TACCIMO Literature Report
Literature Report – Annotated Bibliography Format
Report Date: April 1, 2013

Content Selections:
FACTORS – ALL
CATEGORIES – Fish
REGIONS – National, East, R9: Eastern, North Atlantic, R8: Southern, South Atlantic, South Central
KEYWORDS – Mussel

How to cite the information contained within this report

Each source found within the TACICMO literature report should be cited individually. APA 6th edition formatted citations are given for each source. The use of TACCIMO may be recognized using the following acknowledgement:

"*We acknowledge the Template for Assessing Climate Change Impacts and Management Options (TACCIMO) for its role in making available their database of climate change science. Support of this database is provided by the Eastern Forest Environmental Threat Assessment Center, USDA Forest Service.*"

Best available scientific information justification

Content in this Literature report is based on peer reviewed literature available and reviewed as of the date of this report. The inclusion of information in TACCIMO is performed following documented methods and criteria designed to ensure scientific credibility. This information reflects a comprehensive literature review process concentrating on focal resources within the geographic areas of interest.

Suggested next steps

TACCIMO provides information to support the initial phase of a more comprehensive and rigorous evaluation of climate change within a broader science assessment and decision support framework. Possible next steps include:

1. Highlighting key sources and excerpts
2. Reviewing primary sources where needed
3. Consulting with local experts
4. Summarizing excerpts within a broader context

More information can be found in the user guide. The section entitled Content Guidance provides a detailed explanation of the purpose, strengths, limitations, and intended applications of the provided information.

Where this document goes

The TACCIMO literature report may be appropriate as an appendix to the main document or may simply be included in the administrative record.

Brief content methods

Content in the Literature Reports is the product of a rigorous literature review process focused on cataloguing sources describing the effects of climate change on natural resources and adaptive management options to use in the face of climate change. Excerpts are selected from the body of the source papers to capture key points, focusing on the results and discussions sections and those results that are most pertinent to land managers and natural resource planners. Both primary effects (e.g., increasing temperatures and changing precipitation patterns) and secondary effects (e.g., impacts of high temperatures on biological communities) are considered. Guidelines and other background information are documented in the user guide. The section entitled Content Production System fully explains methods and criteria for the inclusion of content in TACCIMO.

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Effects by Source

Tuesday, April 02, 2013

RESOURCE AREA (FACTOR): ANIMAL COMMUNITIES

FISH

NATIONAL

Carpenter, S. R., Fisher, S. G., Grimm, N. B., & Kitchell, J. F. (1992). Global change and freshwater ecosytems. Annual Review Ecological Systems, 119-139.

"Warming will alter the stream habitat of coldwater fishes such as trout [Salmonidae], charr [Salvelinus] , and salmon [Salmonidae](Meisner et al., 1988). Projected increases in air temperature will be transferred, with local modification, to groundwaters, resulting in elevated temperatures and reduced oxygen concentrations. At low latitudes and altitudes these changes may have immediate adverse effects on eggs and larvae, which are usually deposited at sites of groundwater discharge. They may also reduce suitable habitat during summer months. Conversely, the winter stressors of osmoregulation at extremely low temperatures and physical damage by ice will be diminished. At higher latitudes and altitudes, elevated groundwater temperatures will increase the duration and extent of optimal temperatures; all life history stages benefit accordingly (Meisner et al., 1988)."

Fang, X., Stefan, H. G., Eaton, J., G., McCormick, J. H., & Alam, S. R. (2004). Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios Part 1. Cool-water fish in the contiguous US. Ecological Modelling, 172, 13-

"Under the projected 2 × CO_2 CCC [Canadian Climate Centre General Circulation Model] climate scenario, low DO [dissolved oxygen] concentrations and resulting winterkill are projected to disappear in shallow lakes (bottom of Fig. 1), because the ice cover period is projected to be up to 90 days shorter than under past conditions. Ice formation is delayed by as much as 40 days, and ice cover melts earlier by up to 67 days (Stefan and Fang, 1997). This influence of climate warming on [cool water] fish survival is positive. In this study it was assumed that low DO is the only factor to control winterkill of fish in

"When thermal stratification starts earlier under a 2 × CO_2 scenario and sedimentary and water column oxygen demands increase with water temperature, DO [dissolved oxygen] concentrations start to decrease earlier and decrease more rapidly over time. Lake volumes where DO is less than the survival limit for cool-water fish are therefore greater under a 2 × CO_2 scenario (Figs. 2 and 3). This and the increase of surface water temperatures under a projected 2 × CO_2 scenario destroy cool-water fish habitat in medium-depth lakes near Austin, Texas, during the summer (Fig. 3), but not near Kansas City, Missouri (Fig. 2). Thus lakes near Austin, Texas, that currently provide fish habitat during both winter and summer periods, are projected to become uninhabitable for cool-water fish during the summer under a 2 × CO_2 climate scenario."

"For 172 locations with cool-water fish habitat remaining under a projected 2 × CO_2 climate scenario, good-growth periods [GSL] range from 111 to 365 days with a mean value of 179 days (Fig. 5 middle and Table 3b). Good-growth periods are projected to increase by up to 127 days in the northern states and to decrease by up to 72 days in several southeastern states (e.g. Tennessee, Kentucky, and Florida, USA) for this medium-depth lake. Projected changes of GSL due to climate warming range from a 60% increase to a 35% decrease from the past values with an average 20% increase."

