Limnol. Oceanogr., 41(5), 1996, 1109–1115

Effects of climate warming on fish thermal habitat in streams of the United States

John G. Eaton
U.S. Environmental Protection Agency, Mid-Continent Ecology Division, 6201 Congdon Blvd., Duluth, Minnesota 55804

Robert M. Scheller
DynTel Corp., Duluth, Minnesota

Abstract

The effects of climate warming on the thermal habitat of 57 species of fish of the U.S. were estimated using results for a doubling of atmospheric carbon dioxide that were predicted by the Canadian Climate Center general circulation model. Baseline water temperature conditions were calculated from data collected at 1,700 U.S. Geological Survey stream monitoring stations across the U.S. Water temperatures after predicted climate change were obtained by multiplying air temperature changes by 0.9, a factor based on several field studies, and adding them to baseline water temperatures at stations in corresponding grid cells. Results indicated that habitat for cold and cool water fish would be reduced by ~50%, and that this effect would be distributed throughout the existing range of these species. Habitat losses were greater among species with smaller initial distributions and in geographic regions with the greatest warming (e.g. the central Midwest). Results for warm water fish habitat were less certain because of the poor state of knowledge regarding their high and low temperature tolerances; however, the habitat of many species of this thermal guild likely will also be substantially reduced by climate warming, whereas the habitat of other species will be increased.

The threat of global climate change has stimulated the publication of numerous research papers dealing with the potential effects of surface and groundwater warming on the thermal habitat of freshwater fish (e.g. Coutant 1990; Magnuson et al. 1990; Meisner 1990; Stefan et al. 1995). With few exceptions (e.g. Shuter and Post 1990), most of these studies deal with responses to temperature in single water bodies or small geographic regions, so we decided to attempt an assessment of effects at a much larger scale consisting of the lower 48 states. Most of the studies cited above also dealt with effects of climate change on lake fish or habitat. We expected that using less detailed input data would keep the analysis manageable, but that we would use information compiled for or generated from previous smaller scale studies. These existing data include a quality-assured database of historical surface water temperature maxima at U.S. Geological Survey (USGS) stream monitoring stations and maximum temperature tolerances estimated from a field database for several dozen freshwater species of fish, as reported by Eaton et al. (1995); results of analyses of the relationship between air temperature and stream-water temperatures (Stefan and Preud'homme 1993; Sinokrot and Stefan 1993); and a geographic information system (GIS) for spatially relating geographically referenced stream temperatures, fish species occurrences, and climate model grid cell meteorological projections.

The broad range of data collected geographically (throughout the U.S.) and historically (over several decades) make the USGS data valuable for analysis of changes in fish thermal habitat. Although some inaccuracies may result because of the uneven distribution of monitoring stations, this is still the largest and most comprehensive survey of rivers available. Several major information gaps interfere with an analysis of water quality and fish responses to climate change, including the lack of comprehensive knowledge of the thermal tolerance of most species and uncertainties in the driving factors (future climate projections). Therefore, our objective was to conduct a preliminary, semiquantitative analysis of the effects of climate warming on fish thermal habitat in the U.S.

Materials and methods

Surface water temperature data—Records from the USGS national water data storage and retrieval (WATSTORE) daily values file (Showen 1980) were the source of baseline stream-water temperatures that were used to estimate climate change effects. The daily values used in this study were either provided by USGS or calculated from at least two daily measurements, usually a minimum and maximum. Weekly means were then calculated from these daily means. Data were quality assured using a computer program that finds values obviously beyond normal temperature extremes or values recorded in differing units

Acknowledgments

We thank Doug Fairchild for assistance in locating and acquiring records of water temperatures and fish collections, for assimilating information on the current distribution of the 57 subject fish species, and for critical review of the analysis procedure and the manuscript. We also thank Don Fruehling for conducting many GIS analyses of data and providing the map figures, and two anonymous reviewers for their comments on the manuscript.

