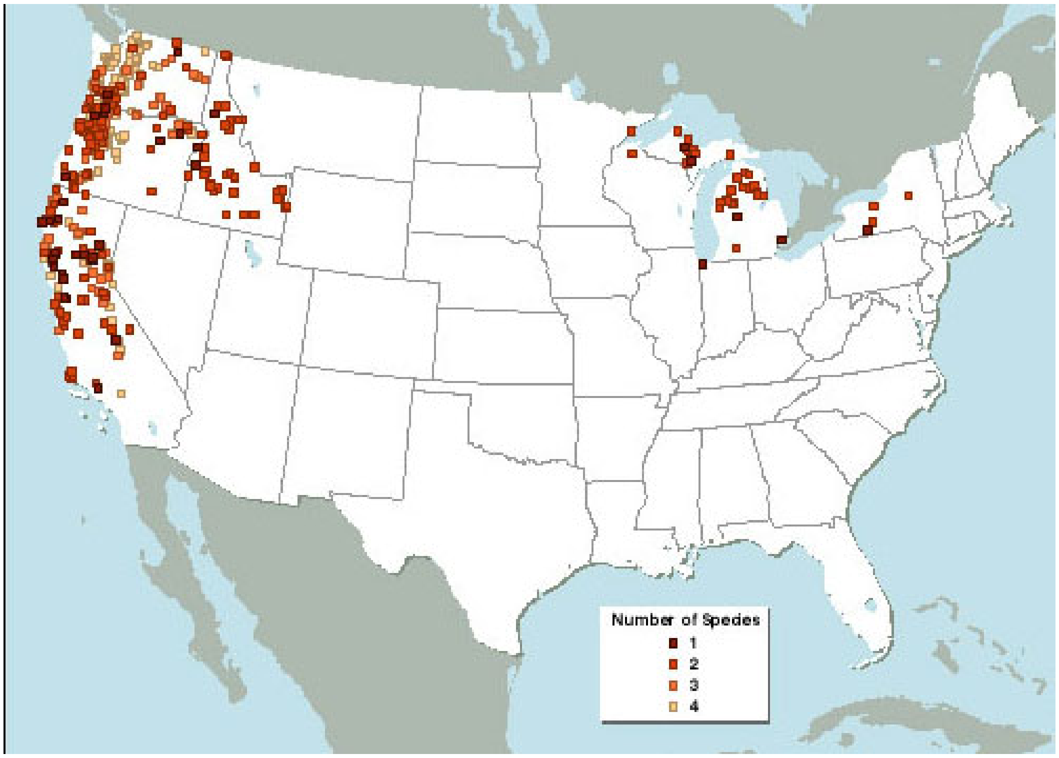


Figure 11: Modeled Suitability of Habitat for Salmon Species (Baseline)



too warm to support any trout or salmon species are not included in these figures. At some sites, warming could result in the elimination of available habitat for *all* the species modeled in this study (Figure 12). Choice of GCM and choice of emissions scenario are of roughly the same importance in determining these results, at least within the range of selections available for this study (Figures 13 and 14). By the year 2090, as many as 25-38% of locations (for emissions scenarios A1 and A2)[6], or as many as 18-28% of locations (for scenarios B1 and B2) could become unsuitable for all cold water species. Because the denominator for these percentage losses is the total, weighted number of locations providing suitable baseline habitat for at least one species of trout or salmon, results can be higher or lower than projected percentage losses for individual species.

Changes in the Geographic Distribution of Habitat

By simulating changes in water temperatures at sample locations across the U.S., one can examine the geographic variation of changes in habitat for each species. Figures 15 and 16, for example, show sites becoming unsuitable for all trout or salmon species, based on results from the Canadian Climate Center's CGCM2 model with the A2 emissions scenario. Losses of habitat occur in warmer streams throughout these species' ranges, but the extent of losses differs by region. Unfortunately, the usefulness of such regional findings is limited by the lack of reliability in GCM projections at spatial scales close to their grid spacing and by the uneven spacing of USGS gaging stations among states. In fact, there is relatively poor agreement among GCMs at resolutions as large as multi-state regions within the U.S. Even the same GCM can predict different geographic distributions of warming depending on the emissions scenario used.

Still, despite inconsistencies among model predictions, certain regions appear more vulnerable than others when results from all three GCMs and four emissions scenarios are considered together. Sites in the southern and southwestern states appear most vulnerable to losing all existing species of trout; Great Lakes and northwestern states appear least vulnerable (Figure 17)[7]. Additional detail is provided in Appendix Table A4.

For salmon, California and Oregon appear likely to have the highest percentage of sites losing suitable habitat for all species, with lesser losses projected for Washington, Idaho, and the Great Lakes region (Figure 18).

Sensitivity Analysis

Results presented thus far in this report are based on numerous modeling assumptions and parameter estimates. Of interest is the question of how these results might change if the model were specified differently or other plausible values were used for key input parameters. To answer this question we performed four types of sensitivity tests at the national level in which we varied key modeling specifications, methods, and parameter estimates to determine their importance to model results (Table 4).

First, we used estimates of the standard errors for upper thermal tolerances (Eaton *et al.*, 1995) to test how model results might be sensitive to statistical uncertainty inherent in these parameter values. Higher thermal tolerances increase the percent of baseline locations suitable for cold water fish from 34% to 40%, but they either slightly increase or slightly decrease effects of climate change relative to estimates based on the original tolerances, depending on the time period, GCM, emissions scenario, and whether or not the additional sites incorporated into the baseline become unsuitable for cold water fish. Lower thermal tolerances reduce suitable baseline habitat to only 29% of locations, but slightly decrease percentage changes caused by climate change.

Second, we tested the sensitivity of model results to uncertainty in estimates of α, β, γ, and μ, and to other parts of our regression analysis. Estimates for these parameters were derived independently for each of the 2,050 sites in our sample. Under the extreme test hypothesis that the true value for each of these independent estimates might be either above or below its 95% confidence interval, we added or subtracted two standard errors for each parameter estimate. We also tested the sensitivity of model results to our decision to exclude all sites for which the R^2 of logistic regression was lower than 0.7, and to our separate treatment of the spring and fall limbs of data for streams with detected hysteresis.

[6] For emissions scenarios A1 and B1, estimated changes to air temperatures were available for the CSIRO-Mk2 model only. For this reason, the corresponding bars in Figure 14 represent single values and are without width.

[7] "South" is defined to include Alabama, Arkansas, Florida, Kansas, Kentucky, Georgia, Louisiana, Mississippi, Nebraska, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, Virginia, and West Virginia. "Northeast" includes Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. "Great Lakes" includes Indiana, Illinois, Iowa, Michigan, Minnesota, Missouri, Ohio,, and Wisconsin. "Southwest" includes Arizona, Colorado, California, Nevada, New Mexico, and Utah. "Northwest" includes Idaho, Montana, North Dakota, Oregon, South Dakota, Washington, and Wyoming.