"Under a 2 × CO_2 climate scenario, projected increases of the GSL [good-growth season], GGHA [good-growth habitat area] and GGHV [good-growth habitat volume] for cool-water fish are on average 20, 10, and 8% from the past values in medium-depth lakes of the contiguous US. Projections of changes due to climate warming range from a 60% increase in the northern states to a 35% decrease in the southeastern states for the length of the good-growth season (GSL), an 80% increase to a 25% decrease for GGHA, and an 80% increase to a 95% decrease for GGHV, for medium-depth lakes. "

"Under the projected 2×CO_2 climate scenario, shallow lakes in the southeastern states are projected to experience summerkill of cool-water fish. Reductions due to climate warming in the number of locations with suitable cool-water fish habitat in the past (1962–1979) are on average 56, 42, and 7 for shallow, medium-depth, and deep lakes, respectively. Thus shallow lakes are projected to experience the most loss of cool-water fish habitat."

Ficke, A. D., Myrick, C. A., & Hansen, L. J. (2007). Potential impacts of global climate change on freshwater fisheries. Rev Fish Biol Fisheries, 581-613.

"Therefore, increasing global temperatures can affect individual fish by altering physiological functions such as thermal tolerance, growth, metabolism, food consumption, reproductive success, and the ability to maintain internal homeostasis in the face of a variable external environment (Fry 1971). Temperature tolerance ranges are species-specific and include both stenothermal (narrow thermal range) species such as Arctic charr (Salvelinus alpinus), and eurythermal (wide tolerance range) species such as common carp (Cyprinus carpio) (Table 1). Fish populations that are faced with changing thermal regimes may increase or decrease in abundance, experience range expansions or contractions, or face extinction."

"Despite their increased ability to metabolize pollutants at warmer temperatures, fishes may still experience increased negative, toxicant-specific effects at higher temperatures. Kock et al. (1996) suggested that non-essential metals such as cadmium and lead are difficult for fish to depurate because no specific metabolic pathway exists to process them. Therefore, fish accumulate these toxins more quickly at higher temperatures. Kock et al. (1996) documented this effect with wild arctic charr (Salvelinus alpinus). Fish exposed to cadmium and lead were unable to completely metabolize the metals, which accumulated in fish tissue and organs. This resulted in positive correlations between metal body burdens and water temperature, and the age of the fish. "

"The suitability of the hypolimnion, an important thermal refuge for numerous cold stenothermal fishes (Brett 1971; Coutant 1985) can be compromised by prolonged and more distinct periods of stratification. An increase in mean temperature will affect hypolimnetic dissolved oxygen concentrations in two ways: increased metabolism of fish and other organisms in a slightly warmer hypolimnion will lead to the faster depletion of the limited oxygen supply, and lake overturn, the primary means of replenishing hypolimnetic dissolved oxygen, will occur less frequently (Regier and Meisner 1990; Gerdaux 1998)."

"When the oxygen demand in the hypolimnion exceeds the supply, hypoxic or anoxic conditions will occur. Fishes that depend upon these thermal compartments are then faced with a ‘‘temperature-oxygen squeeze’’ (Fig. 2); they are confined to a habitat whose boundaries are defined by the warm temperatures in the epilimnion and the low levels of dissolved oxygen in the hypolimnion (Matthews et al. 1985). This severely limits their available spring and summer habitat, because increased ambient temperatures thicken the epilimnion and cause accelerated oxygen depletion in the hypolimnion (Christie and Regier 1988; Gerdaux 1998). As was discussed above, the size of these thermal refugia can be reduced by increased water temperatures. When thermal refugia are reduced in size, the fish are crowded into a smaller volume of water where factors such as rapid oxygen depletion, low prey availability, stress, and the probability of increased disease transmission are present (Coutant 1985)."

Joyce, L. A., Blate, G. M., Littell, J. S., McNulty, S. G., Millar, C. I., Moser, S. C., . . . Peterson, D. L. (2008). National forests. in: Preliminary review of adaptation options for climate-sensitive ecosystems and resources. a report by the U.S. climate change science program and the subcommittee on global change research. U.S.Environmental Protection Agency, 1-127.

"One estimate indicates that cold-water fish habitat may decrease by 30% nationally and by 50% in the Rocky Mountains by 2100 (Preston, 2006)."

"The projected changes in fish habitat associated with increases in temperature and changes in hydrology (Preston, 2006) would cause shifts in the distributions of fish and other aquatic species (Kling et al., 2003)."

Meyer, J. L., Sale, M. J., Mulholland, P. J., & Poff, N. L. (1999). Impacts of climate change on aquatic ecosystem functioning and health. Journal of the American Water Resources Association, 1373-1386.

"The direct effects of increasing temperatures on aquatic ecosystems will be both positive and negative. Species-specific habitat requirements for temperature and dissolved oxygen are sufficiently well known for many game fish species so that likely responses to changing climates can be predicted (Coutant, 1990). In general, climatic warming will produce a general shift in species distributions northward, with extinctions and extirpations of cold-water species at lower latitudes and range expansion of warm-water and cool-water species intohigher latitudes."

Mohseni, O., Stefan, H. G., & Eaton, J. G. (2003). Global warming and potential changes in fish habitat in U.S. streams. Climatic Change, 59, 389-409.

"The results show that there would be a 33% to 39% decrease in the number of streams thermally suitable for cold water fishes, an 11% to 22% decrease for cool water fishes and almost no change for warm water fishes. For most warm water fishes, more than 760 stream reaches (gaging stations) of the 764 investigated had thermally suitable habitat (Figure 4)."