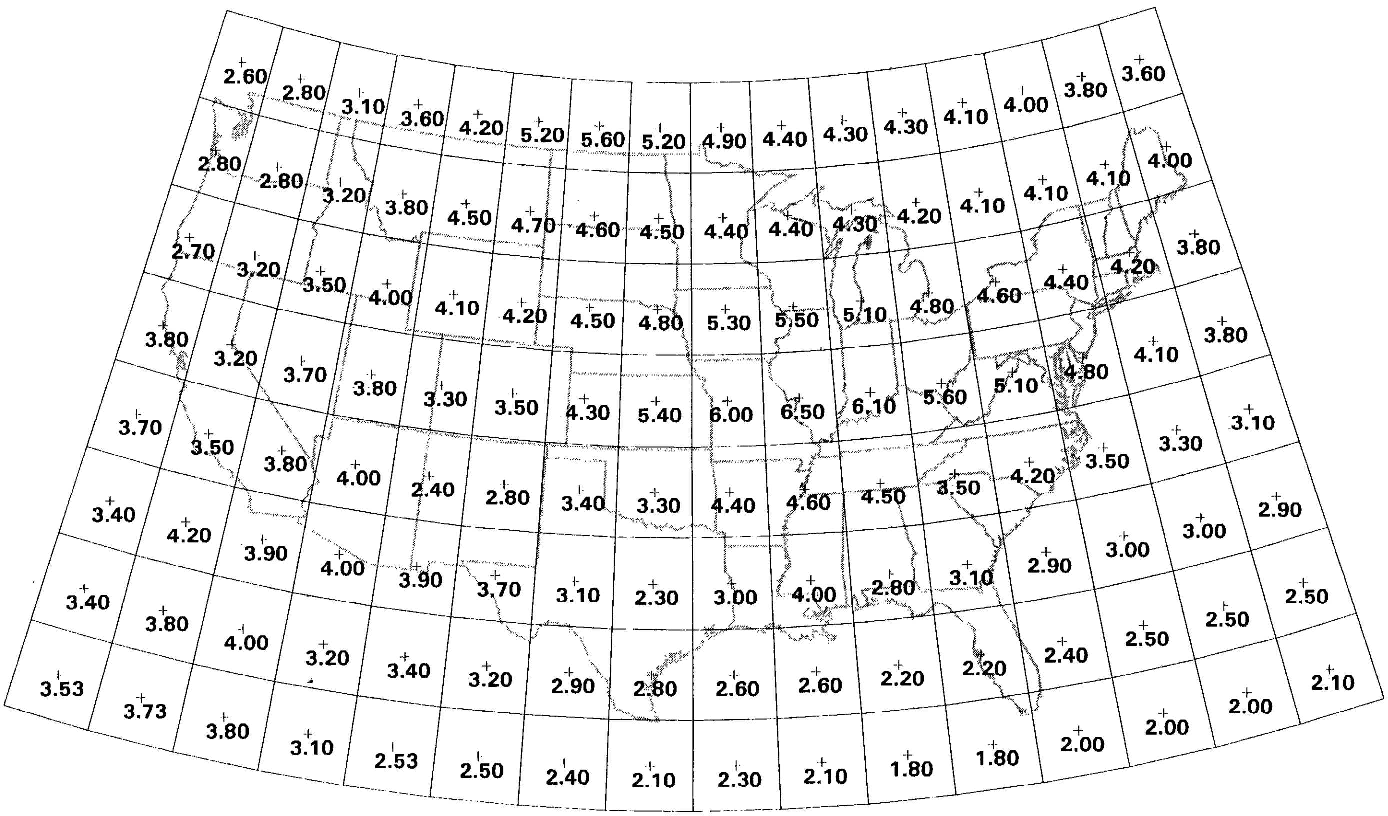

Fig. 1. The average of July, August, and September $2 \times CO_2$ air temperature increases projected by the CCC-GCM for each grid cell.

that were considered flawed and were ignored in subsequent manipulations. The temperature files were uploaded to the U.S. EPA Cray C94 supercomputer to calculate weekly mean temperatures for every week on record for every USGS stream sampling station.

The effect of climate change on stream temperatures was estimated by integrating projections from the Canadian Climate Center general circulation model (CCC-GCM) with the USGS stream temperatures. The CCC-GCM predicted monthly climate change for grid cell areas of $3.75 \times 3.75°$ and was run for current climate conditions and to predict future climate conditions after a doubling of the atmospheric CO_2 concentration ($2 \times CO_2$) (McFarlane et al. 1992). The difference between these monthly grid cell values was calculated to be the predicted change in air temperature. The means of the predicted changes for summer months (July, August, and September) when stream temperatures are highest, are shown in Fig. 1. To put these increases into a broader perspective, the CCC-GCM predicted a change in global mean surface air temperature over land of +4.4°C, although for some grid cells a negative change in temperature for 1 or 2 months was predicted (P. T. Y. Louie in prep.).

Because the information on thermal tolerances of fish species was expressed in terms of the maximum weekly average water temperature (i.e. the highest of the 52 weekly average temperatures in a year), this time-temperature unit was used also as the baseline for climate change. The maximum weekly mean temperature was calculated for each USGS station for which there were more than 104 weeks (2 yr) of acceptable data. The USGS station is matched with the corresponding CCC-GCM grid cell to obtain the predicted $2 \times CO_2$ air temperature change, which was then added to the baseline water temperature to estimate $2 \times CO_2$ water temperatures. Based on field studies of the air–water temperature relationship, Stefan and Preud'homme (1993) found weekly water temperature changes to average 0.86 the weekly air temperature changes for several streams of various sizes in the southern and northern U.S.; therefore, we multiplied the CCC-GCM air temperature change by 0.9 before adding it to the baseline stream temperature. This method produced baseline and predicted climate change maximum water temperatures for 1,776 stream stations located throughout the continental U.S.

A list of CCC-GCM grid cells that contain populations of each species was used to associate USGS stations and climate projections with the current geographic distribution of fish. Species were assumed to have the potential for inhabiting all streams in a grid cell on which monitoring stations were located if available records indicated that the fish had been found anywhere in that grid cell (Lee et al. 1980; Boschung et al. 1983; Page and Burr 1991). Eight species that have been widely introduced outside their native range (common carp, smallmouth bass, largemouth bass, bluegill, black crappie, brook trout, brown trout, and rainbow trout) were assumed to be present throughout the U.S. wherever suitable thermal habitat existed. Although this procedure is based on crude approximation of a species' natural range, it reduces errors that would be introduced by including results for stations in areas where species are thought to be absent. The technique is probably less accurate in estimating baseline habitats for species inhabiting the largest rivers or for those species having specialized environmental requirements other than temperature. An analysis in which fish were located by state instead of grid cell, but was otherwise identical to that described above, produced similar results.