Figure 12: Locations Losing All Suitable Habitat for Trout and Salmon

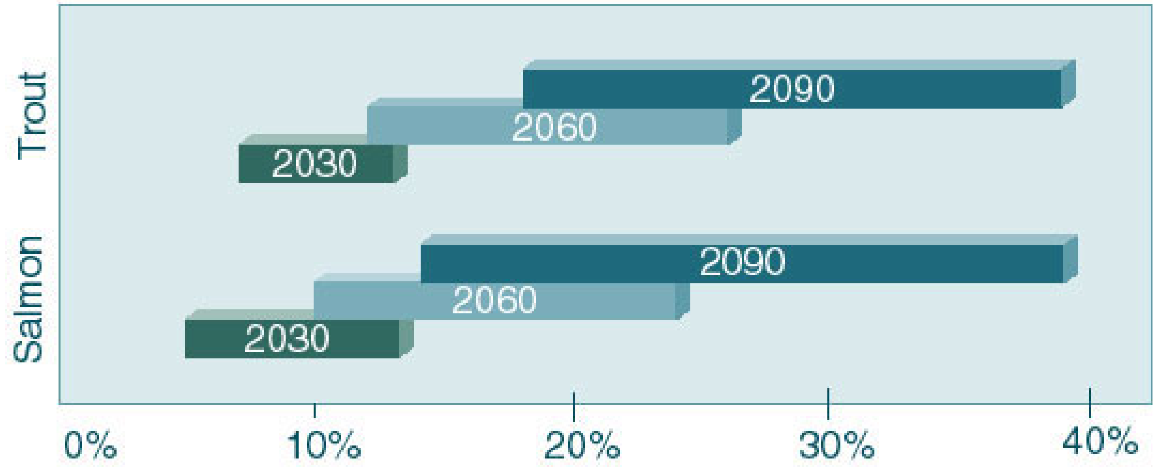
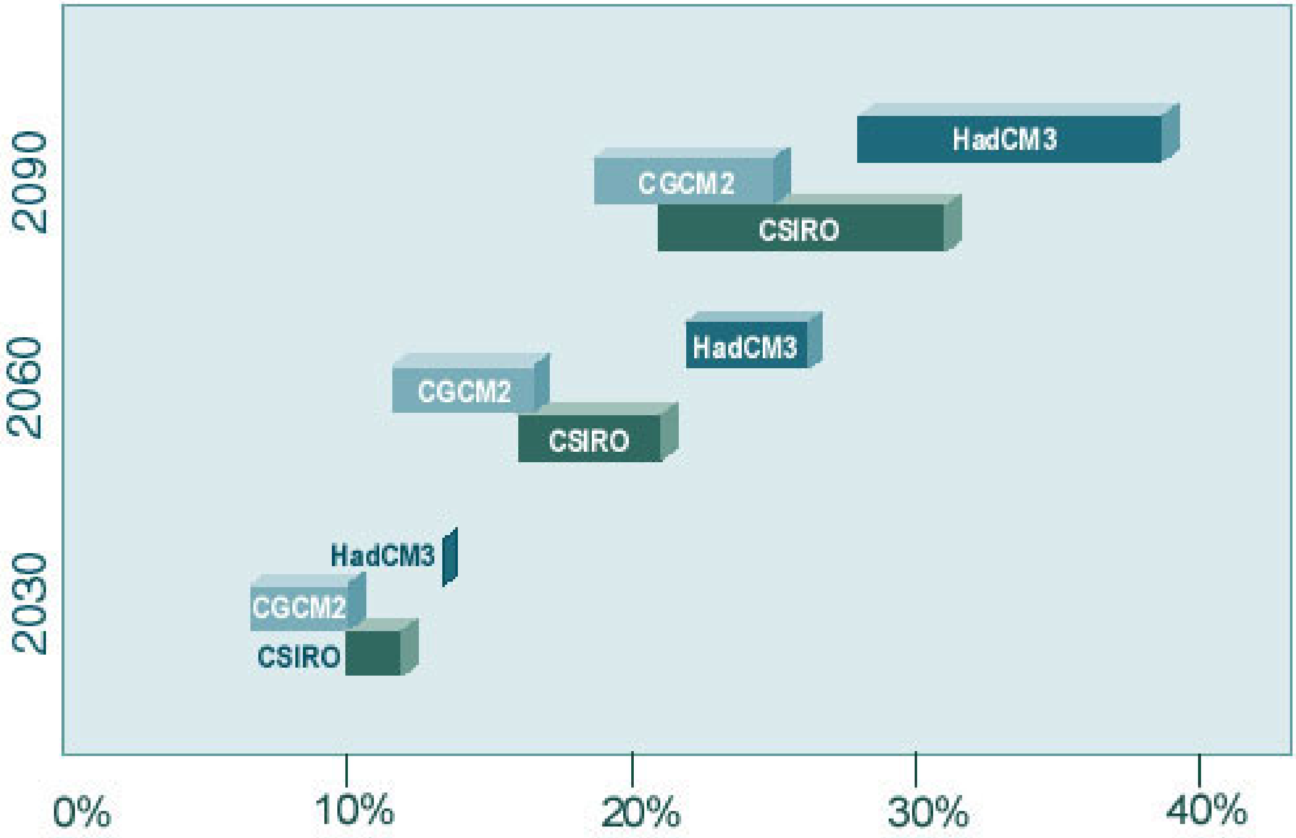


Figure 13: Locations Losing All Cold Water Habitat by General Circulation Model



Photograph provided by Art Today (www.arttoday.com)

Figure 14: Locations Losing All Cold Water Habitat by Emissions Scenario

Figure 15: Future Status of Trout Habitat (CGCM2 Model with A2 Emisisons)

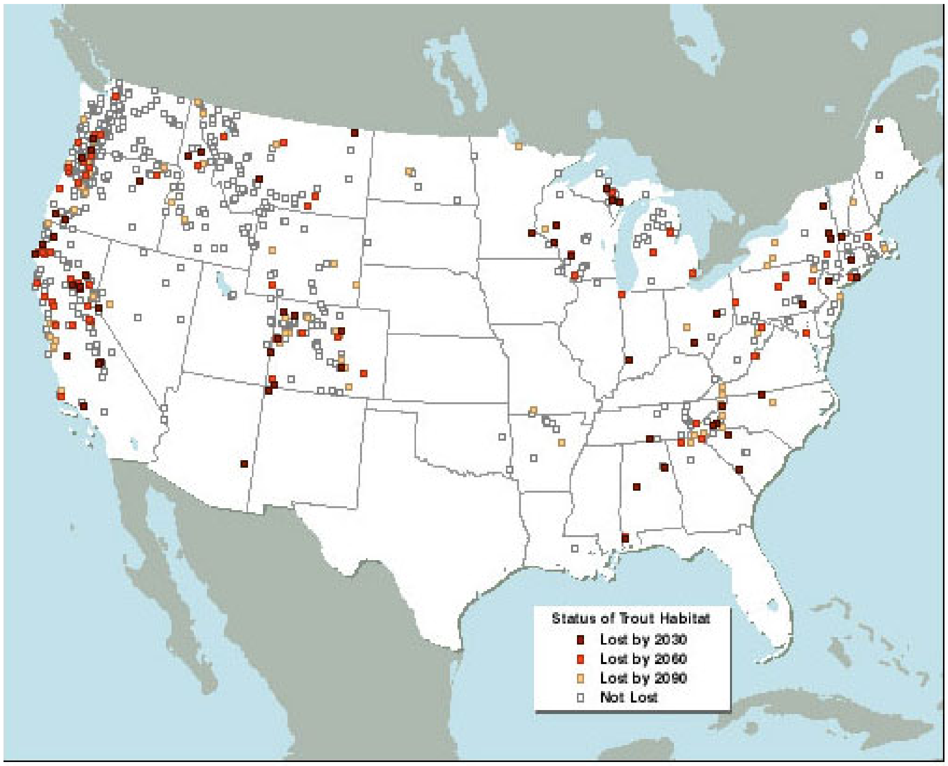


Figure 16: Future Status of Salmon Habitat (CGCM2 Model with A2 Emisisons)