"Figure 5 shows that under the $2 \times CO_2$ climate condition, rainbow trout (Oncorhynchus mykiss), for example, would disappear from the gaging stations located in the Midwest, the Ohio River basin and the East Coast. More precisely, rainbow trout would not vanish from stream reaches at higher altitudes (e.g., the Rocky Mountains and the Appalachian Mountains) because those stations are not projected to experience very warm water temperatures under the $2 \times CO_2$ climate scenario."

"Warm water fishes encounter more thermally suitable habitats under $1 \times CO_2$ (present) climate conditions and a 33% increase is projected for most of them. Warm water streams would not experience a high water temperature rise under a $2 \times CO_2$ climate condition due to evaporative cooling. Hence, most stream gaging stations retain suitable thermal habitat for warm water fishes. In cool streams, minimum stream temperatures rise due to climate warming from say 0 ◦C to 3 ◦C, therefore, the presence of warm water fishes would be much facilitated. For example, there would be a 33% increase in the number of stations thermally suitable for largemouth bass, Micropterus salmoides (Figure 8). More rivers in the Rocky Mountains and at northern latitudes would become inhabited by largemouth bass. Figure 8 shows that there would likely be a northward spread of largemouth bass under the $2 \times CO_2$ climate scenario."

"The results of this study also show that the maximum temperature tolerance will not have a crucial effect on warm water fish habitats because of the evaporative cooling of streams. The maximum temperature tolerance is, however, a limiting factor, which will cause the range of cold water fish to contract northward, i.e., losing habitat in lower latitudes with a northward range extension. Conversely, the lower temperature constraint plays an important role for habitats of cool and warm water fishes. The percentage decrease in suitable thermal habitat of cool water fishes, and northward expansion of the warm water fish range depend upon their minimum temperature tolerances, which need to be determined more accurately."

Noyes, P. D., McElwee, M. K., Miller, H. D., Clark, B. W., Van Tiem, L. A., Walcott, K. C., … & Levin, E. D. (2009). The toxicology of climate change: Environmental contaminants in a warming world. Environment International, 35(6), 971-986.

"Gaunt and Barker (2000) found that the toxicity of the herbicide atrazine to catfish (Ictalurus punctatus) increased with increasing temperature or decreasing dissolved oxygen. They predicted that changes in these two parameters, which would likely occur simultaneously in climate change scenarios, could greatly enhance the toxicity of atrazine to some aquatic species."

Olden, J. D., Kennard, M. J., Lawler, J. J., & Poff, N. L. (2011). Challenges and opportunities in implementing managed relocations for conservation of freshwater species. Conservation Biology, 25(1), 40-47.

"In contrast to many terrestrial species, responses of freshwater fishes and most other obligatory aquatic organisms (with the exception of overland dispersal of adult aquatic insects and some amphibians and water dependent reptiles) to climate change are constrained because they are limited to dispersal along pathways of connected water. The linear nature of dendritic riverine systems makes them highly prone to fragmentation that can disrupt completion of life cycles for many freshwater organisms (Schlosser 1991; Fausch et al. 2002). "

Rahel, F. J., & Olden, J. D. (2008). Assessing the Effects of Climate Change on Aquatic Invasive Species. Conservation Biology, 22(3), 521–533. doi: 10.1111/j.1523-1739.2008.00950.x

"The virulence of M. cerebralis [Myxobolus cerebralis, which causes whirling disease in fish] increases with temperature and thus warmer streams will likely magnify the impact of this parasite on populations of native salmonids."

Sharma, S., Jackson, D. A., Minns, C. K., & Shuter, B. J. (2007). Will northern fish populations be in hot water because of climate change? Global Change Biology, 13, 2052 – 2064.

"Predicted increases in water temperature in response to climate change will have large implications for aquatic ecosystems, such as altering thermal habitat and potential range expansion of fish species. Warmwater fish species, such as smallmouth bass, Micropterus dolomieu, may have access to additional favourable thermal habitat under increased surface-water temperatures, thereby shifting the northern limit of the distribution of the species further north in Canada and potentially negatively impacting native fish communities."

"Increases in water temperatures resulting from climate change are predicted to have a dramatic impact on the water quality and availability of suitable fish habitat. By July 2100, many lakes may experience water temperatures as high as 30 °C. As temperatures warm, there is an expected increase in the rate of evapouration and evapotranspiration which may result in decreased runoff and a decline in water levels (Mortsch & Quinn, 1996). Holomixis is predicted to decrease as the duration of stratification increases, thus reducing hypolimnetic oxygen concentrations and negatively impacting many aquatic organisms, particularly fishes (Stefan & Fang, 1993; Stefan et al., 1993; Rouse et al., 1997; Lehman, 2002)."

"Limnological changes in response to climate change may affect ecosystem productivity and fish biology. Changes in climate will affect all members of the foodweb, for example declines in diatom production (Schindler et al., 1996) and changes in the production of phytoplankton and zooplankton (Mortsch & Quinn, 1996). A decline in water levels and low flow could negatively affect spawning, nursery and feeding grounds in shallow regions (Meisner et al., 1987; Schindler et al., 1996). Such water-level reductions could lead to reduced access to spawning regions, increased exposure to turbidity, wave action and an alteration in habitat necessary for developing eggs and larvae (Meisner et al., 1987). As temperatures increase and dissolved oxygen levels decline, respiration rates and metabolism in aquatic organisms could increase and stages of embryonic development could be impaired (Lehman, 2002). "

"As temperatures increase and the thermal regime is shifted northward, smallmouth bass [Micropterus dolomieu] populations are expected to follow the northerly shift in thermal habitat (King et al., 1999; Casselman et al., 2002; Jackson & Mandrak, 2002; Shuter et al., 2002) where they had been previously restricted by a cooler thermal habitat preventing successful overwintering (Shuter et al., 2002). We have shown that climate change has the potential to greatly influence the smallmouth bass distribution by increasing the amount of thermal habitat available to the warmwater fish species over thousands of kilometres. By July 2100, the majority of the lakes in Canada could potentially contain suitable thermal habitat to sustain smallmouth bass populations."