Fish thermal tolerance—The fish and temperature database matching system (FTDMS) described by Eaton et al. (1995) has been used to obtain maximum temperatures tolerated by 57 fish species found throughout the U.S. (Table 1). The technique matches fish presence records in space and time with stream temperature records using computer databases to estimate the highest weekly mean temperatures encountered by each species in its natural environment. The use of thermal refuges by fish is to some extent incorporated into this field data-based method for estimating maximum temperature tolerances (*see* Eaton et al. 1995). In the opinion of Eaton and coworkers, the resulting temperature values closely approximate the maximum temperature tolerance of cold and cool water fish, but underestimate the tolerance of some warm water fish due to the southern limit (the U.S. border) of data collected for use in the FTDMS.

For our study, where species' ranges were determined to extend to or beyond the southern U.S. border, the upper zero net growth temperature (UZNG), if available, was used as a maximum tolerance temperature. The UZNG value is a high temperature at which fish can live for several days but at which they do not ingest enough food to gain weight under ad libidum feeding conditions in the laboratory. For the 12 warm water species for which no UZNG value was found, 34°C was estimated to be a reasonable mean UZNG temperature and was assigned to each species. UZNG and FTDMS values are similar for several fish species, for example 21 (Casselman 1978) and 22.4°C for brook trout, 23 (Baldwin 1956) and 24°C for rainbow trout, 28 (Casselman 1978) and 28°C for northern pike, and 29 (Smith and Koenst 1975) and 29°C for walleye. For other species, some UZNG values are higher and some lower than FTDMS values.

We can also assume that some warm water species are restricted by an intolerance of low temperatures in the U.S. (*see* Shuter et al. 1989; McCormick and Jensen 1992). Minimum winter temperature tolerance limits for the species in our study have not yet been calculated from the available field database used to estimate maximum tolerances. Instead, an approximation consisting of the winter temperatures of stations with a maximum summer temperature of 26°C or higher, which is above the FTDMS tolerance range for cold water species but includes the range for all cool water species, was used to define the low temperature tolerance limit for warm water species.

Table 1. The 57 fish species used in the analysis, with the number of thermally suitable stations under baseline conditions, the number of thermally suitable stations after predicted global climate change, percent change in number of stations, and the maximum weekly average temperature tolerance used in our estimates of habitat suitability.

		No. of USGS stations		Change in stations (%)	Max tolerance* (°C)
		Baseline	GCC		
Cold water					
Chum salmon	*Oncorhynchus keta*	102	57	−44.1	19.8
Pink salmon	*Oncorhynchus gorbuscha*	129	67	−48.1	21.0
Brook trout	*Salvelinus fontinalis*	471	213	−54.8	22.4