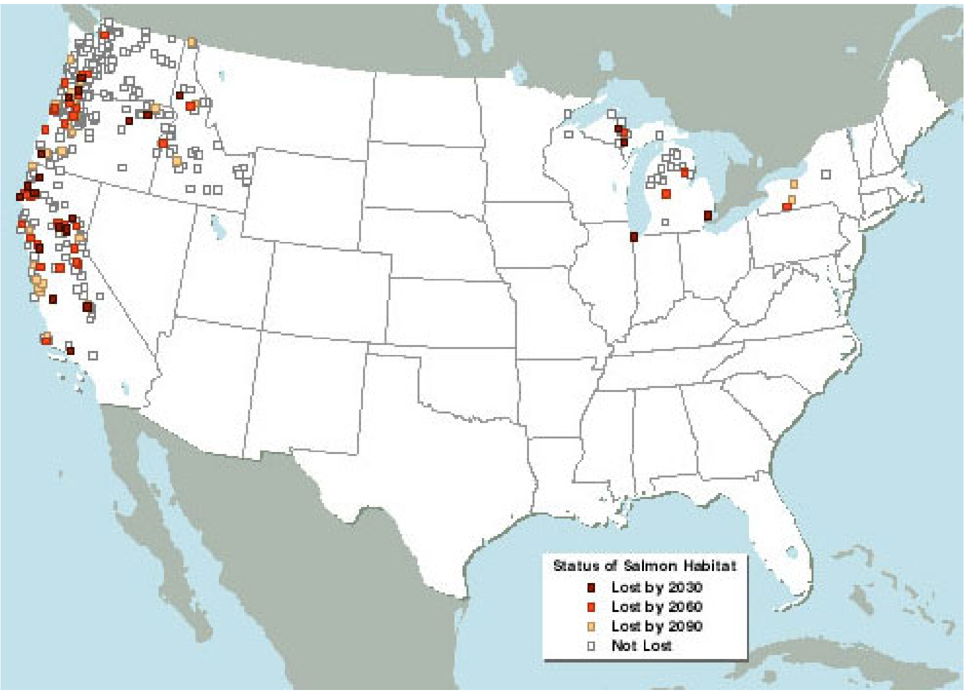


Figure 17: Locations Losing All Trout Habitat by Region

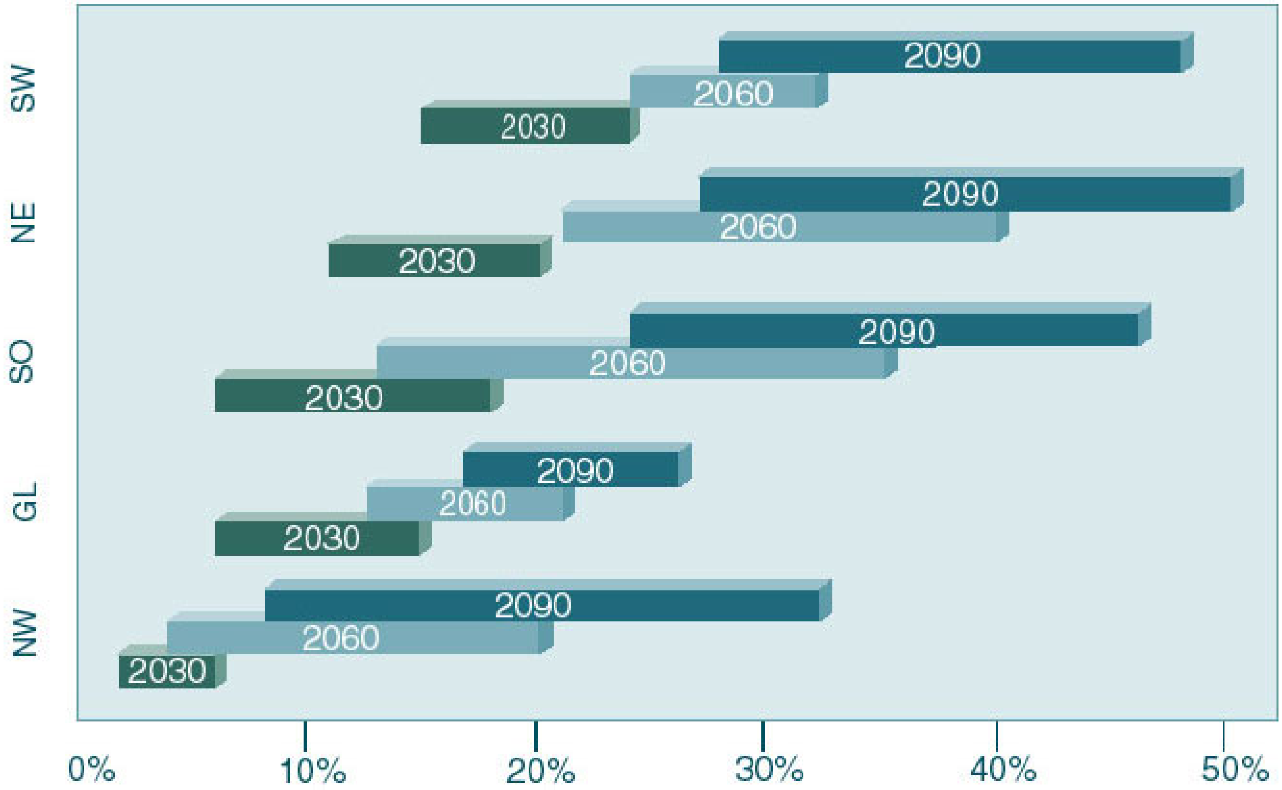
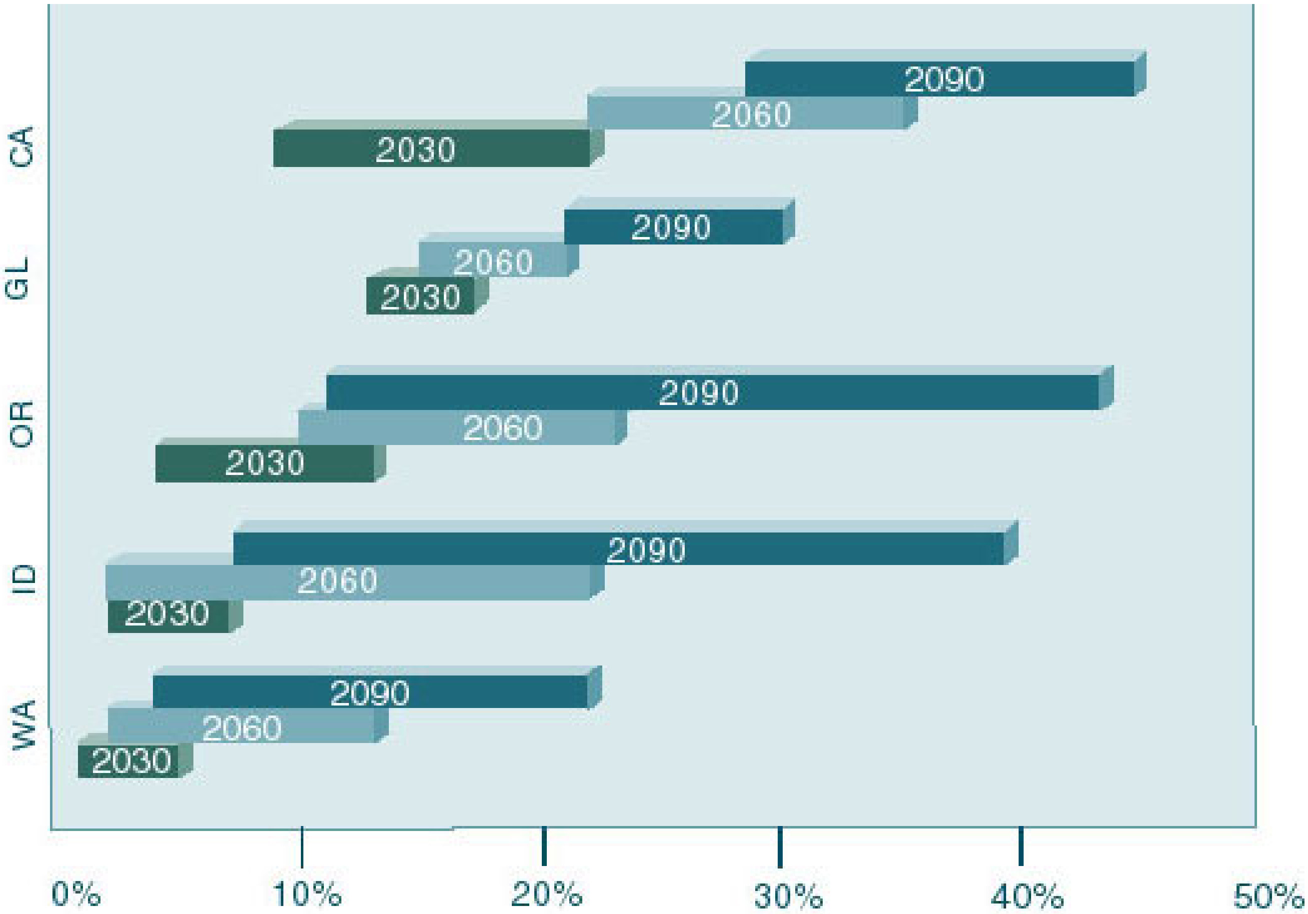