Stefan, H. G., Fang, X. & Eaton, J. G. (2001). Simulated fish habitat changes in North American lakes in response to projected climate warming. Transactions of the American Fisheries Society, 130, 459 – 477.

"Overall, climate warming is projected to reduce the number of locations with suitable coldwater fish habitat by up to 94 or 45% of the 209 locations investigated (Table 3). The reductions in the number of shallow, medium-depth, and deep lakes with year-round coldwater fish habitat are on average 29, 90, and 65 locations, respectively. Therefore, the strongest loss of coldwater fish habitat due to climate warming is projected for medium-depth lakes. At up to 30 locations in northern latitudes (e.g., Duluth, Minnesota; Figure 4), shallow eutrophic lakes are projected to experience a shift from winterkill to summerkill (Case A in Table 6). Only at 3 or 4 northern locations are small and medium-size eutrophic shallow lakes projected to show a shift from winterkill to suitable year-round fish habitat (Case B in Table 6). This is the only positive impact of climate warming on coldwater fish."

"In summary, the positive impact of global warming on fish habitat is to eliminate winterkill in shallow lakes for all three fish guilds; on the negative side, however, there is a shift from winterkill to summerkill (Case A in Table 6) for coldwater fish. For coolwater and warmwater fish, locations with winterkill are projected to support year-round fish habitat after climate change. The projected negative impacts of climate warming on fish habitat clearly outweigh the positive ones. Loss of coldwater and coolwater fish habitat in many locations is indicated by the numbers in Tables 3–5 and the geographic distribution in Figure 5."

"At present, coldwater fish in seasonally stratified lakes find habitat as far south as Nevada, Utah, Colorado, Kansas, Iowa, Ohio, and Pennsylvania (Figure 6). Climate warming will change that, except for a small fringe along the Canadian border and the west coast, where the good-growth period for coldwater fishes will shorten from about 150 d to 100 d (Figure 6). Coolwater fish currently find habitat in seasonally stratified lakes everywhere in the country (Figure 7). Climate warming will introduce summerkill of coolwater species in the southeastern states (Florida, Texas, Louisiana, Mississippi, Alabama, Georgia, North Carolina, and South Carolina). The good-growth period will be lengthened by up to 50 d in the northern and middle latitudes of the contiguous United States (Figure 7). "

"Warmwater fish are projected to exist at all locations in seasonally stratified lakes (Figure 8) under both climate scenarios. Going from north to south, the good-growth length for coldwater fish decreases (Figure 6), but it increases for coolwater and warmwater fish guilds (Figures 7, 8). GSL [good-growth season length] is higher for coolwater fish than for warmwater fish."

Xenopoulos, M. A., & Lodge, D. M. (2006). Going with the flow: using species-discharge relationships to forecast losses in fish biodiversity. Ecology, 87(8), 1907-1914. doi:10.1890/0012-9658(2006)87[1907:GWTFUS]2.0.CO;2

"At the global scale we predicted fish losses up to 75% using climate and water consumption scenarios from the IPCC [Intergovernmental Pannel on Climate Change] (Xenopoulos et al. 2005)."

NORTH CENTRAL

Sharma, S., Vander Zanden, M. J., Magnuson, J. J., & Lyons, J. (2011). Comparing Climate Change and Species Invasions as Drivers of Coldwater Fish Population Extirpations. PLoS ONE, 6(8), e22906. doi:10.1371/journal.pone.0022906

"As water temperatures increase, the duration of the lake stratification period is expected to increase, isolating the deep waters from exchanges with the atmosphere, making it more likely that metabolic activity will reduce dissolved oxygen concentrations in the hypolimnion to stressful or lethal levels (Hondzo & Stefan 1993, De Stasio et al. 1996, Stefan et al. 1996). The combination of warmer water temperatures and lower dissolved oxygen concentrations under climate change scenarios in larger, deeper lakes typically suitable for coldwater fishes could result in their extirpation."

"We found, not surprisingly, that the largest percent cisco extirpations were expected with the A2 climate change scenarios (business-as-usual) and the best-case climate change scenario (B1) predicted the lowest loss of cisco [Corgeonus artedii] both for the middle and end of the century (Table S1)."

"The number of cisco [Corgeonus artedii] extirpations depends on the magnitude of climate warming. For example, an increase in mean annual air temperatures across Wisconsin of 5°C is expected to result in a loss of 50% of cisco populations. Our application of the conservative MIROC-A1 climate change scenario developed by the Division of Climate System Research in Tokyo, Japan, projects the extirpation of over 70% of cisco populations in Wisconsin by the end of the century."

"Under climate change scenarios, the intensity of stratification is expected to increase which may reduce the amount of coldwater habitat available during the summer (Mackenzie-Grieve & Post 2006). For example, hypolimnetic water temperatures in deep Minnesota lakes are projected to increase by 1°C in the north and by 3°C in the south (Stefan & Fang 1993). This would still be in the range suitable for cisco [Corgeonus artedii]."

