Climate Change Impacts on Freshwater Fishes: A Canadian Perspective

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Current and projected patterns of global climate change are a major concern to freshwater fisheries in Canada. The magnitude of the impacts of climate change vary among species and ecoregions. The latest climate change scenario projections for Canada suggest that by 2050 temperatures will increase between about 4.9°C ± 1.7°C (average mean ± standard deviation) and 6.6°C ± 2.3°C under the Representative Concentration Pathways (RCPs) 2.6 and 8.5 emission scenarios, respectively. These changes will have an important influence on the physiology, distribution, and survival of freshwater fishes, as well as other ecological processes in direct, indirect, and complex ways. Here we provide a perspective from the Canadian Aquatic Resources Section on the impacts of climate change to freshwater fishes. Given the geographic size and diversity of landscapes within Canada, we have divided our perspective into three regions: eastern, western, and northern Canada. We outline the impacts of climate change to these regions and outline challenges for fisheries managers. Because climate change does not operate in isolation of other environmental threats, nor does it impact species in isolation, we suggest improved interjurisdictional integration and the use of an adaptive and ecosystem-based approach to management of these threats.

INTRODUCTION

The Canadian Aquatic Resources Section (CARS) has a mandate to promote the conservation, development, and wise management of aquatic resources in Canada, within the context of sound ecological principles and sustainability. Inland recreational fisheries in Canada encompasses over 3.6 million anglers and represents CDN$2.5 billion in direct expenditures and $8.7 billion in other purchases annually (DFO 2013). Current and projected patterns of global climate change are a major concern to freshwater fisheries in Canada. The magnitude of the impacts of climate change vary among species and ecoregions, but it has been predicted to be higher particularly in northern freshwater ecosystems as water temperature is predicted to rise faster in northern regions due to reduced ice cover and decreased albedo effects (Hansen et al. 2006; Karl et al. 2009). A study has already shown that in the experiment lake areas (Ontario), mean annual air temperatures have risen by 2°C and evaporation rates have increased by 30% within a 20-year period (1960s to mid-1980s; Schindler et al. 1990), and the latest climate change scenario projections for Canada suggest that by 2050 temperatures will increase between about 4.9°C ± 1.7°C (average mean ± standard deviation) and 6.6°C ± 2.3°C under the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCPs) 2.6 and 8.5 emission scenarios, respectively (Figure 1). Because temperature affects ectothermic species such as freshwater fishes (Whitney et al., this issue), changes in water temperature, snowpack, and permafrost will have an important influence on the physiology, distribution, and survival of freshwater fishes, as well as other ecological processes in direct, indirect, and complex ways (Table 1).

EASTERN CANADA

Eastern Canada, defined here as the region spanning the provinces of Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island, and Newfoundland and Labrador, encompasses an area of 2.7 million km². The region includes hundreds of thousands of freshwater lakes, thousands of kilometers of natural and regulated rivers, and some of the largest tracks of pristine wetlands and boreal forests in the world (NRCan 2010). These aquatic ecosystems drain into the St. Lawrence River, Hudson Bay, and Atlantic Ocean (NRCan 2010) and include eight freshwater ecoregions of the world (Abell et al. 2008). The latest IPCC RCP projections indicate that by the 2070s, air temperatures will increase throughout eastern Canada by 2°C–11°C, with greater warming in the north (Figure 1). Precipitation will generally increase throughout the region, but northern Quebec and Labrador will have the greatest
increases of 150–350 mm by the 2070s. In addition to these general regional patterns, the water budgets of the lakes, rivers, and wetlands will be affected by variations in the seasonal timing and magnitude of temperature and precipitation.

The highest biodiversity of freshwater fishes in Canada is found in the Laurentian Great Lakes Ecoregion (approximately 120 species) and decreases with latitude (Abell et al. 2008). Fish assemblages in southern watersheds are dominated by warmwater and coolwater species, such as centrarchids and percids, whereas more northern watersheds are dominated by coldwater salmonids (Chu et al. 2014). Several studies have projected the impacts of climate change on aquatic ecosystems in different regions of eastern Canada. These include increases in lake and stream temperatures in Ontario and New Brunswick (Kurylyk et al. 2013; Chu 2015); increases in winter discharges, earlier spring freshets, and decreases in spring discharges in tributaries of the St. Lawrence River in Quebec (Boyer et al. 2010); decreases in winter stream surface temperatures due to snow melt in east–central New Brunswick (Kurylyk et al. 2013); and degradation of perennially frozen peatlands and severe drying of peatlands in the northern region of eastern Canada (Tarnocai 2009). Documented effects of climate change on freshwater habitats in eastern Canada are rare, but a handful of studies suggest that lake temperatures have increased (Dobiesz and Lester 2009), and winter flows in some rivers have increased due to snowmelt (Beauchamp et al. 2015). These changes will likely be amplified into the next century under the temperature and precipitation changes. Evidence of the impacts of climate change on freshwater fish species distributions, phenology, and population and assemblage dynamics is mounting (Casselman 2002; Robillard and Fox 2006; Alofs et al. 2014; Lynch et al., this issue). The northern range limits of centrarchids that prefer warm waters are moving poleward at the rate of 13 km/decade (Alofs et al. 2014); earlier spawning runs and smolt outmigration in Atlantic Salmon *Salmo salar* (Russell et al. 2012); mismatch between the timing of smolting (Friedland et al. 2003); biogeochemical conditions in the marine environment; and the proportion of coolwater and warmwater species in fish assemblages are shifting from coldwater and coolwater assemblages to those dominated by coolwater and warmwater species (Robillard and Fox 2006). These observations are consistent with the forecasted changes in species distributions, phenology, and assemblages in eastern Canada (Power 1990; Chu et al. 2005; Jonsson and Jonsson 2009).