Mountain whitefish	*Prosopium williamsoni*	265	172	−35.1	23.1
Cutthroat trout	*Oncorhynchus clarki*	378	226	−40.2	23.3
Coho salmon	*Oncorhynchus kisutch*	323	169	−47.7	23.4
Chinook salmon	*Oncorhynchus tshawytscha*	379	215	−43.3	24.0
Rainbow trout	*Oncorhynchus mykiss*	632	322	−49.1	24.0
Brown trout	*Salmo trutta*	638	330	−48.3	24.1
Mottled sculpin	*Cottus bairdi*	324	159	−50.9	24.3
Total		3,641	1,930	−47.0	
Cool water					
Johnny darter	*Etheostoma nigrum*	260	79	−69.6	26.5
Longnose dace	*Rhinichthys cataractae*	712	450	−36.8	26.5
Creek chub	*Semotilus atromaculatus*	492	176	−64.2	27.1
Blacknose dace	*Rhinichthys atratulus*	406	126	−69.0	27.2
White sucker	*Catostomus commersoni*	643	283	−55.9	27.4
Northern pike	*Esox lucius*	277	128	−53.8	28.0
Walleye	*Stizostedion vitreum*	1,313	803	−38.8	29.0
Pumpkinseed	*Lepomis gibbosus*	842	537	−36.2	29.1
Yellow perch	*Perca flavescens*	872	528	−39.4	29.1
Common shiner	*Luxilus cornutus*	505	198	−60.8	29.2
Rock bass	*Ambloplites rupestris*	485	183	−62.3	29.3
Brown bullhead	*Ameiurus nebulosus*	695	286	−58.8	29.4
Smallmouth bass	*Micropterus dolomieui*	1,396	872	−37.5	29.5
Golden redhorse	*Moxostoma erythrurum*	481	182	−62.2	29.6
Northern hog sucker	*Hypentelium nigricans*	572	225	−60.7	29.6
Silver redhorse	*Moxostoma anisurum*	424	159	−62.5	29.6
Total		10,375	5,215	−49.7	
Warm water					
Bluntnose minnow	*Pimephales notatus*	376	181	−51.9	30.1
Sauger	*Stizostedion canadense*	339	158	−53.4	30.1
Black crappie	*Pomoxis nigromaculatus*	660	487	−26.2	30.5
Golden shiner	*Notemigonus crysoleucas*	639	451	−29.4	30.9
Spotted bass	*Micropterus punctulatus*	287	97	−66.2	30.9
White perch	*Morone americana*	166	142	−14.5	30.9
White crappie	*Pomoxis annularis*	566	315	−44.3	31.0
White bass	*Morone chrysops*	461	243	−47.3	31.4
Longnose gar	*Lepisosteus osseus*	586	337	−42.5	31.5
Emerald shiner	*Notropis atherinoides*	467	308	−34.0	31.6
Sand shiner	*Notropis stramineus*	342	201	−41.2	31.8
River carpsucker	*Carpiodes carpio*	404	203	−49.8	32.1
Suckermouth minnow	*Phenacobius mirabilis*	355	150	−57.7	32.1
Orange spotted sunfish	*Lepomis humilis*	355	150	−57.7	32.5
Freshwater drum	*Aplodinotus grunniens*	516	348	−32.6	32.6
Bullhead minnow	*Pimephales vigilax*	479	365	−23.8	34.0*
Black bullhead	*Amieurus melas*	662	701	5.9	34.0*
Flathead catfish	*Pylodictis olivaris*	525	442	−15.8	34.0*
Fathead minnow	*Pimephales promelas*	653	692	6.0	34.0*
Ghost shiner	*Notropis buchanani*	388	298	−23.2	34.0*
Gizzard shad	*Dorosoma cepedianum*	746	684	−8.3	34.0*
Green sunfish	*Lepomis cyanellus*	847	910	7.4	34.0*
Longear sunfish	*Lepomis megalotis*	511	442	−13.5	34.0*
Mosquitofish	*Gambusia affinis*	603	572	−5.1	34.0*
Red shiner	*Cyprinella lutrensis*	236	154	−34.7	34.0*
Smallmouth buffalo	*Ictiobus bubalus*	540	443	−18.0	34.0*
Warmouth	*Lepomis gulosus*	668	559	−16.3	34.0*
Common carp	*Cyprinus carpio*	890	1,116	25.4	35.0[a]
Channel catfish	*Ictalurus punctatus*	682	854	25.2	35.0[b]
Largemouth bass	*Micropterus salmoides*	892	1,163	30.4	35.5[c]
Bluegill	*Lepomis macrochirus*	894	1,192	33.3	36.0[d]
Total		16,735	14,358	−14.2	