"Climate change is expected to lead to warmer air and epilimnetic water temperatures (Sharma et al. 2007) and a longer growing season (Walther et al. 2002) which could lead to higher pelagic primary productivity (Rouse et al. 1997). Increased primary productivity will lead to greater respiration ultimately leading to increased depletion rates of dissolved oxygen in the hypolimnion which can approach stressful or lethal levels for coldwater fishes (Magnuson et al. 1997, Schindler et al. 1996, Rennie et al. 2010)."

"Climate change in conjunction with changes in lake productivity owing to increased runoff from extreme precipitation events would be expected to exacerbate lake eutrophication and present a greater threat to cisco [Corgeonus artedii]. Climate change is expected to lead to warmer air and epilimnetic water temperatures (Sharma et al. 2007) and a longer growing season (Walther et al. 2002) which could lead to higher pelagic primary productivity (Rouse et al. 1997). Increased primary productivity will lead to greater respiration ultimately leading to increased depletion rates of dissolved oxygen in the hypolimnion which can approach stressful or lethal levels for coldwater fishes (Magnuson et al. 1997, Schindler et al. 1996, Rennie et al. 2010). Shallow, eutrophic lakes that are deep enough to have deep, cold waters are expected to be at a higher risk (Fang et al. 2004)."

"In conjunction with increases in air temperature, more extreme rainfall events attributed to climate change (Easterling et al. 2000) could lead to greater runoff, increased nutrient inputs, higher primary productivity, and consequently a decline in coldwater fish habitat suitability (Magnuson et al. 1997)."

"The distribution and growth of rainbow smelt [Corgeonus artedii] may also be altered by climate change. Rainbow smelt are a coldwater fish species preferring large, deep, clear, unproductive lakes and may experience similar responses as cisco [Corgeonus artedii] populations to climate change (Evans & Loftus 1987). As such, rainbow smelt may experience loss of habitat under climate change scenarios further reducing the impact of rainbow smelt on cisco populations in Wisconsin."

R8: SOUTHERN

Coutant, C. C. (1990). Temperature-Oxygen habitat for freshwater and coastal striped bass in a changing climate. Transactions of the American Fisheries Society, 119(2), 240-253. doi:10.1577/1548-8659(1990)

"Stocks [of striped bass, Morone saxatilis] along the Gulf of Mexico and Florida east coast may be reduced or extirpated. Summer water temperatures there could be much in excess of those that the fish can tolerate, except where cool river waters are maintained by summer hypolimnetic discharges from reservoirs or artesian water from large springs—which seem to be major factors in survival now (Wooley and Crateau 1983; Coutant 1985)."

Mulholland, P. J., Best, G. R., Coutant, C. C., Hornberger, G. M., Meyer, J. L., Robinson, P. J, Stenberg, J. R., … & Wetzel, R. G. (1997). Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. Hydrological Processes, 11, 949-970. doi: 10.1002/(SICI)1099-1085(19970630)11:8<949::AID-HYP513>3.0.CO;2-G

"By relating the southern limits of brook trout [Salvelinus fontinalis] distribution to the 15°C groundwater temperature isotherm, Meisner (1990) projected that a 3.8°C increase in mean annual air temperature would result in elimination of this species in Georgia, South Carolina and parts of Virginia, and increased fragmentation of its distribution in Tennessee and North Carolina."

"Summer warming of surface waters and dissolved oxygen depletion in deeper waters forces cool water species such as trout, striped bass [Morone saxatilis], sauger [Sander Canadensis] and walleye [Sander vitreus] into a habitat `squeeze' as areas with suitable temperatures and adequate dissolved oxygen contract (Figure 3). Increases in summer temperatures and changes in both natural and managed hydrological regimes that increase water residence times (reduce flow) will intensify the summer habitat squeeze as cool water refugia become more restricted and microbial metabolism depletes oxygen levels faster in the deeper layers. Increased habitat constriction will increase the vulnerability of cool water fishes to food depletion, overharvest and disease."

Waldman, J. (2011). Conservation and restoration of Acipenser oxyrinchus in the USA. In Williot, P., Rochard, E., Desse-Berset, N., Kirschbaum, F., and Gessner, J., editors, Biology and Conservation of the European Sturgeon Acipenser sturio L. 1758, 517-526. Springer Berlin Heidelberg. doi:10.1007/978-3-642-20611-5_39

"Climate change remains a threat, in particular warming experienced by Gulf sturgeon [Acipenser oxyrinchus desotoi] and southern populations of Atlantic sturgeon [Acipenser oxyrinchus] that already exist under marginal thermal conditions, as has been seen for another partly sympatric anadromous species, rainbow smelt Osmerus mordax, which has retreated from the southern portion of its Atlantic coast range (Waldman et al. 2006)."

R9: EASTERN

Jones, M. L., Shuter, B. J., Zhao, Y., & Stockwell, J. D. (2006). Forecasting effects of climate change on great lakes fisheries: Models that link habitat supply to population dynamics can help. Canadian Journal of Fisheries and Aquatic Sciences, 457-468.

"Climate change will affect fish populations and communities through its effect on fish habitat. For a particular species, the effect can operate directly on habitat important to that species or indirectly via effects on the habitat of another species (e.g., a competitor). In either case, predictions of the effect of climate change will depend on understanding (i) expected changes in physical conditions that comprise habitat for fishes and (ii) the link between changes to physical habitat and the demographic performance of the affected species (e.g., growth, survival, and reproduction). In the latter case, effects will also depend on the strength of interactions between species affected by the habitat change and thespecies of interest."