In eastern Canada, inland commercial fisheries support a $37.5 million industry, whereas recreational fisheries support a $3.39 billion industry (DFO 2013). The most harvested commercial species are Yellow Perch *Perca flavescens* and Walleye *Sander vitreus*. Recreational harvest varies by region, but the most sought after species are Brook Trout *Salvelinus fontinalis* (Russell et al. 2012) and Walleye (DFO 2013). The potential decline or increase in habitat availability and...
Table 1. Summary of some key environmental changes (ongoing and anticipated) in Canadian freshwater ecosystems and potential consequences to their fish communities resulting from climate change. The table is not meant to be read across; that is, changes and effects in the same “row” do not imply direct links; rather, effects are likely the result of interactions among several environmental changes. Also listed are anticipated effects of increased human population and development activities. This table is a synthesis of the following sources: Schindler et al. (1990); Minns and Moore (1992, 1995); Prowse et al. (2011); Reist et al. (2006, 2013, 2015); Schindler and Donahue (2006); Ficke et al. (2007); Angers et al. (2010); Vincent et al. (2011); Culp et al. (2012); Linnansaari et al. (2012); Shuter et al. (2012); CAFF (2013); Nielsen et al. (2013); Salinas et al. (2013). ↑ = increase; ∆ = change.

<table>
<thead>
<tr>
<th>Expected changes</th>
<th>Environmental effects</th>
<th>Biotic effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑ frequency of extreme climate events</td>
<td>↑ permafrost degradation and ∆ thermokarst processes</td>
<td>∆ quantity and access to critical habitat</td>
</tr>
<tr>
<td>∆ seasonal phenology</td>
<td>∆ drainage patterns</td>
<td>↑ mismatch of phenology and life history</td>
</tr>
<tr>
<td>↑ air temperature (especially winter)</td>
<td>∆ ice breakup processes and timing</td>
<td>∆ contaminant bioaccumulation</td>
</tr>
<tr>
<td>↑ water temperature</td>
<td>∆ freshet timing, duration, and magnitude</td>
<td>∆ population structure (e.g., age and size classes)</td>
</tr>
<tr>
<td>∆ precipitation (amount and form)</td>
<td>∆ groundwater levels</td>
<td>∆ demographic parameters</td>
</tr>
<tr>
<td>∆ ice cover duration</td>
<td>∆ evaporation, surface water levels, and habitat connectivity</td>
<td>∆ phenotype and genotypes</td>
</tr>
<tr>
<td>∆ ice thickness</td>
<td>∆ timing and magnitude of nutrient and dissolved organic carbon (DOC)</td>
<td>∆ ecosystem productivity and relative contributions from terrestrial, pelagic and benthic sources</td>
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<tr>
<td>∆ wind patterns</td>
<td>∆ ecosystem productivity</td>
<td>∆ geographical range limits of northern and southern species</td>
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<tr>
<td>∆ atmospheric pressure</td>
<td>∆ turbidity and light regime</td>
<td>∆ community composition and relative abundance (predators, prey, competitors, parasites)</td>
</tr>
<tr>
<td>↑ human population and activities</td>
<td>∆ sedimentation</td>
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</tr>
<tr>
<td>∆ drainage patterns</td>
<td>∆ carbon source/sinks/availability</td>
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<tr>
<td>∆ ice breakup processes and timing</td>
<td>∆ mixing/stratification patterns, oxygen, and thermal profiles</td>
<td></td>
</tr>
<tr>
<td>∆ freshet timing, duration, and magnitude</td>
<td>↑ mobilization and toxicity of contaminants</td>
<td></td>
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<tr>
<td>∆ groundwater levels</td>
<td>∆ contaminant catchments (air and water)</td>
<td></td>
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<tr>
<td>∆ evaporation, surface water levels, and habitat connectivity</td>
<td>↑ industrial activities and infrastructure</td>
<td></td>
</tr>
<tr>
<td>∆ timing and magnitude of nutrient and DOC</td>
<td>↑ resource exploitation (commercial, recreational)</td>
<td></td>
</tr>
<tr>
<td>∆ ecosystem productivity</td>
<td>↑ contaminant export from the south via long-range atmospheric transport</td>
<td></td>
</tr>
<tr>
<td>∆ turbidity and light regime</td>
<td>∆ sedimentation</td>
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<td>∆ resource exploitation (commercial, recreational)</td>
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<tr>
<td>↑ contaminant export from the south via long-range atmospheric transport</td>
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<td>↑ mismatch of phenology and life history</td>
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<tr>
<td>∆ population structure (e.g., age and size classes)</td>
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<td>∆ demographic parameters</td>
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<td>∆ geographical range limits of northern and southern species</td>
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<tr>
<td>∆ community composition and relative abundance (predators, prey, competitors, parasites)</td>
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productivity of coldwater versus warmwater species will bring a variety of social and economic challenges as novel fishing opportunities for warmwater species may not offset declines in the coldwater or coolwater fisheries. Therefore, adaptive management is required throughout eastern Canada with the known and potential effects of climate change incorporated into fisheries management plans (Dove-Thompson et al. 2011). Climate change adaptation plans have been developed for several jurisdictions within eastern Canada (Gleeson et al. 2011; Government of Quebec 2012). All outline policy, potential adaptation options, research and monitoring needs, and implementation plans to address climate change impacts. These plans provide guidelines that, if realized, should assist in the conservation and sustainability of fishes and fisheries in eastern Canada in the future.

WESTERN CANADA

Western Canada defined here is the region spanning the provinces of Manitoba, Saskatchewan, Alberta, and British Columbia. This area includes a diversity of ecoregions: the Pacific coastal range, Okanagan interior plateau, foothills, the Rocky Mountains, open prairie, and northern boreal forest. Freshwater systems and species composition are similarly diverse and include the Pacific Coast, Glaciated Columbia, Upper Missouri, Upper and Middle Saskatchewan, Winnipeg Lakes, Southern Hudson Bay, and the Upper Mackenzie (Abell et al. 2008). Impacts of climate change varies across western Canada from drought in the prairies (Schindler and Donahue 2006), to reduced snow pack in the Rocky Mountains (Stewart et al. 2004; Milner et al. 2009), to changes in precipitation and fire in the boreal forest (Flannigan and Van Wagner 1991). Because the freshwater systems in this region primarily drain from the Rocky Mountains to outlets across the continent such as the Pacific Ocean, Arctic Ocean, and Hudson Bay, issues related to reductions in snowpack and drought remain of high concern throughout the region (Hauer et al. 1997; Stewart et al. 2004; Schindler and Donahue 2006), although understanding the interconnectedness between climatic, environmental, and biotic interactions remains complex (Table 1).