* Species with ranges beyond the U.S. border for which no UZNG (upper zero net growth) values were available. All other maximum tolerances were derived from their FTDMS values. Superscripts indicate references that contain UZNG values for four species found south of the U.S. border: a—Sarig 1966; b—West 1966; c—Coutant and Cox 1976; d—Lemke 1977.

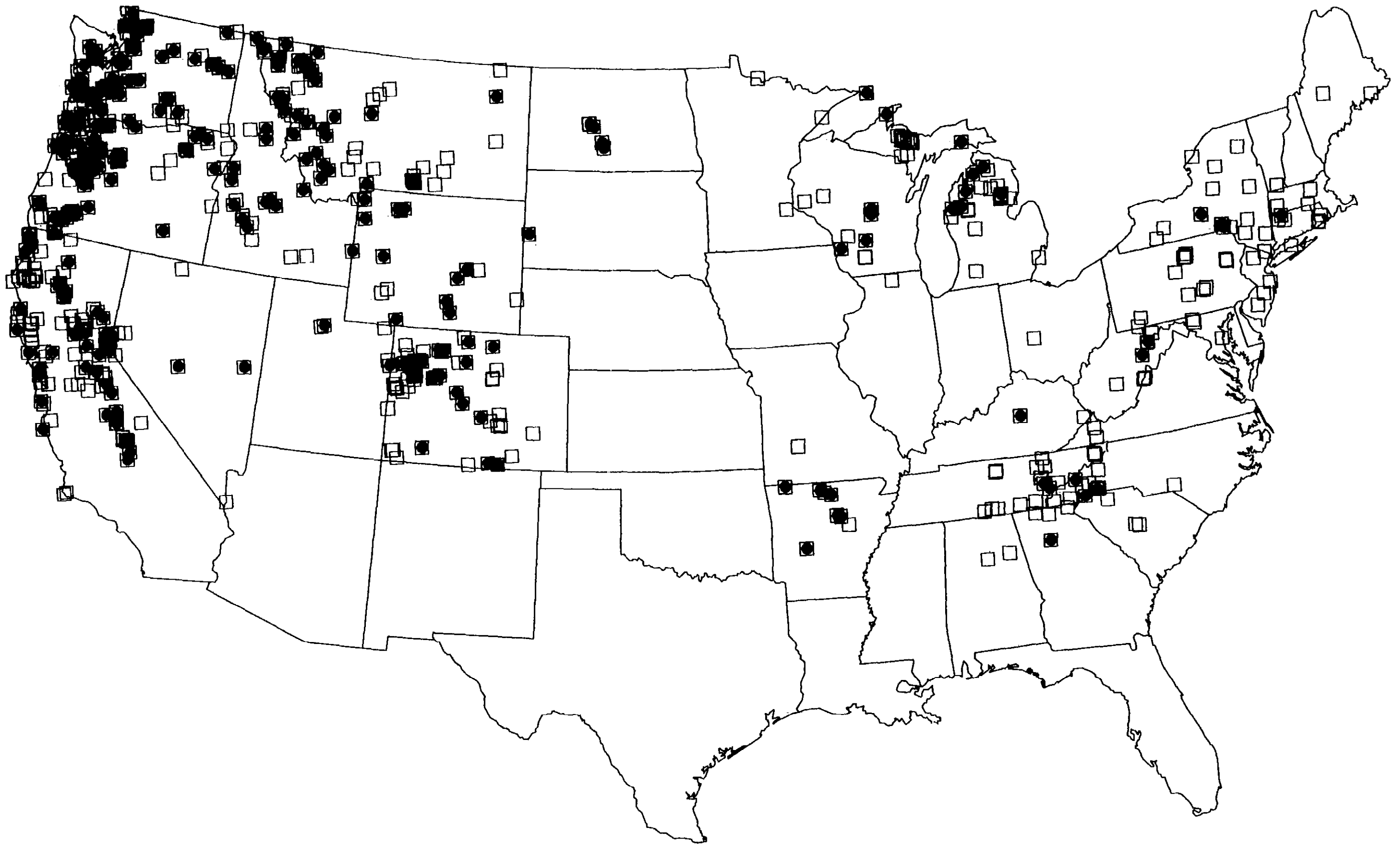

Fig. 2. USGS monitoring stations with suitable thermal habitat for rainbow trout before and after climate warming. The maximum tolerance for rainbow trout was 24.0°C. Before climate change, suitable habitat at 632 sampling sites—□; after climate change, at 322 of 632 sites—●.

The rationale for this value is that cool water and warm water fish frequently occupy the same habitats, but that cold and warm water fish do not. Several investigators (Meisner et al. 1987; Radforth 1944; Legendre and Legendre 1984) have observed a close relationship between summer air temperatures and the northern range limits of cool and warm water fish in the Great Lakes region. Winter thermal conditions may also restrict the distribution of a few cool-water species whose northern range limit is close to the U.S.–Canada border (e.g. northern hog sucker), but the lack of cold tolerance information leaves us no better alternative than to use high temperature tolerances (i.e. FTDMS values).

Climate change effects—We expressed the effect of climate change on species as the number of USGS monitoring stations at which suitable thermal habitat exists after climate change as compared to the number of stations before climate change and the percentage reduction or increase in the number of stations. The effects were also estimated by assigning species to cold, cool, or warm water thermal guilds and calculating an aggregate change for each guild. The cold water guild includes species with a maximum tolerance ≤24.3°C, cool water fish include those with a tolerance of 26.5–29.9°C, and warm water fish are those with a tolerance ≥30°C. As pointed out by Eaton et al. (1995) and seen in Table 1, the thermal boundary between cool and warm water fish guilds is indistinct and the separation used here is arbitrary.

Results and discussion

The results of the analysis of climate warming effects for the 57 species considered are presented in Table 1. A nearly 50% reduction in thermal habitat is projected for cold and cool water species, but only a 14.2% decrease is estimated for warm water fish. The distribution of USGS monitoring sites where suitable habitat is projected before and after climate warming is illustrated in Figs. 2–4 by representative cold (rainbow trout), cool (white sucker), and warm (largemouth bass) water fish. Rainbow trout and white sucker distributions indicate that cold and cool water fish will be least affected in higher latitude or elevation locations. Suitable habitat will be eliminated by climate warming throughout the range of a species—north as well as south. Largemouth bass show a graded increase in suitable habitat with latitude from the midsouth to the northern border of the U.S., resulting in a net increase in stations of 30% for this species. The high level of loss of warm water fish habitat in southern Indiana and Illinois and in Missouri can be explained by the particularly high