Figure 18: Locations Losing All Salmon Habitat by State or Region



Results were somewhat sensitive to parameter estimates for α, β, but showed little sensitivity to changes in γ, and μ, to the exclusion of sites for which $R^2<0.7$, or to special treatment for streams with hysteresis.

A third test concerned the use of maximum values obtained from water temperature series of different lengths. For some sites, the maximum weekly average for a particular calendar week (and consequently for the maximum over all weeks) was determined from as few as three years of recorded temperatures. For others, as many as 47 years were available. Out of concern that (1) maximum weekly average values determined for these longer series might be systematically higher than those obtained from shorter series, and (2) the maximum of up to 47 weekly averages might be too extreme a value for comparison to upper thermal tolerances, we performed a test in which we defined the "maximum" as the 75th percentile of weekly averages for each calendar week (corresponding to the maximum from a sample of three), regardless of the number of years of data available. Use of these lower baseline maximum temperatures raises estimates for the number of locations with suitable baseline habitat for all eight species, but has little effect on the estimated percentage of such locations lost because of climate change. In general, these first three groups of tests showed the logistic model to be relatively insensitive to all the tests we performed. Greatest sensitivity was observed in tests for the parameters α and β.

Fourth, we tested how results might differ if instead they had been estimated with a linear model (Equation 1) for the relationship between air and water temperatures. As expected, use of a linear model produced higher estimates of expected losses. Interestingly, the linear model's results closely resemble those of the logistic model if regressions are restricted for each site to the upper range of observed temperatures (close to where the maximum weekly average occurs, and therefore most appropriate for predicting maximum temperatures).

In addition, we tested the sensitivity of regional and national results for coho and chinook salmon to our methods of modeling habitat for these species in the Great Lakes region. As discussed earlier, the scarcity of appropriate USGS gaging stations presents a challenge for modeling habitat for these two species in the Great Lakes region. As an alternative to the method chosen for this study, we extended the baseline distribution of coho and chinook salmon to include all sites with appropriate temperatures within the eight states bordering the Great Lakes. With this method (which is more consistent with the state-level assignments we used for chum salmon, pink salmon, and cutthroat trout), the percentage of modeled locations projected to lose all existing salmon habitat by 2090 changed to 22-32% for the Great Lake region, and to 16-39% nationally, compared to the respective "best estimates" of 21-30% and 14-38%. Without inclusion of Great Lakes fisheries for coho and chinook salmon, estimated national losses would be 14-39%. These tests suggest that our results are insensitive to modeling limitations imposed by the shortage of available data within the Great Lakes drainage area.

Based on these five groups of tests, we found model results to be quite robust with respect to the model specifications and data used for this analysis. As discussed earlier (and illustrated by each range of estimates reported in Table 4), sensitivity of model results is greater for the choice of general circulation model and emissions scenario: estimates for effects on habitat vary by about a factor of two according to the GCM and emissions scenario selected. This result highlights the fact that differences among GCMs and emissions scenarios dominate the uncertainty in estimates provided by this report. Nevertheless, all three GCMs predict substantial losses of suitable habitat with all available emissions scenarios.