Each ecoregion in western Canada supports important recreational fisheries, representing approximately CDN$1 billion in direct expenditures and $2.5 billion in additional purchases (DFO 2013). The Pacific coast and interior plateau are composed of 46 species, most as postglacial migrants, with large runs of anadromous salmon. The Rocky Mountains and foothill natural regions support numerous trout species, including pure Westslope Cutthroat Trout Oncorhynchus clarkia lewisi and Bull Trout Salvelinus confluentus populations, as well as Lake Whitefish Coregonus clupeaformis and Arctic Grayling Thymallus arcticus. The prairies have popular game species such as Yellow Perch, Northern Pike Esox lucius, and Lake Whitefish. The boreal forest ecoregion supports common game fish species including Arctic Grayling, Mooneye Hiodon tergisus, Goldeye Hiodon alosoides, Lake Trout S. namaycush, Mountain Whitefish Prosopium williamsoni, Lake Whitefish, Northern Pike, Walleye, and Yellow Perch. Many of the freshwater species found throughout western Canada are already undergoing dramatic declines that are predicted to be amplified with climate change. For example, Arctic Grayling have declined by over 40% from their historical range in Alberta (AESRD 2005), and 78% of Bull Trout core areas are considered to be at high risk (AESRD 2012). Athabasca Rainbow Trout O. mykiss are a subform in the Rainbow Trout complex that remain east of the Continental Divide (Carl et al. 1994) that are susceptible to impacts from climate change through shifting distributions and competition with nonnative species (AESRD 2009). Coho Salmon O. kisutch spawning has declined substantially in the Pacific region (Bradford and Irvine 2011).

Mitigation of climate change impacts to fisheries in western Canada will require concerted effort from management agencies and is complicated by other large drivers such as overfishing, invasive species, land-use change, resource development, and habitat alteration (Bradford and Irvine 2011; Maitland et al. 2016). Knowledge gaps include understanding changing ocean conditions on returning anadromous salmon (Bradford and Irvine 2011), the influence of snowpack on water availability (Stewart et al. 2004; Milner et al. 2009), and how water quantity will influence fisheries productivity (Schindler and Donahue 2006). Given the diversity of landscapes in western Canada, the challenges faced by climate change will vary across the region and will require adaptive management approaches. Management plans for many declining species have been developed across jurisdictions in western Canada (AESRD 2005, 2009, 2012) and include mitigating impacts of climate change. However, these plans are often species specific and are therefore not ecosystem based. Future management will require integrated interjurisdiction coordination and ecosystem-based approaches to help mitigate the impacts of climate change.

NORTHERN CANADA

Northern Canada defined here includes all Canada territories: Nunavut, Northwest Territories, and the Yukon. Freshwater ecoregions found in northern Canada are the Upper MacKenzie basin, central Arctic coasts, western Hudson Bay, the Upper Yukon, and the Canadian Arctic archipelago (Abell et al. 2008). Climate change represents the most serious anthropogenic challenge to northern, and especially arctic, ecosystems, not only threatening biodiversity directly but also by contributing to other significant threats; for example, increases in industrial activity, pollution, and overharvest, and the spread of nonnative species (CAFF 2013). The Arctic is warming at a rate twice the rest of the planet (Solomon 2007); a trend that is expected to continue throughout the 21st century. Arctic lake and river ecosystems in Canada will be affected by climate change through changes in the annual thermal and hydrological regimes (Figure 1), changes that will significantly impact the systems’ hydrological and limnological properties and contaminant burdens. These environmental changes will, in turn, affect freshwater biodiversity, including potential new species moving northward (Table 2). To develop management plans for the fisheries (and other biotic resources) of these ecosystems, we need to understand and anticipate how northern Canada’s freshwater fauna will respond to such dramatic and rapid changes.

Canadian Arctic and Subarctic freshwaters support 13 families of fishes, with Salmonidae being the most diverse, many of which are important in various fisheries. Many fishes of northern Canada, including many of the important salmonids, are winter specialists, exhibiting adaptations for extended periods of low temperature, light, and food levels (Shuter and Meisner 1992; Minns and Moore 1995). These cold-climate adaptations, however, will likely leave many Arctic fishes vulnerable to climate change, because they bring decreasing winter duration and increasing summer surface-water temperatures, as well as other cumulative, cascading, and synergetic effects (Table 1). Given the extent of their adaptations to the harsh Arctic environment and the speed of the predicted
Table 2. List of species that have potential to extend their range and/or abundance northward into the Arctic, with some biological characteristics related to expansion of their existing ranges. Temperatures are for adult individuals; values in parentheses capture spatial variation across populations found in the literature.