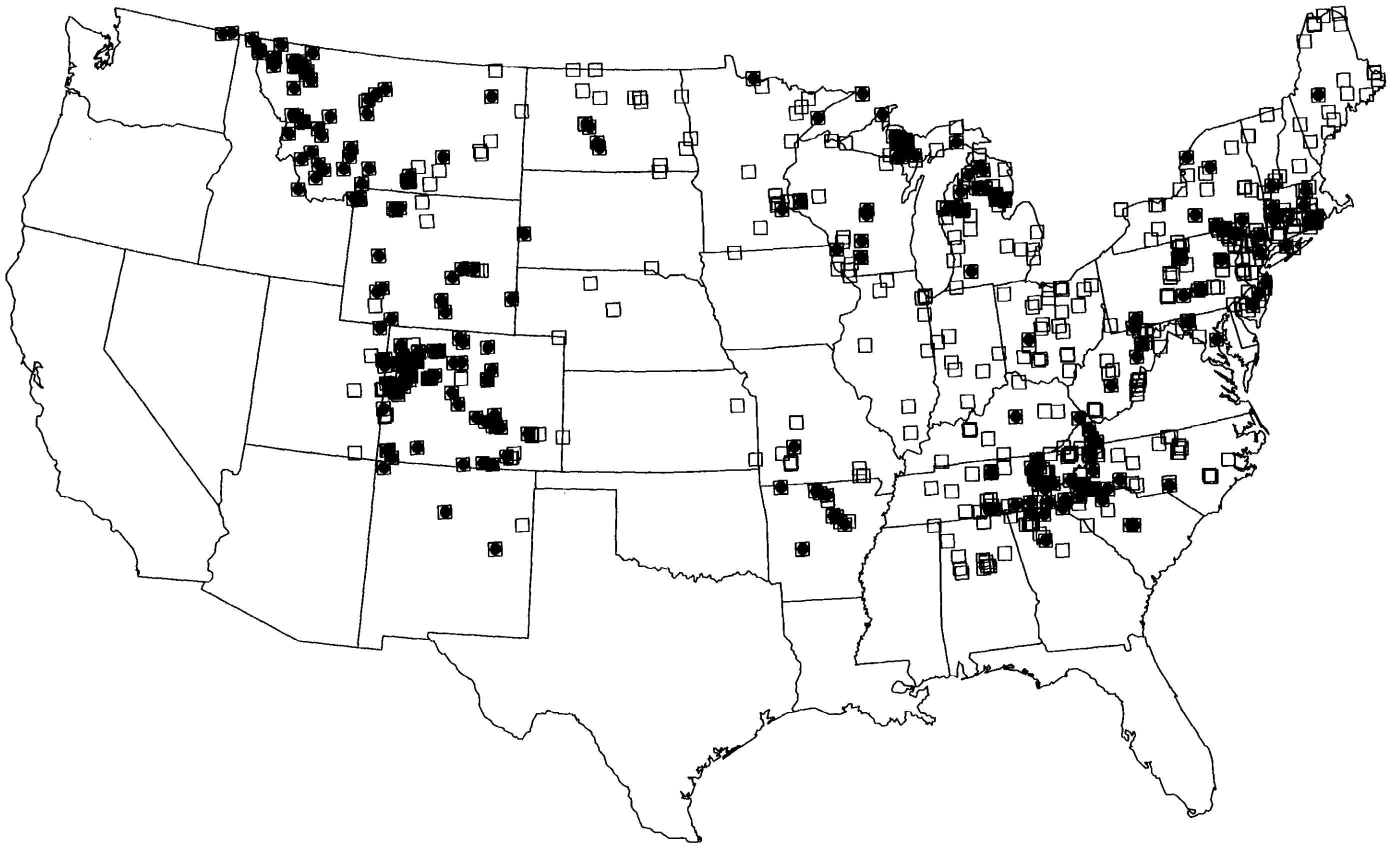

Fig. 3. As Fig. 2, but for white sucker. The maximum tolerance for white sucker was 27.4°C. Before climate change, suitable habitat at 643 sites—□; after climate change, at 283 of 643 sites—●.

degree of climate warming projected for this region (Fig. 1). As the distribution map for rainbow trout indicates (Fig. 2), there is a major regional effect in the northeastern U.S. where an air temperature increase of ~4.5°C is projected (Fig. 1).

Meisner (1990) and others have pointed out that the southern distribution of brook trout in the U.S. is largely determined by the inflow to low-order streams of cooler groundwater. He calculated that the range limits of brook trout correspond to an annual groundwater mean of 15°C, which is ~1–2°C higher than mean annual air temperature. In summer, however, these low-order stream reaches with relatively more groundwater inflow have cooler temperatures than those containing a higher proportion of surface water runoff. Therefore, the effect of climate warming in groundwater-fed stream reaches often occupied by trout and certain other species probably is somewhat overestimated by the 0.9 air–water conversion factor used in our analysis. The type and amount of riparian vegetation also affects this air–water relationship and the rate of downstream warming (Sinokrot and Stefan 1993). When they are near equilibrium with air temperature, mean daily water temperatures during summer are generally slightly cooler than corresponding air temperatures, although water can be warmer than the air and exceed a factor of 1.0 (Stefan and Preud'homme 1993).

Among all the cool water fish species, those with the smallest baseline distribution are projected to incur the greatest percentage of thermal habitat loss (correlation coefficient = 0.79, n = 16) and vice-versa (Table 1). Baseline geographic distribution seems to be more significant in determining vulnerability than the degree of high temperature tolerance (correlation coefficient for maximum temperature tolerance and percentage change in stations = 0.16, n = 16). These results are due to a scale effect whereby it is less likely that suitable temperatures will still exist in a small geographic area (species range) after climate change than in a larger geographic area with its greater diversity of thermal conditions. Other detrimental environmental conditions caused by climate change, such as reduced stream flow or vegetation changes and reduced shading, will also influence future distribution, and these effects could likewise be magnified for species with the smallest initial distribution.