Table 4: Sensitivity of Model Results to Selected Specifications and Parameter Estimates

	Locations Losing All Coldwater Species by 2030	Locations Losing All Coldwater Species by 2060	Locations Losing All Coldwater Species by 2090
Best Estimate	**7-13%**	**12-26%**	**18-38%**
Logistic:			
Thermal tolerances +2 standard errors	5-12%	9-28%	20-38%
Thermal tolerances -2 standard errors	7-12%	11-26%	15-38%
Logistic:			
α+2 standard errors	11-18%	15-33%	22-47%
α-2 standard errors[a]	6-12%	10-20%	15-28%
Logistic:			
ß+2 standard errors	10-15%	14-30%	19-44%
ß-2 standard errors[a]	6-10%	10-20%	15-27%
Logistic:			
γ+2 standard errors	7-14%	11-27%	18-38%
γ-2 standard errors[a]	7-13%	12-24%	16-37%
Logistic:			
μ +2 standard errors[a]	7-13%	12-25%	16-36%
μ -2 standard errors[a]	7-14%	13-27%	18-40%
Logistic: Without special treatment of hysteresis	7-13%	12-24%	18-35%
Logistic: Sites with $R^2<0.7$ retained in analysis	7-13%	12-25%	17-37%
Logistic: Uses 75%ile water as "maximum"	8-14%	13-30%	21-40%
Linear: Fit to top 10% of air temperatures for each site	11-16%	15-32%	20-44%
Linear: Fit to top 20% of air temperatures for each site	11-18%	16-38%	23-56%
Linear: Fit to all available data for each site	14-22%	19-44%	28-61%
Linear: With $B=0.9$ for all sites	16-26%	23-56%	34-78%

[a] For these tests (as in all model simulations) all parameters for Equation 2 were constrained to be greater than or equal to zero. In addition, α was constrained to be greater than or equal to μ, and μ was constrained to be less than or equal to α.

Discussion

Comparison with Results from Other Studies

As mentioned earlier, this study differs from two previous efforts in the methods and data used to determine future changes in air temperatures and their effects on stream temperatures. Equation 2 tends to predict less warming of surface water than the linear relationships between air and water temperatures used in U.S. EPA (1995) and Eaton and Scheller (1996), but the updated emissions scenarios used in this study generally result in more simulated warming (as a result of significantly lower SO_2 emissions) than was projected with earlier GCMs based on IS92 emissions scenarios.

Eaton and Scheller (1996) used the CCC-GCM (the predecessor of the Canadian Climate Center's CGCM2 model) to project that a doubling of atmospheric concentrations of carbon dioxide (2 x CO_2) would lead to losses of available habitat ranging from 40-55% of USGS stations for individual trout or salmon species. Similarly, U.S. EPA (1995) used four GCMs and multiple emissions scenarios to estimate that losses of cold water fish habitat would range from 27-45% of "fishable acres" for the approximate equivalent of a doubling of atmospheric CO_2. Such a doubling (over today's CO_2 concentration) is expected by about 2090 for the A2 emissions scenario tested with the GCMs used in this study. For the CGCM2 model and the A2 emissions scenario, we estimate that individual species lose available habitat at 21-27% of stream locations by 2090. Across all GCMs and emissions scenarios, we estimate a range of 14-42%.

Strengths of this Study

Unlike U.S. EPA (1995) and Eaton and Scheller (1996), this study uses site-specific regression relationships to project future water temperatures at sample locations. Relationships between air and water temperatures naturally differ by location, because local differences in solar radiation, relative humidity, wind speed, water depth, groundwater inflow, riparian shading, artificial heat inputs, and thermal conductivity of the sediments all influence water temperatures in streams (Stefan and Preud'homme, 1993; Tschaplinski, 2000). Insomuch as these differences are captured implicitly by the logistic relationships we fit to each model site, our methods should provide a more representative simulation of changes in stream temperatures.

In addition, our use of a logistic function better represents the thermal relationship by accommodating its non-linearity. If higher water temperatures are indeed increasingly less responsive to further warming of air temperatures, use of linear regression relationships to project stream temperatures beyond their current range probably

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overstates expected impacts from climate change (Mohseni *et al.*, 1990). Even with the more conservative (and we believe more realistic) methods used in this study, however, potential impacts from climate change appear to be substantial for cold water fish.

Limitations

This study has been limited to a single metric of habitat suitability for cold water fish: the comparison of maximum weekly average stream temperatures to upper thermal tolerances. For a national study simulating effects of climate change at more than 2000 sample locations, more parameter-intensive modeling techniques (*e.g.* Stefan and Sinokrot, 1993; Clark *et al.*, 2001), were not feasible. As a consequence, our modeling of fish habitat does not address several important dimensions of the habitat and ecology of trout and salmon species. These include groundwater inflows, effects of upstream releases from reservoirs, water temperatures at other parts of the seasonal cycle, potential changes in precipitation, evapotranspiration and stream flows, potential changes in stream ecology and marine conditions, and present and future anthropogenic stresses or rehabilitation efforts.

Effects of Groundwater Inflows

Meisner *et al.* (1988) have described the importance of groundwater discharge to habitat for cold water fish. By providing relatively cool water in the summer and relatively warm water in winter, groundwater discharge provides stable habitat for developing eggs and fry (Meisner *et al.*, 1988). Cold water fish are known to move to the headwaters of groundwater-dominated streams to find cool refugia when stream temperatures become too warm in summer (Power *et al.*, 1999). If, as argued by Meisner *et al.* (1988), future increases in average annual air temperatures lead to roughly equal increases in groundwater temperatures, such warming could have a much greater effect on maximum summer stream temperatures than would elevated summer air temperatures (Meisner, 1990b). Habitat for brook trout, in particular, would be greatly reduced in streams at low latitudes and low altitudes (Meisner, 1990a; Meisner 1990b). In addition, groundwater temperatures also affect the temperature of intragravel (or hyporheic) flows within the stream substrates. Changes in groundwater temperatures could therefore influence the timing and hatching of salmonid eggs and the development of aquatic insects (Cassie and Satish, 2001).

As modeled by the techniques described in this report, locations at which local groundwater discharge contributes substantially to stream flow should yield lower estimated slopes for the curves associated with Equation (2). Simulated impacts from climate change would be expected to be *milder* for those locations, as the effects of higher summer air temperatures would be moderated by the implicitly modeled inflow of groundwater at unaffected, cooler temperatures. If, as pointed out by Meisner *et al.* (1988), however, each degree increase in annual average air temperature would raise groundwater temperatures by about one degree, water temperatures at such sites could instead warm *more* than downstream locations. For this reason, Equation (2), which models stream temperatures as if the temperature-moderating effects of groundwater discharge remain undiminished with a changing climate, almost certainly understates expected warming (and consequent losses of habitat for cold water species) for headwaters of streams with substantial groundwater inflows.


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Effects of Impoundments on Stream Temperatures

Similarly, water temperatures at gaging stations downstream of impoundments can be cooled in summer by releases from upstream lakes or reservoirs. In particular, water released from a cold, bottom layer (hypolimnion) of a reservoir can reduce stream temperatures by as much as 10ºC (18ºF) immediately below the reservoir, with lesser cooling observed as far as 48km (30 miles) downstream (Sinokrot *et al.*, 1995). For those sample gaging stations in this study that are downstream of reservoirs, the moderating effect of upstream releases is captured implicitly in the parameters estimated for Equation 2, and tends to be associated with hysteresis in the annual cycle of stream temperatures (Mohseni *et al.*, 1998). By relying on regression relationships derived from concurrent weekly average water and air temperatures, our model in effect holds this moderating effect constant when simulating how climate change could affect water temperatures. Because the temperature of hypolimnetic releases could increase in a warmer environment however (e.g., Sinokrot *et al.*, 1995), our model probably underestimates the future temperature of streams affected by upstream reservoirs, thereby underestimating potential losses of habitat.