<table>
<thead>
<tr>
<th>Species</th>
<th>Optimum temperature (growth; °C)</th>
<th>Lower/upper range for survival</th>
<th>Salinity tolerance</th>
<th>Colonization potential</th>
<th>Current/projected status</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic Salmon</td>
<td>16-19</td>
<td>0–(23.3–26.7)</td>
<td>Euryhaline</td>
<td>Populations in Ungava Bay (QC) but never colonized habitat outside of their native range to date</td>
<td>Large range of temperature tolerance but least tolerant to low temperatures of Salmo species, northern tip of Québec may be a migration barrier</td>
<td>Scott and Crossman (1973); ACIA (2010); Elliott and Elliott (2010); Hasnain et al. (2010); Nielsen et al. (2013)</td>
</tr>
<tr>
<td>Chinook Salmon</td>
<td>14.8–20</td>
<td>0.8–(24.7–26.2)</td>
<td>Euryhaline</td>
<td>Pacific salmon have been documented in the Arctic for over 100 years</td>
<td>Since 2003, only seven observations reported</td>
<td>Brett (1952); Scott and Crossman (1973); Jobling (1981); Raleigh et al. (1986); Wismer and Christie (1987); McCullough (1999); Sullivan et al. (2000); ACIA (2010); Hasnain et al. (2010); Dunnall et al. (2013); Nielsen et al. (2013)</td>
</tr>
<tr>
<td>Coho Salmon</td>
<td>15-17</td>
<td>1.7–(25.8–28)</td>
<td>Euryhaline</td>
<td>Pacific salmon have been documented in the Arctic for over 100 years</td>
<td>Since 2003, only one observation reported</td>
<td>Brett (1952); Scott and Crossman (1973); Jobling (1981); ACIA (2010); Hasnain et al. (2010); Dunnall et al. (2013); Nielsen et al. (2013)</td>
</tr>
<tr>
<td>Chum Salmon</td>
<td>12-14</td>
<td>-0.5 to (23.2–25.8)</td>
<td>Euryhaline</td>
<td>Chum Salmon juveniles are presumed relatively tolerant of low freshwater temperatures, spend less time postemergence in freshwater, and grow rapidly in marine habitats</td>
<td>Chum Salmon have been harvested annually since 1997 and abundant harvests are becoming more frequent. Spawning populations are reported in the Upper Mackenzie</td>
<td>Brett (1952); Scott and Crossman (1973); Jobling (1981); ACIA (2010); Hasnain et al. (2010); Dunnall et al. (2013); Nielsen et al. (2013)</td>
</tr>
<tr>
<td>Pink Salmon</td>
<td>15.5</td>
<td>0-23.9</td>
<td>Euryhaline</td>
<td>Pink Salmon juveniles are presumed tolerant of the low freshwater temperatures, spend less time postemergence in freshwater, and grow rapidly in marine habitats</td>
<td>Pink Salmon has the broadest distribution of all Pacific salmon in the Arctic, and harvests have increased, but spawning populations in Canadian Arctic remain elusive</td>
<td>Brett (1952); Scott and Crossman (1973); Jobling (1981); ACIA (2010); Wismer and Christie (1987); Sullivan et al. (2000); ACIA (2010); Hasnain et al. (2010); Dunnall et al. (2013); Nielsen et al. (2013)</td>
</tr>
<tr>
<td>Sockeye Salmon</td>
<td>15</td>
<td>3.1–(23.5–25.8)</td>
<td>Euryhaline</td>
<td>Pacific salmon have been documented in the Arctic for over 100 years</td>
<td>Since 2003, only 10 observations reported</td>
<td>Brett (1952); Scott and Crossman (1973); Jobling (1981); ACIA (2010); Hasnain et al. (2010); Dunnall et al. (2013); Nielsen et al. (2013)</td>
</tr>
<tr>
<td>Lake Whitefish</td>
<td>12-16.8</td>
<td>0.1–26.6</td>
<td>Stenohaline</td>
<td>Whitefish have expanded northward into the low Arctic, up to Cambridge Bay (NU)</td>
<td>Whitefish yields are projected to increase threefold</td>
<td>Scott and Crossman (1973); Jobling (1981); Christie and Regier (1988); Wismer and Christie (1987); Minns and Moore (1992); Casselman (1996); Hillman et al. (1999); Reist et al. (2006); ACIA (2010); Hasnain et al. (2010)</td>
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<tr>
<td>Smallmouth Bass</td>
<td>25-29</td>
<td>(1.6–10.1)–35</td>
<td>Stenohaline</td>
<td>Not present currently in Arctic</td>
<td>Lakes in the Arctic are predicted to be thermally suitable by 2100</td>
<td>Horning and Pearson (1973); Scott and Crossman (1973); Jobling (1981); Wismer and Christie (1987); Jack- son and Mandrak (2002); Chu et al. (2005); Reist et al. (2006); Sharma et al. (2007, 2009); Hasnain et al. (2010)</td>
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<tr>
<td>Northern Pike</td>
<td>23</td>
<td>0.1–(28.4–34)</td>
<td>Stenohaline</td>
<td>Temperate center of distribution but ranges widely into the Arctic, up to coastal area of Arctic Ocean</td>
<td>Northern Pike yields in Arctic/Subarctic are projected to increase threefold</td>
<td>Scott and Crossman (1973); Jobling (1981); Wismer and Christie (1987); Christie and Regier (1988); Minns and Moore (1992); Casselman (1996); Hill- man et al. (1999); Reist et al. (2006); ACIA (2010); Hasnain et al. (2010)</td>
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<tr>
<td>Walleye</td>
<td>18-22</td>
<td>&lt;4–(29-35)</td>
<td>Stenohaline</td>
<td>Temperate center of distribution but ranges into southern Arctic, extending to the Mackenzie River delta</td>
<td>Walleye yields in Subarctic are projected to increase tenfold</td>
<td>Scott and Crossman (1973); Kitchell et al. (1977); Jobling (1981); Wismer and Christie (1987); Christie and Regier (1988); Minns and Moore (1992); Armore (1993); Hillman et al. (1999); Chu et al. (2005); Reist et al. (2006); Zhao et al. (2008); ACIA (2010); Hasnain et al. (2010)</td>
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<tr>
<td>Yellow Perch</td>
<td>21-24</td>
<td>11–(29.2–32.3)</td>
<td>Stenohaline</td>
<td>Temperate center of distribution but ranges into Subarctic (Great Slave Lake)</td>
<td>Northward range extensions of 2° to 8° latitude are projected</td>
<td>Scott and Crossman (1973); Kitchell et al. (1977); Jobling (1981); Wismer and Christie (1987); Hillman et al. (1999); Reist et al. (2006); ACIA (2010); Hasnain et al. (2010)</td>
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changes in their environment, coldwater specialists may be unable to respond sufficiently (Reist et al. 2006, 2013, 2015; Shuter et al. 2012). Impacts from climate change, therefore, may directly and indirectly affect abundances of local populations and cause range reductions along southern distributional boundaries, just as more eurythermal species become increasingly better suited and extend their ranges northward (CAFF 2013). First-order responses of fish populations—for example, changes in growth and survival—are expected to be followed by mostly negative second-order effects, including loss of coldwater refugia, mismatches between environmental phenology and life history, and increased competition from eurythermal species (Table 1; Reist et al. 2006; Prowse et al. 2011). These effects would alter community composition and diversity, likely to the detriment of northern specialists.