NORTH ATLANTIC

Coutant, C. C. (1990). Temperature-Oxygen habitat for freshwater and coastal striped bass in a changing climate. Transactions of the American Fisheries Society, 119(2), 240-253. doi:10.1577/1548-8659(1990)

"The estimated change in timing of [striped bass, Morone saxatilis] spawning depends on both location and climate change model (Figure 5). In northern latitudes, exemplified by coastal water temperatures at Bar Harbor, Maine, the two [climate] models [Goddard Institute for Space Studies and Geophysical Fluid Dynamics Laboratory models] differ by nearly 1 month in the estimated time at which spawning temperatures will be reached. Because striped bass in Canada are reported to spawn over a wide range of temperatures, it is difficult to estimate a timing change."

SOUTH ATLANTIC

Coutant, C. C. (1990). Temperature-Oxygen habitat for freshwater and coastal striped bass in a changing climate. Transactions of the American Fisheries Society, 119(2), 240-253. doi:10.1577/1548-8659(1990)

"A pronounced upward shifting of estimated annual [eastern] coastal temperatures characterizes both [Goddard Institute for Space Studies and Geophysical Fluid Dynamics Laboratory] climate models (Figure 3). The South Carolina coast could be above 25°C, and avoided by striped bass [Morone saxatilis], from April to early November, during which time temperatures may peak well above 30°C."

"The [North Carolina] Roanoke River-Albemarle Sound striped bass [Morone saxatilis], which lie at the boundary between the coastal migratory habits of the more northern fish and the riverine habits of the more southern stocks, could become clearly riverine and congregate in summer in the cool dam tailwaters upriver."

EAST

Coutant, C. C. (1990). Temperature-Oxygen habitat for freshwater and coastal striped bass in a changing climate. Transactions of the American Fisheries Society, 119(2), 240-253. doi:10.1577/1548-8659(1990)

"The zone of optimal coastal temperatures for striped bass [Morone saxatilis] in summer could shift to mid-New England, north of Cape Cod. The latitude of Chesapeake Bay, where males and perhaps half of the females are resident throughout the year (Kohlenstein 1981), would probably become too warm (as discussed in more detail later in this paper)."

"Particularly important in these northern regions [of northern Maine and Canada] would be warmer conditions for juvenile [striped bass, Morone saxatilis] rearing, because the juvenile thermal niche of 24-28°C would be more likely to occur in the shallow estuaries."

"At other sites, exemplified by the Hudson River, the Chesapeake Bay, and the Savannah River, the estimated differences in [striped bass, Morone saxatilis] spawning times [from two climate change models] are more clear, ranging from 3 to 4 weeks."

"Concurrent with temperature change can be a flooding of the [striped bass, Morone saxatilis] spawning estuaries and wetland nursery areas by rising sea levels (Orson et al. 1985). Predictions of how the coastal environment necessary for striped bass spawning and juvenile rearing will respond to a rising sea level require consideration of many coastal processes (Mehta et al. 1987) including tidal ranges, storm surges, intrusion of ground water and surface water, and sedimentary processes, as well as the responses by the plant communities of coastal ecosystems to changes in these processes. The results are likely to be highly site specific and to include changes both in temperature and dissolved oxygen structure and in physiographic features."

"As climate warms, estuaries now highly important for fish species such as the striped bass [Morone saxatilis] may no longer provide suitable thermal niche space, especially in summer."

"The month-long periods of unsuitably high temperatures for adult striped bass [Morone saxatilis] that have occurred in a large portion of the [Chesapeake] bay in recent years may increase to about 3 months of equally or more unsuitable thermal conditions in the future."

"A current problem for striped bass [Morone saxatilis] in Chesapeake Bay—expanded anoxia in the deeper waters over the past two decades (Officer et al. 1984; Price et al. 1985)—may be intensified by climate warming. Earlier temperature rise and protracted fall cooling may mean both earlier and more prolonged hypoxia. Thus, the deeper layers with cooler temperatures closer to those preferred are likely to be unavailable to striped bass; only waters much warmer than 25°C may remain oxygenated in the middle and upper bay."

"Despite the loss of suitable temperature-oxygen habitats in summer, conditions in the [Chesapeake] bay during the remainder of the year might be more suitable for striped bass [Morone saxatilis]—closer to the thermal niche—than they are now, and thus might promote higher annual striped bass production."

Najjar, R. G., Walker, H. A., Anderson, P. J., Barron, E. J., Bord, R. J., Gibson, J. R., Kennedy, V. S., … & Swanson, R. S. (2000). The potential impacts of climate change on the mid-Atlantic coastal region. Climate Research, 14, 219-233.

"There is a historical basis for expecting warming to have significant impacts on estuarine and marine fish and shellfish in the mid-Atlantic. For example, Murawski (1993) found that marine temperature variation on the North American east coast explained changes in the north-south distribution of 12 of 36 species of fish."

"The interactions between higher temperatures and depleted oxygen noted earlier could constrict the available habitat for a variety of species along the North American east coast, including striped bass Morone saxatilis in Chesapeake Bay, an important spawning center for this species (Coutant 1990)."

Ospina-Alvarez, N., & Piferrer, F. (2008). Temperature-dependent sex determination in fish revisited: prevalence, a single sex ratio response pattern, and possible effects of climate change. PLoS One, 3(7), e2837. doi:10.1371/journal.pone.0002837

"In fish, observations made with [Menidia menidia, Atlantic silverside] eggs collected from the wild have shown that differences of 2°C during the thermosensitive period can result in sex ratio shifts from 50% to 69% males [Conover & Heins 1987]."