Exclusive Focus on Maximum Stream Temperatures

In addition to the summer maximum temperatures included in this modeling effort, stream temperatures in fall, winter, and spring also affect the survival and productivity of fisheries. Both the length of the growing season and the length of winter, for example, can determine the extent of winter mortality from starvation, to which young-of-the year are considered especially vulnerable (Shuter and Post, 1990). For many warm water fish species, climate change could be beneficial by allowing expansion of habitat ranges into higher elevations and latitudes. Trout at high altitudes and latitudes (*e.g.*, northern Canada) could also benefit in winter from climate change, through increases in warm water refugia and decreases in anchor ice (Meisner *et al.*, 1988). Similarly, cold summer temperatures are known to delay spawning and prolong egg incubation for cutthroat trout in small streams of Colorado and New Mexico, thereby reducing the growth of fry and likely limiting their overwinter survival (Harig and Fausch, 2002). Because northern geographical boundaries within the contiguous U.S. are not evident for the present ranges of any of the eight species included in this study, however, significant expansion of the geographical distribution of trout and salmon seems an unlikely consequence of climate change. Although increased summer and winter temperatures might benefit cold water fish in a few, high-elevation streams, these gains are unlikely to offset losses of the scale projected by this study.

Another limitation of exclusive focus on maximum weekly average temperatures is that some streams may not be occupied during the summer, but may still provide habitat for trout and salmon at other times of the year. Different runs of chinook salmon, for example, are known to spawn at different times and locations in the same river. In the Cascade Mountains of Washington, one run begins in the Columbia River in the spring and waits in the Methow River and its tributaries until August, when it spawns upstream. A second run begins in late summer and spawns during November in the lower reaches of the Methow (Beer and Anderson, 2000). Upstream summer temperatures are therefore unlikely to be limiting for the fall chinook.

Competitive Interactions

Taniguchi *et al.* (1998) have examined competitive interactions between brook trout and brown trout at different stream temperatures. They note that while brook trout are dominant at higher elevations of the Rocky Mountain region, they are replaced by brown trout at middle elevations. Closer to the southern limits of their distribution, brook trout compete with both brown and rainbow trout in North Carolina and Virginia, with brook trout dominating at higher latitudes and elevations but rainbow and brown trout more successful to the south and at lower elevations (Flebbe, 1994). If climate raises stream temperatures, brown and rainbow trout could be expected to push brook trout further into headwater areas (Meisner, 1990b). As waters warm, cold water species with lower “thermal niches” become competitively disadvantaged with respect to other species for which the warmer temperatures are optimal (Magnuson *et al.*, 1979). Species (such as brown and rainbow trout) with higher thermal tolerances could therefore benefit from climate change, but only at the expense of other cold water fish.

Cold Water Habitat in Lakes

Although lakes were not included in this study, they provide substantial habitat for trout and salmon. In 1996, about half of all recreational fishing for trout and salmon took place in lakes (excluding the Great Lakes) and an additional 3% and 23%, respectively, occurred in the Great Lakes.[8] Like rivers and streams, lakes could also be affected by climate change. In a study of 27 types of lakes at 209 locations in the contiguous U.S., Stefan *et al.* (2001) simulated both water temperatures and concentrations of dissolved oxygen. Under present conditions, the simulations showed that deep (24m or 79 ft) to medium-depth (13m or 43 ft.) lakes can support cold water fish at northern latitudes of the contiguous U.S., but that habitat in most shallow lakes (4 m or 13 ft) was limited by either winterkill or summerkill. Under a 2 x CO_2 climate change scenario, cold water fish habitat was eliminated from almost all shallow lakes in the contiguous U.S., and the region where even deep lakes could support cold water fish habitat contracted northwards. The number of locations where lakes could provide cold water fish habitat was reduced by 45% (Stefan *et al.*, 2001).

Changes in the summer temperatures within tributaries to the Great Lakes could reduce habitat for coho salmon, chinook salmon, and steelhead trout, as reflected in regional results from this study. Effects of climate change on the

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[8] Based on our analysis of data from the 1996 National Survey of Fishing, Hunting, and Wildlife Associated Recreation (U.S. Department of the Interior and U.S. Department of Commerce, 1997).

Great Lakes themselves could also be important, however. In contrast to trends over the last century, future changes in precipitation and air temperatures for a 2 x CO_2 scenario are expected to produce marked declines in water levels and outflows from the Great Lakes (Magnuson *et al.*, 1997). Plausible changes in water levels range from +0.03 to –1.5m (+1.2in to –4.9 ft) for Lake Ontario, +0.04m to –2m (+1.6 in to –6.6 ft) for Lake Erie, -0.2m to –3.5m (-8 in to -11 ft) or Lake Michigan and Lake Huron, and –0.2m to –11m (-8 in to –36 ft) for Lake Superior (Mortch, 1998). Despite this loss of volume, thermal habitat space for cold water fish within the Great Lakes is generally expected to increase (Magnuson *et al.*, 1997), and some fish species within the Great Lakes could be expected to benefit from warmer winter temperatures and reduced ice cover.

Warmer temperatures within the Great Lakes could be especially beneficial to species with higher thermal tolerances. The white perch (*Morone americana*), for example, is believed to have invaded the Great Lakes between 1946 and 1948, and to have become a dominant member of the fish community within a few years. Numbers declined dramatically during the severe winter of 1977-1978, however, and have not since recovered. If climate warms, winter survival of white perch could be enhanced, leading to an expansion of their range within the Great Lakes (Johnson and Evans, 1990). Similarly, 27 exotic fish species from the surrounding area could potentially invade the Great Lakes as a result of climate warming, dramatically altering present communities (Mandrak, 1989, as cited in Magnuson *et al.*, 1997).

Changes in Flow Regimes

Another important consideration outside the scope of this study is of effects from potential changes in streamflow. Clark *et al.* (2001), for example, have noted that flow regimes will probably change in response to alterations in weather patterns, precipitation, and evapotranspiration. Their models show that changes in flow regimes can be of equal importance or even more significant than changes in temperature for predicting how trout will respond to climate change. Effects could be both beneficial and damaging, depending on the species of concern, and the timing of thermal and hydrological changes with respect to a species' or population's life-cycle strategy (Jager *et al.*, 1997; Clark *et al.*, 2001).

High velocity flows, for example, can affect mortality and recruitment of trout (Clark *et al.*, 2001). Snow accumulation could be substantially reduced in some areas, resulting in a shift of rivers' high flow season from spring to winter (Lettenmaier *et al.*, 1992). Changes in the timing of snowmelt could also lead to a reduction of summer flows (Rango and Katwijk, 1990). Potential increases in winter flooding (constrained to narrower channels by snow banks) could decimate the eggs of fall-spawning brook trout in California and possibly elsewhere (Seegrist and Gard, 1972; Erman *et al.*, 1988). Fall-spawning chinook salmon might also be vulnerable.

For salmon, low flows could limit numbers migrating upstream, impede their progress, and reduce the surface area suitable for egg laying on river bottoms (Pulwarty and Redmond, 1997). Low flows could especially affect coho salmon, which need smaller streams and creeks for rearing their young (Pulwarty and Redmond, 1997). For all fish, low flows could result in higher water temperatures (Bradford and Irvine, 2000; Petersen and Kitchell, 2001), and more generally in the reduction of habitat space (Regier and Meisner, 1990).