In face of climate change, fisheries management will need to mitigate effects on fish populations at different timescales, because increases in extreme climatic events can induce short-term variability (i.e., 1–5 years), whereas longer timescales should bring about more consistent climatic change impacts (Brander 2010). However, our limited knowledge about the biology of Arctic fishes and their ecosystems, combined with uncertainty regarding the specifics of climate projections, limits our ability to prepare for the predicted changes. Nevertheless, a number of general response recommendations have been put forward by Heller and Zavaleta (2009). Because climate change does not operate in isolation of other environmental threats, nor does it impact species in isolation, we need to (a) develop and implement integrated techniques for monitoring (early detection), reporting, and management of these anthropogenic biodiversity threats (climate change, invasive species, pollution, overharvesting) across large spatial scales; and (b) take an ecosystem-based approach to management of these threats at local scales; (c) establish a connected network of protected areas to safeguard Arctic ecosystem resilience and better enable species to adapt to climate change; (d) identify and protect refugial areas for Arctic specialists; and (e) increase research efforts aimed at addressing knowledge gaps for Arctic taxa; for example, advance our understanding of physiological, behavioral, and demographic responses to drivers of climate change and the responses of the freshwater ecosystems that support Arctic specialists.

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Round-the-Coast: Snapshots of Estuarine Climate Change Effects

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ALASKA

Recent declines in Arctic Ocean summer sea ice constitute one of the most tangible effects of climate change anywhere. Notable environmental effects are increased water temperature, solar exposure, and freshwater inputs, which have led to enhanced primary production and a distributional shift north for many marine organisms including fish. Adult Pacific salmon Oncorhynchus spp. are occasionally captured along the north coast of Alaska and northwest Canada, and there is a widespread public expectation that they will become an abundant resource over time. However, winter still falls on the land and sea, and few northern rivers maintain adequate flow and temperature for successful spawning and egg incubation. If young are produced in northern rivers, they would smolt into the Beaufort Sea, where they would face a long migration against prevailing currents into the southern Bering Sea before winter sea ice covers the ocean. Temperature under sea ice drops to about −1.7°C, which is too cold for salmonids. Eventually, the Arctic region may warm enough that the entire Pacific salmon life cycle will work and colonization will be successful. In the meantime, small numbers of Pacific salmon will continue to probe the northern limits of available habitat.

–R. Brown

ROGUE RIVER, OREGON

The city of Gold Beach and much of Curry County, Oregon, depend economically on the lower Rogue River and its estuary and the fish, wildlife, and recreation values they impart. The estuary is the vital interface between ocean and freshwater that is critical to the health and survival of threatened anadromous species such as Coho Salmon Oncorhynchus kisutch and Chinook Salmon Oncorhynchus tshawytscha, Green Sturgeon Acipenser medirostris and White Sturgeon A. transmontanus, steelhead O. mykiss, and Pacific Lamprey Lampetra tridentata. Climate change affects salmon throughout their life stages and poses an additional stress. As more winter precipitation falls as rain rather than snow, higher winter streamflows scour streambeds, damaging spawning nests and washing away incubating eggs. Earlier peak streamflows flush young salmon from rivers to estuaries before they are physically competent for the transition, increasing a variety of stresses including the risk of being eaten by predators. Lower summer streamflows and warmer water temperatures create less favorable summer stream conditions for salmon and other coldwater fish species in many parts of the Northwest. To help brace against the effects of climate change, the Lower Rogue Watershed Council is working to restore freshwater and tidal wetlands, floodplain connectivity, and streamflow regimes to increase habitat diversity and population resilience.

–K. Timchak

SAN FRANCISCO ESTUARY

San Francisco’s estuary, the largest on the U.S. West Coast, provides habitat to 14 imperiled migratory or estuary-resident fishes (e.g., Delta Smelt Hypomesus transpacificus, Chinook Salmon) and marine species supporting fisheries (e.g., dungeness crab Metacarcinus magister). The freshwater region of the estuary supplies water to 25 million people and irrigates economically important farmland. Floods and droughts are part of the historical ecology of the estuary and its 163,000 km² watershed. Yet, there is growing concern that large-scale loss and degradation of diverse aquatic habitats due to land- and water-use practices will compromise the ability of species to respond/adapt to climate change. Projections suggest that the region will become warmer and drier with increased environmental variability, placing the ecosystem into novel regimes. California’s current four-year drought, exhibiting low freshwater outflow and record air and water temperatures, together with anomalously warm ocean conditions, foreshadows these conditions. Record low abundances of native pelagic fishes and poor survival of endangered juvenile salmon appear to have been exacerbated by the drought. Warm, dry conditions likely favored nonnative resident fishes (e.g., centrarchids), nonnative aquatic vegetation, and harmful algal blooms. Threats of sea level rise and armored shorelines further reduce shallow marsh habitats, already in short supply. Managing fish populations in a highly degraded and diminished natural habitat and changing climate will likely further constrain California’s limited water supply, providing daunting challenges for resource managers.