Spooner, D. E., Xenopoulos, M. A., Schneider, C., and Woolnough, D. A. (2011). Coextirpation of host–affiliate relationships in rivers: the role of climate change, water withdrawal, and host-specificity. Global Change Biology, 17(4), 1720-1732. doi:10.1111/j.1365-2486.2010.02372.x

"Fish extirpations associated with decreased [river] discharge, on average, ranged from 1 to 20 fish species (Fig. 4c) representing 5–60% of the fish species in the river [across the eastern US] (Fig. 4d). In extreme examples, fish extirpations are forecasted to be as high as 30–40 species representing up to 80–100% of the river-wide fish fauna. While these numbers appear to be high because they represent one of the more extreme climate scenarios (IPCC SRES A2), they corroborate both extreme (30–40 species) and average (0–10 species) historical losses documented via the Natureserve database (Fig. 4b) (NatureServe, 2004)."

"Our simulations [of river discharge alterations governing mussel and fish extirpations in the eastern US] indicate that continued climate-related stressors and water use pressures on rivers will result in considerably more extirpations of aquatic fauna. We show for the first-time that host–affiliate coextirpations are also possible in aquatic environments, and that the intensity of these losses will depend upon the unique abilities of both hosts and affiliates to respond to alterations in water availability as well as the degree in overlap that affiliates share among their respective hosts."

Xenopoulos, M. A., & Lodge, D. M. (2006). Going with the flow: using species-discharge relationships to forecast losses in fish biodiversity. Ecology, 87(8), 1907-1914. doi:10.1890/0012-9658(2006)87[1907:GWTFUS]2.0.CO;2

"Although caution is necessary in applying these regressions in a forecasting mode (Prairie 1996), we modeled hypothetical fish extinctions, given hypothetical reductions of 20–90% in river discharge (Table 3). The hypothetical percentage of fish species becoming extinct ranged among rivers and flow reduction scenarios from 2% to 30% in the Lower Ohio–Upper Mississippi basin and 3% to 38% in the Southeastern U.S. biogeographic region (Table 3)."

RESOURCE AREA (FACTOR): ANIMAL COMMUNITIES

FISH

EAST

Spooner, D. E., Xenopoulos, M. A., Schneider, C., and Woolnough, D. A. (2011). Coextirpation of host–affiliate relationships in rivers: the role of climate change, water withdrawal, and host-specificity. Global Change Biology, 17(4), 1720-1732. doi:10.1111/j.1365-2486.2010.02372.x

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INVERTEBRATES

NATIONAL

Golladay, S. W., Gagnon, P., Kearns, M., Battle, J. M., & Hicks, D. W. (2004). Response of freshwater mussel assemblages (Bivalvia: Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. Freshwater Science, 23(3), 494-506. doi: 10.1899/0887-3593(2004)023<0494:ROFMAB>2.0.CO;2

"Several mechanisms for enduring drought-related environmental change have evolved among the Unionidae. Some freshwater mussels have the capacity to lower metabolic activity in response to temporary temperature changes and DO [dissolved oxygen] stress (e.g., [Elliptio complanta], [Utterbackia imbecillis], Pyganodon grandis) (Bayne 1967, Burky 1983, Sheldon and Walker 1989, McMahon 1991)."

NORTH ATLANTIC

Taner, M. Ь., Carleton, J. N., Wellman, M. (2011). Integrated model projections of climate change impacts on a North American lake. Ecological Modelling, 222, 3380-3393. doi:10.1016/j.ecolmodel.2011.07.015

"Benthic macroinvertebrate dynamics [for Onondaga Lake, New York] appear complex and nonlinear, with the direction and magnitude of responses showing substantial variability among different scenarios. In general, zebra mussels [Dreissena polymorpha] are projected to benefit from climate change, while chironomids [non-biting midges from the family Chironomidae] are projected to decline."

SOUTH ATLANTIC

Golladay, S. W., Gagnon, P., Kearns, M., Battle, J. M., & Hicks, D. W. (2004). Response of freshwater mussel assemblages (Bivalvia: Unionidae) to a record drought in the Gulf Coastal Plain of southwestern Georgia. Freshwater Science, 23(3), 494-506. doi: 10.1899/0887-3593(2004)023<0494:ROFMAB>2.0.CO;2

"The results of our study [in the Flint River Basin of southwestern Georgia] generally concur with the observations of Johnson (2001). We observed substantial declines in mussel abundance in non-flowing streams, but substantial numbers of [Elliptio complanta/icterina], [Villosa lienosa], and [Villosa villosa] survived at some of the sites. Several of the special concern species including, [Lampsilis straminea claibornensis], V. villosa, and [Lampsilis subangulata] showed declining trends or disappeared from a number of non-flowing sites suggesting intolerance to drought stress. The drought tolerance of other mussel species in the lower FRB remains undocumented."

"Declines in mussel populations appear to be associated with unusual climatic conditions and increasing demand on the streams in the area and the regional aquifer system for irrigation water supply. Thus, infrequent disturbances, such as the 2000 drought [experienced in the Flint River Basin (FRB) of southwestern Georgia], stress the remaining populations and accelerate the loss of freshwater mussel diversity from the lower FRB."