Current projections of future precipitation are considered less reliable than those for temperatures (Cubasch *et al.*, 2001). A warming climate is generally expected to cause an enhanced and more energetic global hydrological cycle, but effects at regional scales cannot yet be predicted (Trenberth, 1998). In general, the intensity of daily rainfall is expected to increase as penetrative convective rainfall becomes more common and large-scale (non-convective) rainfall declines (Gordon *et al.*, 1992), a trend possibly evident in precipitation records for this century (Karl and Knight, 1998). The intensity of extreme rainfall events is also expected to increase, and some models project a higher frequency of extreme precipitation (Cubasch *et al.*, 2001). Such changes could increase the intensity and reduce the return times of high-velocity flooding, which can cause year-class failures through destruction of eggs and fry (Clark *et al.*, 2001).

Although a continuing trend for increasing precipitation in the U.S. as a whole seems plausible, regional decreases in precipitation are also possible for some regions: The HadCM3 model, for example, predicts diminishing precipitation in the Southwest (NAST, 2001). Whether or not precipitation increases, accelerated evaporation and transpiration from a warmer climate could cause a general drying of mid-continental areas during summer (Cubasch *et al.*, 2001). For each 1°C (1.8°F) rise in temperature, the capacity of air for evaporated water increases by about 6% (Waggoner, 1990), so changes in potential evaporation could be substantial for the range of temperature changes projected for U.S. regions. Warming could also increase agricultural demand for irrigation, which might place additional demands on water resources currently allocated to streamflow.

Changes in Stream Ecology and Marine Conditions

This study does not explicitly consider possible alterations in the ecology of streams inhabited by trout and salmon. For example, as water temperatures increase, predation of juvenile salmon in the Columbia River may also increase, both because predators grow more rapidly in

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warmer waters and because they consume more (Petersen and Kitchell, 2001). For salmon, sufficiently cold, rapidly flowing water is required throughout a stream so that the fish can avoid disease and predation on their way to the sea (Pulwarty and Redmond, 1997).

Nor does this study consider possible impacts of climate change on the marine environments required by anadromous species. Salmon may spend as much as 90% of their lives in the ocean (Pulwarty and Redmond, 1997), and shifts in sea surface temperatures can affect the survival of salmon to adulthood by affecting food abundance and predator distribution (Coronado and Hillborn, 1998). Changes in salinity and other marine conditions can also profoundly affect migratory patterns of anadromous fishes (Beamish *et al.*, 1999). Annual and decadal-scale variability in ocean temperatures has been linked to variability in populations of Pacific salmon, with sharp declines occurring during the extraordinarily long El Niño Southern Oscillation (ENSO) event of the 1990s (Pulwarty and Redmond, 1997).

Current GCMs suggest that statistics of the ENSO cycle are likely to be altered by climate change, but the character of projected changes is inconsistent among models (Stocker *et al.*, 2001). One model, which is based on a finer equatorial resolution and achieves more successful simulation of ENSO, has found climate change likely to increase both the frequency of El Niño-like conditions and the strength of cold events in the tropical Pacific Ocean (Timmerman *et al.*, 1999).

Present and Future Stresses

Viewed within the broader context of other anthropogenic stresses, risks to trout and salmon appear greater than those reported for this study. Existing trout and salmon stocks are already in decline and several are at risk of extinction. The ability of native trout and salmon species to survive existing stresses could be further compromised if the warming of surface waters causes the fragmentation of species populations, which could become isolated from one another in cooler headwater tributaries as water temperatures increase (Rahel *et al.*, 1996). Such fragmentation might further increase the risk of extinction as genetic variability decreases (Sanz *et al.*, 2000). Similarly, any sizable reduction in available habitat for trout and salmon will likely reduce the diversity of habitats available, further limiting the resilience of these species to natural shocks from extreme climatic or hydrological events. To succeed, future strategies to protect trout and salmon will need to address these and other potential effects of global warming.

Conclusion

This study supports an abundant scientific literature in concluding that highly-valued cold water fisheries are vulnerable to severe losses of habitat from the warming of streams. We estimate that 18-38% of presently-suitable stream locations could become unsuitable for all trout and salmon by the year 2090. Projected losses occur for all of the eight species modeled, and across all regions of the U.S. with existing cold water habitat. Estimated losses are substantial, regardless of the general circulation model or emissions scenarios used for the calculations, and are robust with respect to modeling techniques and specifications. Because this study has been restricted to direct thermal effects only, because it does not account for expected warming of groundwater and its role in the all-important headwaters of groundwater–dominated streams, and because it does not consider present and future stresses on trout and salmon habitat from other anthropogenic sources, these estimates are conservative. If future changes to air temperatures do indeed fall within the ranges projected by the general circulation models available for this study, true impacts from climate change are likely to exceed the estimates provided in this report.

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Appendix

Table A-1: Percent of Existing Trout and Salmon Habitat Lost by 2030[1]

	CGCM2[2] A2[3]	CSIRO[4] A2[3]	HadCM3[5] A2[3]	CGCM-2[2] B2[3]	CSIRO[4] B2[3]	HadCM3[5] B2[3]	CSIRO[4] A1	CSIRO[4] B1
Brook Trout	9%	8%	13%	8%	13%	14%	11%	8%
Cutthroat Trout	5%	5%	10%	4%	9%	11%	6%	4%
Rainbow Trout	8%	8%	11%	7%	8%	11%	8%	8%
Brown Trout	10%	10%	13%	7%	12%	13%	11%	10%
Chum Salmon	6%	5%	13%	4%	14%	17%	13%	10%
Pink Salmon	9%	8%	17%	8%	15%	20%	12%	11%
Coho Salmon	6%	6%	14%	6%	12%	13%	9%	8%
Chinook Salmon	6%	7%	11%	5%	12%	13%	9%	9%
Average[6]	7%	7%	13%	6%	12%	14%	10%	9%

[1] Weighted percent of sites for which the species is present under baseline climate conditions but is lost by the year 2030.
[2] Canadian Center for Climate Modelling and Analysis: CGCM2. Flato and Boer (2001).
[3] A2, B2, A1, and B1 emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES). Nakicenovic, et al. (2000). A1 and B1 results are available only for CSIRO-Mk2.
[4] Australia's Commonwealth Scientific and Industrial Research Organisation: CSIRO-Mk2. Gordon and O'Farrell (1997).
[5] Hadley Centre for Climate Prediction and Research: HadCM3. Gordon et al. (2000); Hadley Centre (1998).
[6] Unweighted mean of eight table values.