–R. Johnson
TEXAS GULF COAST

In Texas estuaries, the watchword is “drought.” The region has a long history of interannual aperiodic cycles of freshwater inflow, but rising average temperatures coupled with intensifying droughts drive estuarine dynamics in worrying directions. Reduced inflows lead to hypersalinity in systems enclosed by barrier islands, a characteristic of many Texas estuaries. The most recent statewide drought in 2015 exceeded the intensity and duration of the record drought in the 1950s. The effects of aperiodic inflow variation on estuarine-dependent organisms are of great concern, although clear relationships between inflow dynamics and biotic responses are elusive. A central question is whether Texas populations of estuarine-dependent species have sufficient tolerance to withstand hypersaline regimes given the historical propensity for drought in the region or whether inherent tolerance thresholds will be exceeded if droughts intensify. These dynamics will be further shaped by range expansions of tropical species (e.g., black mangrove *Avicennia germinans*) that may alter nursery habitats for important fishery species. Understanding these altered biotic interactions along with threshold tolerance responses to hypersalinity will be crucial for unraveling the multifaceted effects of climate change.

—B. Walther

FLORIDA

Estuaries in Florida provide key economic and ecological benefit to a state highly dependent on natural resources to drive the tourism, agriculture, and development segments of the economy. With more than 2,100 km of coastline and a human population of over 20 million people (and growing by about 1,000 people a day), climate change is important to every citizen and visitor to the Sunshine State. In the highly developed southeastern corner of Florida, climate change–related sea level rise is contributing to increases in coastal flooding of metropolitan areas, such as Miami Beach during spring and fall high tides. Lesser known, yet equally dramatic, impacts to marshes and estuaries are also occurring throughout the state including the sparsely developed “Big Bend” region in the northeastern Gulf of Mexico, where estuaries are squeezed by rising sea levels and changes in freshwater inputs contribute to die offs in coastal vegetation and loss of oyster reefs. Between 60% and 90% of the key commercial and recreational fisheries in Florida are dependent on estuaries for some part of their life history necessitating protection of these habitats for these resources to remain viable. Addressing climate change and the related impacts to coastal Florida is likely one of the biggest challenges ever faced by the state.

—B. Pine

Concerns in estuaries include the rates of sea level rise and temperature warming. We examined data sets for trends in our geographic areas. Sea level rise is variable; highest rates occur mostly in the central Gulf of Mexico coast, but even off the Atlantic coast, there are hot spots of rise. West Coast rates tend to be lower, and in southern Alaska they are negative because of isostatic rebound. On the other hand, increases in temperature show a latitudinal gradient. To make this comparison, we restricted our data sets to be as consistent as possible; that is, from 1995 to 2015. In this case, highest rates are observed in Alaska and lowest rates at more southerly latitudes. This is in accordance with climatological predictions. Knowledge of such trends provides managers with broad guidance for planning.

**Sources**

Sea level rise: Data are from the National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) Sea Level Trends display (co-ops.nos.noaa.gov/sltrends/sltrends.html; see also NOAA 2001, 2009). These are based upon observations of a minimum 30 years from the National Water Level Observation Network.

Water temperature: Annual temperature trends (1995–2015) were gathered from a variety of sources. National Estuarine Research Reserve (NERR) data were summarized for Maine (Wells), Florida (Apalachicola), and Oregon (South Slough) NERRs (NERR Centralized Data Management Office, cdmobaruch.sc.edu). Data for the Hudson River were collected at Poughkeepsie, New York, by the U.S. Geological Survey (monitoring station 01372058) and the Chesapeake Biological Laboratory Pier and for the Neuse River basin by the Albemarle–Pamlico National Estuary Program (compiled by M. Chad Smith, received from Roger Rulifson via personal communication). The NOAA CO-OPS’ PORTS data product (tidesandcurrents.noaa.gov/ports.html) was used to obtain water temperature data for Galveston Channel (station 8771450) and Sabine Pass North (station 8770570) in Texas, Port Chicago (station 9415144), Suisun Bay, California, and Port of Anchorage, Alaska (station 9455920). Finally, data were used from the Kuparuk River on the Alaskan North Slope; these were collected by the Arctic Long Term Ecological Research program and are described in Kane and Hinzman (2013). Data for each site mentioned may be found at catalog.ioos.us/datasets/filter and entering corresponding the station number.
The last individual was observed in 1998, and Rainbow Smelt *Osisma eperlanus*, at its southern range limit, began to get scarce. Warming in the 1980s, when Rainbow Smelt *Osisma eperlanus* began to get scarce, was consistent with poleward range expansion for this warmwater species. Alewife *Alosa pseudoharengus* is at the southern limit of its range and appears to be losing ground as temperatures warm. Striped Bass *Morone saxatilis*, which historically overwinter off the Outer Banks and provide a popular winter surf fishery, have moved northward over the past decade to waters off Chesapeake Bay. The Bull Shark *Carcharhinus leucas* is now using habitats in Pamlico Sound as pinking grounds since about 2010; the previous known northern habitat for pinking was in northern Florida. Sea level rise over the next 100 years will cover large expanses of coastal counties that currently flood routinely; saltwater intrusion has poisoned significant expanses of agricultural lands, which are extensively ditched for freshwater runoff. Tough regulations regarding bulkheading and beach hardening may allow marsh systems to migrate landward more easily than in other states with minimal hardening regulations.

—R. Rulifson

### CHESAPEAKE BAY

“America’s estuary” serves as the dominant source of recruits for Atlantic Menhaden *Brevoortia tyrannus*, blue crabs *Callinectes sapidus*, and Striped Bass. Winter weather sets the clock for nursery conditions of these and other living resource species within the Chesapeake. Cold, wet conditions favor Striped Bass and other anadromous species; warm winters favor blue crab, *Bluefish Pomatomus saltatrix*, and other coastal spawning fishes. Recent, modest declines in Striped Bass recruitment coincide with a period of warm winters. Striped Bass now spawn earlier in the Potomac River, which may affect the foraging and thermal environments that offspring encounter.