The projected decrease in habitat for warm water fish (Table 1) was less expected. It seems logical to assume that warm water species would expand their ranges into habitats vacated by cold and cool water species because of climate change and therefore would experience an increase in habitat without significant loss. However, the thermal tolerance of the least tolerant warm water species is very close to that of cool water species and these species will all be similarly sensitive to climate warming. Furthermore, the magnitude of water temperature change in

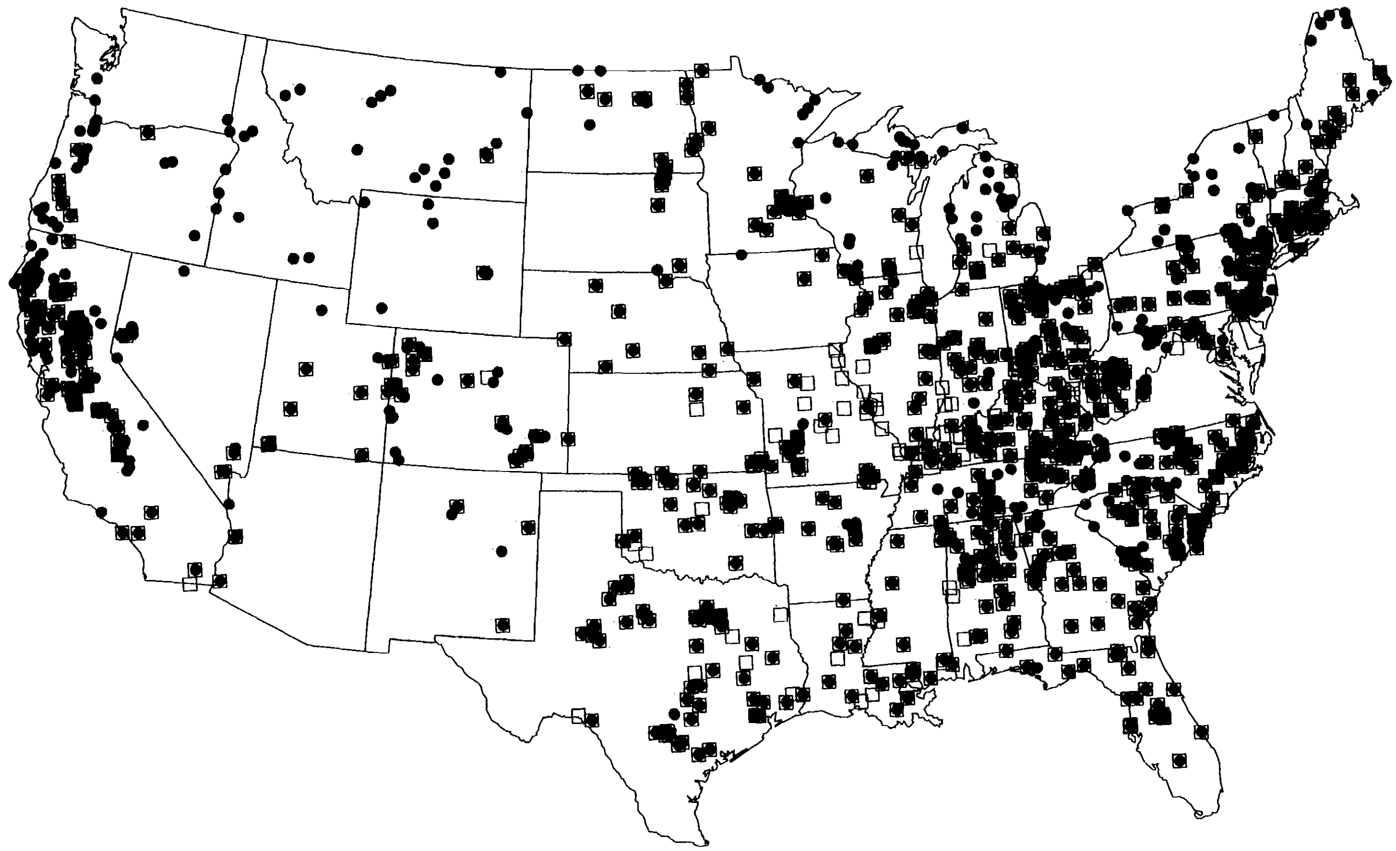

Fig. 4. As Fig. 2, but for largemouth bass. The tolerance range for largemouth bass was 26.0–35.5°C. Before climate change, suitable habitat at 892 of 1,776 sites—□; after climate change, at 1,163 of 1,776 sites—●.

many areas approaches or exceeds the entire range in high tolerance temperatures for the cool and warm water fish guilds (4 and 6°C, respectively). The exact maximum tolerance temperature used to differentiate cool and warm water fish has only a minor effect on this result unless it is changed greatly. The results in Table 1 indicate again that the most widely distributed warm water species (fathead minnows, green sunfish, channel catfish, etc.) will benefit most from climate warming.

Another possible influence on the results is that the region (grid cells) where a species had been observed to establish a baseline distribution (except for the eight universally distributed species) was also the only area within which a species could expand under climate warming conditions. Therefore, the results of our analysis may overestimate the effect of climate change (habitat reduction) on some warm and cool water fish with limited distributions by inadequately allowing for replacement of cooler water fish by warmer water fish. Many species might be expected to migrate to, or be introduced into, additional areas where thermal and other habitat conditions become suitable as climate changes. We did not consider possible immigration of tropical or subtropical species currently outside or low in number inside the U.S. Many factors beyond the scope of our analysis will influence these movements, such as the availability of migration corridors (Matthews and Zimmerman 1990; Rahel et al. 1996) or the rate of climate change. We also expect that where thermal conditions become favorable, other environmental conditions may be sufficiently unfavorable to prevent colonization.