Table A-2: Percent of Existing Trout and Salmon Habitat Lost by 2060[1]

	CGCM2[2] A2[3]	CSIRO[4] A2[3]	HadCM3[5] A2[3]	CGCM-2[2] B2[3]	CSIRO[4] B2[3]	HadCM3[5] B2[3]	CSIRO[4] A1[3]	CSIRO[4] B1[3]
Brook Trout	16%	21%	29%	11%	19%	25%	24%	16%
Cutthroat Trout	15%	18%	28%	7%	15%	24%	21%	13%
Rainbow Trout	14%	18%	24%	10%	15%	20%	19%	14%
Brown Trout	17%	20%	26%	12%	17%	22%	21%	16%
Chum Salmon	18%	21%	27%	12%	20%	25%	25%	17%
Pink Salmon	18%	25%	34%	13%	24%	31%	29%	17%
Coho Salmon	16%	20%	30%	10%	18%	24%	23%	16%
Chinook Salmon	15%	19%	25%	10%	17%	21%	21%	15%
Average[6]	16%	20%	28%	11%	18%	24%	23%	15%

[1] Weighted percent of sites for which the species is present under baseline climate conditions but is lost by the year 2060.
[2] Canadian Center for Climate Modelling and Analysis: CGCM2. Flato and Boer (2001).
[3] A2, B2, A1, and B1 emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES). Nakicenovic, et al. (2000). A1 and B1 results are available only for CSIRO-Mk2.
[4] Australia's Commonwealth Scientific and Industrial Research Organisation: CSIRO-Mk2. Gordon and O'Farrell (1997).
[5] Hadley Centre for Climate Prediction and Research: HadCM3. Gordon et al. (2000); Hadley Centre (1998).
[6] Unweighted mean of eight table values.

Table A-3: Percent of Existing Trout and Salmon Habitat Lost by 2090[1]

	CGCM2[2] A2[3]	CSIRO[4] A2[3]	HadCM3[5] A2[3]	CGCM2[2] B2[3]	CSIRO[4] B2[3]	HadCM3[5] B2[3]	CSIRO[4] A1	CSIRO B1
Brook Trout	26%	35%	41%	17%	27%	32%	33%	22%
Cutthroat Trout	24%	32%	40%	16%	26%	31%	31%	19%
Rainbow Trout	24%	30%	38%	15%	22%	28%	29%	19%
Brown Trout	25%	31%	38%	18%	23%	28%	29%	21%
Chum Salmon	24%	29%	38%	17%	26%	31%	29%	24%
Pink Salmon	27%	35%	42%	18%	29%	36%	34%	27%
Coho Salmon	23%	34%	41%	16%	29%	34%	32%	22%
Chinook Salmon	22%	30%	38%	14%	23%	29%	29%	20%
Average[6]	24%	32%	39%	16%	26%	31%	31%	22%

[1] Weighted percent of sites for which the species is present under baseline climate conditions but is lost by the year 2090.

[2] Canadian Center for Climate Modelling and Analysis: CGCM2. Flato and Boer (2001).

[3] A2, B2, A1, and B1 emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES). Nakicenovic, et al. (2000). A1 and B1 results are available only for CSIRO-Mk2.

[4] Australia's Commonwealth Scientific and Industrial Research Organisation: CSIRO-Mk2. Gordon and O'Farrell (1997).

[5] Hadley Centre for Climate Prediction and Research: HadCM3. Gordon et al. (2000); Hadley Centre (1998).

[6] Unweighted mean of eight table values.

Table A-4: Percent of Locations Losing All Trout Habitat

	1996 Person-Days of Trout Fishing in Streams (millions)[1]	Sites with Trout / Total Sites	Percent Losing All Trout by 2030	Percent Losing All Trout by 2060	Percent Losing All Trout by 2090
Alabama	0.02	5/73	0-60%	40-80%	60-100%
Arkansas	0.4	8/23	0%	0-12%	12%
Arizona	0.5	2/8	0-50% [3]	50% [3]	50-100% [3]
California	5.2	110/215	4-20%	22-32%	25-41%
Colorado	3.5	76/105	7-12%	7-26%	18-33%
Connecticut	0.9	4/20	25% [3]	25% [3]	25-50% [3]
Georgia	1.5	4/38	0-50% [3]	0-75% [3]	50-75% [3]
Iowa	0.4	3/8	0% [3]	0% [3]	0% [3]
Idaho	2.1	42/48	5-7%	5-24%	10-38%
Illinois	0.3	2/41	0-50% [3]	50% [3]	50% [3]
Indiana	0.1	1/23	100% [3]	100% [3]	100% [3]
Kentucky	0.2	1/58	0% [3]	0% [3]	0% [3]
Massachusetts	1.1	8/22	12%	25-38%	25-38%
Maryland	0.6	7/24	0%	0-29%	29-43%
Maine	0.5	2/21	0-50% [3]	50% [3]	50% [3]
Michigan	1.9	39/71	3-13%	10-21%	15-28%
Minnesota	0.5	5/32	0-20%	20-40%	20-40%
Missouri	1.1	2/40	0% [3]	0-50% [3]	0-50% [3]
Montana	1.5	73/77	0-5%	3-16%	5-30%
North Carolina	1.6	12/75	17-25%	25-50%	25-67%
North Dakota	0.04	6/20	0%	0-17%	0-17%
Nevada	0.6	13/35	0-8%	8-15%	8-31%

Table A-4: Percent of Locations Losing All Trout Habitat (continued)

	1996 Person-Days of Trout Fishing in Streams (millions)[1]	Sites with Trout / Total Sites	Percent Losing All Trout by 2030	Percent Losing All Trout by 2060	Percent Losing All Trout by 2090
New Jersey	1.5	5/28	20-40%	40%	40-60%
New Mexico	1.0	1/3	100% [3]	100% [3]	100% [3]
New York	1.8	18/44	22-33%	33-56%	39-61%
Ohio	0.2	6/85	33%	33-50%	50-67%
Oklahoma	0.03	3/35	0% [3]	0% [3]	0-33% [3]
Oregon	2.7	130/154	4-14%	9-22%	12-42%
Pennsylvania	6.1	18/59	6-11%	11-28%	17-44%
Rhode Island	0.3	3/10	0% [3]	0% [3]	0% [3]
South Carolina	0.09	4/73	25-50% [3]	50% [3]	50% [3]
South Dakota	0.2	1/9	0% [3]	0% [3]	0% [3]
Tennessee	0.9	15/67	7-13%	13-20%	20-40%
Utah	1.1	8/20	0%	0%	0-38%
Virginia	1.0	5/19	0-40%	40-80%	40-100%
Vermont	0.6	2/6	0% [3]	0-50% [3]	0-50% [3]
Washington	2.8	99/106	1-4%	1-11%	3-21%
Wisconsin	0.6	26/49	12-19%	12-19%	19-27%
West Virginia	1.2	3/29	0% [3]	0% [3]	0-33% [3]
Wyoming	1.2	19/24	0-6%	0-26%	11-32%
U.S.	49.4[2]	791/2050	7-14%	13-26%	18-38%

[1] Based on analysis of data from the National Survey of Hunting, Fishing, and Wildlife Associated Recreation (U.S. DOI, 1996). Seventy-two percent of respondents who reported fishing in streams also reported fishing in lakes.

[2] Excludes Alaska.

[3] These percentages are based on a sample of fewer than five USGS gaging stations. State-level results based on these and other small sample sizes should not be interpreted as reliable indications of expected state-level effects.

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