Resident Striped Bass avoid summertime hypoxic conditions by occupying warmer surface habitats in which they grow poorly. Striped Bass now spawn earlier in the Potomac River, which may affect the foraging and thermal environments that offspring encounter. Resident Striped Bass avoid summertime hypoxic conditions by occupying warmer surface habitats in which they grow poorly. Anglers now encounter sickly or diseased stripers. Warmer conditions could broaden the window of successful recruitment by menhaden, which move from the shelf into the Bay’s tributaries. Warming will allow blue crab juveniles a longer growing season before hunkering down for the winter, yet this applies also to their cannibalistic larger siblings. Increasingly, drums (Sciaenidae) are making a toe-hold in both the lower and upper Chesapeake Bay segments, including Atlantic Croaker *Micropogonias undulatus* and Red Drum *Sciaenops ocellatus*, consistent with poleward range expansion for this warmwater family.

—D. Secor

### NEW YORK

In the 250-km Hudson River estuary, we began to notice warming in the 1980s, when Rainbow Smelt *Osmerus eperlanus*, at its southern range limit, began to get scarce. The last individual was observed in 1998, and Rainbow Smelt became the first known climate-based extirpation. Since then, Atlantic Tomcod *Microgadus tomcod* are barely holding their own, whereas tropical marine strays are increasingly observed. Additionally, earlier onset and shorter duration in spawning season trends are likely due to warmer waters. Atlantic Menhaden *Brevoortia tyrannus*, Alewife *Alosa pseudoharengus*—both now using habitats in Pamlico Sound as pinking grounds since about 2010; the previous known northern habitat for pinking was in northern Florida. Sea level rise over the next 100 years will cover large expanses of coastal counties that currently flood routinely; saltwater intrusion has poisoned significant expanses of agricultural lands, which are extensively ditched for freshwater runoff. Tough regulations regarding bulkheading and beach hardening may allow marsh systems to migrate landward more easily than in other states with minimal hardening regulations.

—R. Rulifson

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Providing Safe Haven for Sensitive Aquatic Species in a Changing Climate

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Fish culture will be affected by climate change, but many aspects of the fish husbandry environment can be controlled through the use of modern technology and engineering. The ability to control the culture environment provides the option to engineer around climate change as it occurs and additionally allows fish culture to be used as a tool to address issues of climate change and associated impacts on native or wild fishes. Aquaculture for coldwater fish species, such as salmon and trout, will likely require modern technologies to supply conditions suitable for fish husbandry in a changing climate. Recirculating aquaculture systems (RAS) have proven effective for production hatcheries and also as an emergency tool to address issues of climate change and mitigate impacts on native or wild fishes. Such work was recently demonstrated by the California Department of Fish and Wildlife (CDFW) to provide drought safe haven for wild fishes that were otherwise jeopardized by unprecedented drought. Other recovery efforts have been planned or implemented recently in Texas, North Carolina, New Mexico, and other locations to protect imperiled fish and mussel populations by bringing populations into culture facilities. These and other efforts worldwide demonstrate innovative approaches to address potential or realized impacts of climate change. These fish culture techniques should be considered part of the available toolbox for all fisheries professionals as they face impacts of climate change.

CASE STUDY: McCloud River Redband Trout

McCloud River Redband Trout *Oncorhynchus mykiss stonei* is one of several sensitive and unique fish species in California that required fish rescue during recent extreme drought to prevent excess fish loss and alleviate population-level effects. McCloud River Redband Trout streams (tributaries of the upper McCloud River) were monitored from late 2013 through mid-2015 for drought-related impacts. Stream monitoring during this period indicated drought effects during two separate seasonal periods—winter and summer. The winter period consisted of reduced stream flows and episodic events of cooler than normal air temperatures, freezing solid significant portions of Redband Trout habitat. Summer period impacts included reduced streamflows sooner and more extensively than long-term averages. These conditions suggested that genetically distinct subpopulations of McCloud River Redband Trout were at risk due to degrading habitat not likely to improve before impacts were realized. Fortunately, minimal Redband mortality was documented before fish rescues were implemented by CDFW. For McCloud River Redband Trout, rescue options included (in order of preference) instream movement, movement to another inner basin stream with genetically distinct McCloud River Redband Trout, and/or holding in a self-contained RAS at a hatchery.

Anticipating potential drought impacts on sensitive wild fish populations, CDFW customized, procured, installed, and employed self-contained RAS in expedited time at select CDFW hatcheries. In close proximity to the McCloud River, the CDFW’s Mt. Shasta Hatchery was selected for providing drought-safe haven for rescued Redband Trout until conditions improved in natal streams. Before RAS were in operation, several logistical and infrastructural hurdles had to be addressed. These included accommodating RAS and electrical needs in a 100-year-old hatchery building, assembly of RAS components, and populating bioreactors with nitrifying bacterial species. By July 2014, RAS were ready to accommodate fish and by September biologists had provided drought safe haven to over 1,000 McCloud River Redband Trout.
In addition to releasing fish back to the wild, CDFW is considering options for subsets of Redband Trout including a conservation program utilizing genetic analysis performed by the University of California at Davis. The CDFW staff rescued and provided drought safe haven for other coldwater fish species including the southern Oregon/northern California Coast Coho Salmon *Oncorhynchus kisutch* evolutionarily significant unit and the California Central Valley steelhead *O. mykiss* distinct population segment. Fish from those efforts were released to the wild as conditions did improve.

Extreme and changing climate and the related effects to aquatic habitats are anticipated products of global warming. As with the McCloud River Redband Trout example, modern fish husbandry offers an aide in the conservation of sensitive aquatic species in peril from climate change. The Fish Culture Section is poised to assist with this growing issue by disseminating information on successful projects, such as the McCloud River Redband Trout holding project; by helping to identify expertise for fisheries managers who need it; and by encouraging continued discussion of issues and solutions related to climate change.

Recirculating aquaculture systems used as drought safe haven by the California Department of Fish and Wildlife.

### Climate Change and Considerations for Fish Health and Fish Health Professionals

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As the warmest years on record (Blunden and Arndt 2015; NOAA NCEI 2016), 2014 and 2015 brought greater attention to the issues of climate change. Though global precipitation has been average, severe drought conditions in the western United States (England 2014) have punctuated growing concern for the future of aquatic systems. A changing climate may affect the way we steward fisheries resources with intrinsic and extrinsic values, including our approach to fish health management.