A third influencing factor relates to the poor state of knowledge about the thermal requirements of warm water fish. This knowledge deficit produces substantial uncertainty in estimates of the number of stations with suitable habitat before and after climate change. A sensitivity analysis revealed that if winter temperature tolerance corresponded to a summer maximum of 28°C instead of 26 and the summer maximum for the south-of-the-border species without UZNGs were 35°C instead of 34 (and therefore closer to the average UZNG), the projected change in habitat after climate warming would be a 14% *increase.* Even under the latter scenario, however, the habitat for half (15) of the warm water species is reduced.

Although our analysis of climate change effects has many uncertainties, several well-founded conclusions are possible. Major reductions in stream habitat for cold and cool water species would result from climate warming, but these effects would likely be reduced for fish living in lakes, especially larger, deeper lakes that stratify in summer, providing thermal refuges for inhabitants (e.g. Magnuson et al. 1990; Stefan et al. 1995). Although effects will be greater in some areas than others because of warming hot spots or regional hydrology, the effects will be broad on species that are widely distributed; habitat will be reduced for warm water fish in the south and increased in the north; habitat will be reduced more uniformly for cold and cool water species across their entire ranges. The primary beneficiaries of climate change will be species that are currently widely distributed in the U.S. Those species with smaller ranges will suffer the greatest initial losses. Very limited knowledge about summer and winter temperature tolerances seriously impedes our quantification of the effects of climate change on warm water fish. Our analysis can serve as an index of the potential effect of climate warming on fish species and guilds of the U.S., and we hope it will stimulate additional relevant research on thermal requirements of fish.

References

BALDWIN, N. S. 1956. Food consumption and growth of brook trout at different temperatures. Trans. Am. Fish. Soc. **86:** 323–328.

BOSCHUNG, H. T., J. D. WILLIAMS, D. W. GOTSHALL, D. K. CALDWELL, AND M. C. CALDWELL. 1983. The Audubon Society field guide to North American fishes, whales and dolphins. Knopf.

CASSELMAN, J. M. 1978. Effects of environmental factors on growth, survival, activity, and exploitation of northern pike, p. 114–128. *In* R. L. Kendall [ed.], Selected coolwater fishes of North America. Am. Fish. Soc. Spec. Publ. 11.

COUTANT, C. C. 1990. Temperature-oxygen habitat for freshwater and coastal striped bass in a changing climate. Trans. Am. Fish. Soc. **119:** 240–253.

———, AND D. K. COX. 1976. Growth rates of subadult largemouth bass at 24 to 35.5°C, p. 118–120. *In* Thermal ecology 2. ERDA Symp. Ser. 40.

EATON, J. G., AND OTHERS. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries **20:** 10–18.

LEE, D. S., AND OTHERS. 1980. Atlas of North American freshwater fishes. N.C. State Mus. Nat. Hist.

LEGENDRE, P., AND V. LEGENDRE. 1984. Postglacial dispersal tential changes in the thermal habitat of Great Lakes fish after global climate warming. Trans. Am. Fish. Soc. **119:** 254–264.

MATTHEWS, W. J., AND E. G. ZIMMERMAN. 1990. Potential effects of global warming on native fishes of the southern Great Plains and the Southwest. Fisheries **15:** 26–32.

MEISNER, J. D. 1990. Effect of climate warming on the southern margins of the native range of brook trout, *Salvelinus fontinalis.* Can. J. Fish. Aquat. Sci. **47:** 1065–1070.

———, J. L. GOODIER, H. A. REGIER, B. J. SHUTER, AND W. J. CHRISTIE. 1987. An assessment of the effects of climate warming on Great Lakes basin fishes. J. Great Lakes Res. **13:** 340–352.

PAGE, L. M., AND B. M. BURR. 1991. A field guide to freshwater fishes. Houghton Mifflin.

RADFORTH, I. 1944. Some considerations on the distribution of fishes in Ontario. Contrib. R. Ont. Mus. Zool. **25:** 1–116.

RAHEL, F. J., C. J. KELEHER, AND J. L. ANDERSON. 1996. Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: Response to climate warming. Limnol. Oceanogr. **41:** 1116–1123.

SARIG, S. 1966. Synopsis of biological data on common carp *Cyprinus carpio* (Linnaeus), 1758 (Near East and Europe). FAO Fish. Synop. 31.2.

SHOWEN, C. R. 1980. Data formats for U.S. Geological Survey compiler files containing daily values for water parameters. U.S. Geol. Surv. Open-File Rep. 76-563 (revised).

SHUTER, B. J., P. E. IHSSEN, D. L. WALES, AND E. J. SNUCINS. 1989. The effects of temperature, pH and water hardness on winter starvation of young-of-the-year smallmouth bass (*Micropterus dolomieui* Lacepede). J. Fish Biol. **35:** 765–780.

———, AND J. R. POST. 1990. Climate, population viability, and the zoogeography of temperate fishes. Trans. Am. Fish. Soc. **119:** 314–336.

SINOKROT, B. A., AND H. G. STEFAN. 1993. Stream temperature dynamics: Measurement and modeling. Water Resour. Res. **29:** 2299–2312.

SMITH, L. L., JR., AND W. M. KOENST. 1975. Temperature