SOUTH CENTRAL

Galbraith, H. S., Spooner, D. E., & Vaughn, C. C. (2010). Synergistic effects of regional climate patterns and local water management on freshwater mussel communities. Biological Conservation, 143(5), 1175-1183. doi:10.1016/j.biocon.2010.02.025

"Mussel communities in the Kiamichi River [a major tributary of the Red River in southeastern Oklahoma] changed over the 15 year period of this study, with overall abundance and species richness decreasing and relative abundance patterns shifting from assemblages dominated by thermally sensitive to thermally tolerant species. These changes corresponded with a period of very low flows in the river, which appear to have been caused by a combination of climate patterns (a regional drought; Figs. 3 and 6a) and local water management practices (reduced reservoir releases; Fig. 6b). These low flows coupled with high summer air temperatures (Fig. 3), changed the Kiamichi River in many locations from a continuously flowing river to a series of shallow, isolated pools where water temperatures sometimes exceeded 40 °C (Figs. 2, 5b; Spooner and Vaughn, 2000)."

"We believe that thermal stress associated with low water levels is one of the proximate causes underlying the declines we observed in mussel abundance and species richness [in the Kiamichi River a major tributary of the Red River in southeastern Oklahoma], and our observation that mussel mortality was related to water depth and thus temperature supports this premise (Fig. 5). In addition, we observed that once mussels began dying in these isolated pools (Fig. 2), tissue decay led to large nutrient pulses (Vaughn et al., 2008), algal blooms, lowered dissolved oxygen levels, and thus further mussel

Spooner, D. E., & Vaughn, C. C. (2008). A trait-based approach to species' roles in stream ecosystems: climate change, community structure, and material cycling. Oecologia, 158(2), 307-317. doi: 10.1007/s00442-008-1132-9

"The magnitude, periodicity, and duration of droughts are increasing in the southern Unites States and mean summer temperatures are predicted to increase by as much as 4°C over the next 50 years (IPCC 2001; Mulholland et al. 1997). Many mussel species are already experiencing temperatures in the upper end of their thermal tolerance zone in this region [the Little River in southeastern Oklahoma], thus these increased temperatures (and associated decreased precipitation) will likely profoundly influence mussel community structure and the resulting ecosystem services in rivers in this region. For example, we detected significant effects of temperature on the physiology and ecological services provided by mussels at 35°C, and we observed mortality of three of the thermally sensitive species at 37–38°C, indicating that these temperatures are their upper limits for survival and reproduction."

"We have already observed changes in mussel community structure that are linked to stream warming. Monitoring data for ten sites in the Kiamichi River show that overall mussel abundance and species richness have declined over the past 17 years as water temperatures have increased, and that mussel beds once dominated by thermally sensitive species are now dominated by thermally tolerant species (H. S. Galbraith et al., unpublished data). Our results [from the Little River in southeastern Oklahoma] indicate that these changes in community composition will lead to changes in ecosystem function."

EAST

Spooner, D. E., Xenopoulos, M. A., Schneider, C., and Woolnough, D. A. (2011). Coextirpation of host–affiliate relationships in rivers: the role of climate change, water withdrawal, and host-specificity. Global Change Biology, 17(4), 1720-1732. doi:10.1111/j.1365-2486.2010.02372.x

"Mussel extirpations resulting from declining discharge were variable and typically ranged from 1 to as many as 20 species (Fig 5a) representing 5–60% (Fig. 5d) of the river-wide mussel fauna [across rivers in the eastern US]. As in the fish extirpation models, a few extreme reductions could result in up to 30–40 species extirpations representing almost the entire river mussel fauna. Secondary mussel extirpations associated with modeled loss of host fish were considerably lower than those stemming from discharge reductions (Figs 5b and 6). Nonetheless, between 1 and 21 species were predicted to be lost due to loss of hosts representing up to 43% of the mussel communities (Fig. 5e)."

RESOURCE AREA (FACTOR): INVASIVE SPECIES

INVASIVE ANIMALS: AQUATIC

NATIONAL

Rahel, F. J., & Olden, J. D. (2008). Assessing the Effects of Climate Change on Aquatic Invasive Species. Conservation Biology, 22(3), 521–533. doi: 10.1111/j.1523-1739.2008.00950.x

"An increase in floods may increase the dispersal of non-native species, such as zebra mussels, whose planktonic larvae are transported through streams (Havel et al. 2005)."

"Reservoirs may also influence biotic interactions between native and non-native species. Non-native species may be minor components of the biota in streams but can become competitively dominant species in reservoirs (e.g., common carp and zebra mussels; Havel et al. 2005)."

R8: SOUTHERN

Drake, J. M., & Bossenbroek, J. M. (2004). The potential distribution of zebra mussels in the United States. BioScience, 54(10), 931-941. doi:10.1641/00063568(2004)054[0931:TPDOZM]2.0.CO;2

"Turning to our projections of invasion risk in the Southeast [using a genetic algorithm for rule-set production (GARP) that includes the IPCC (Intergovernmental Panel on Climate Change) baseline climate dataset to select predictive models of species ranges], where the species richness of unionid mussels is especially high (figure 7), we observe that this region is highly susceptible to zebra mussel [Dreissena polymorpha] invasion, according to model I (with the risk of invasion approaching 100 percent). In the Southeast, unlike the western river systems, models II and III show a significantly lower invasion risk than model I, diminishing our confidence that the region is habitable by zebra mussels. However, this only reduces the risk from high (approaching 100 percent) to moderate (about 50 percent). Given the high density of endemic unionid species, even the lowest estimates of invasion risk in the Southeast are worrisome. We reiterate that even if our models suggest that a region is habitable by zebra mussels in only 50 of 100 models, this is unacceptably high in light of the high biodiversity losses to be expected from invasion by zebra mussels."