Fish health professionals classically refer to a Venn diagram to characterize the factors that contribute to infectious disease; that is, environment, fish (i.e., the host) and pathogen (Figure 1; Sniezsko 1974). This diagram helps to conceptualize the difference between the mere presence of a pathogen and the conditions that make disease likely. For infection to occur, a pathogen must invade a fish, getting past natural barriers such as mucus, skin, and nonspecific immune defenses. Not all pathogen invasions result in disease—whether disease occurs depends on the strength of the fish’s immune defenses, which are strongly influenced by the environment. Favorable environmental conditions can maximize the ability of a fish’s immune system to neutralize a pathogen. Hostile environmental conditions can result in a fish that is stressed, immunocompromised, and vulnerable to infection, but infectious disease will not occur unless a pathogen is also present. Thus, disease in fish requires a specific combination of fish, pathogen, and environmental conditions. Here, we consider how climate change might influence this triad, thereby affecting fish health and work of fish health professionals.

**EFFECTS ON THE ENVIRONMENT**

The effects of climate change on the terrestrial environment and inland waters are numerous and may include increases in temperatures, changes in precipitation patterns (e.g., changes in rainfall, reduced snowpack), alterations in flow regimes (e.g., lower summertime in-stream flows), more frequent extreme weather events (e.g., droughts and floods), and other abiotic...
effects that impact the quantity and quality of surface water needed for aquatic life. Abiotic changes, in turn, cause biotic changes, affecting aquatic organisms whose geographic distributions, life histories, and biological requirements are directly tied to “master variables” like temperature and flow. Biotic shifts, such as advancing eutrophication or changes in species assemblages, may negatively affect the health of wild and hatchery-origin fish at an individual or population scale. Altered environments, defined by new abiotic and biotic norms, may present novel fish–pathogen interactions and the potential for emerging infectious diseases. For example, favorable thermal habitats that provide refuge from pathogens may be lost due to climate change, resulting in increased incidence of disease (Chiaromonte et al. 2016). Future conditions may further stress native fish and favor the introduction, establishment, and distribution of invasives (Hellmann et al. 2008; Quiñones and Moyle 2014), collectively compounding the likelihood of naïve populations (both indigenous and introduced) encountering new and more virulent pathogens.

**EFFECTS ON FISH**

Climate change may affect fish in myriad ways, but here we focus specifically on how temperature could influence interactions between fish and their pathogens. Every organism has a range of environmental temperatures it can tolerate, constrained by the lower and upper lethal limits. Within the tolerable thermal range is a narrower, preferred range of temperatures within which the species performs best—the thermal preferendum. Thermal preferenda vary among fish species and life stages, with larval and maturing or spawning fish typically being the most sensitive (Pörtner and Peck 2010). Thermal preferences and tolerances are somewhat plastic and are influenced by acclimation temperature, rate of thermal change, genetic differences among stocks, diet temperature cycles versus daily mean temperatures, etc. However, when fish are exposed to water temperatures outside the preferred thermal “windows,” their fitness may be reduced. In most climate change scenarios, the likelihood is that fish will encounter temperatures exceeding their upper tolerance. The stress associated with exposure to warmer temperatures may be acute or chronic and can interact with related stressors such as pathogenic infections.

Fish vulnerability to pathogens is a major determinant of disease and one likely to be affected both directly and indirectly by thermal stressors. Whether the result of increased fish susceptibility, greater pathogen virulence, or both, disease-related morbidity and mortality are influenced by water temperature. As long as temperatures do not exceed the pathogen’s thermal preferendum, bacterial and viral infections may progress more rapidly and be more severe when water temperatures are warmer or rising (Trust 1986; see Text Box). The effects of water temperature on parasitic infections are more variable, with warm temperatures associated with more severe infestations of some parasites (e.g., *Ceratonova shasta*; Udey et al. 1975), whereas cooler water temperatures can be more problematic for others (e.g., *Ichthyophthirius multifiliis*). It should be noted that linkages between higher water temperatures and more severe infections/infestations are largely derived from work with coldwater fishes; more rapid pathogenesis and greater disease-related mortality may be associated with colder or declining temperatures in warmwater fishes. Indeed, contrary to the generalizations above, cold water temperatures have been described elsewhere as generally immunosuppressive (Bly and Clem 1992), though these conclusions were based primarily on work with warmwater fish. It is also likely that variation in fish vulnerability is related to differential effects of warm and cold temperatures on different aspects of teleost immunity and the relative importance of these defenses in staving off one pathogen or another. Some mediators of immunity are suppressed by cooler temperatures, whereas others are less functional at warmer temperatures (Le Morvan et al. 1998; Sundh and Sundell 2015), meaning that defense against some, but not all, pathogens may be affected. Though less satisfying than a simple positive or negative relationship, disease in poikilothermic organisms is likely to be most frequent and severe when temperatures are variable and fall outside fish thermal preferenda.

**EFFECTS ON PATHOGENS**

Freshwater temperature increases can affect fish pathogens directly by altering their biological processes or indirectly by influencing the distribution and abundance of the fish they affect. On an organismal scale, temperature changes can affect the rate of pathogen replication inside the fish, the longevity of pathogen life stages outside the fish, the virulence of the pathogen, and the transmission of the pathogen among fish (Marcogliese 2001, 2008). On a population scale, temperature increases can alter the seasonal abundance, timing, and transmission efficiency of pathogens.

As noted above for fish, pathogens have thermal tolerances and preferences within which they perform optimally. Within a pathogen’s tolerable thermal range, increases in ambient temperature will typically accelerate replication of viruses, bacteria, fungi, and parasites in fish, worsening infections and disease (Fryer and Pilcher 1974). For pathogens that exist near the bounds of their thermal tolerances, effects of climate change will be the most evident (Lafferty 2009). In
The temperature of the water is of the utmost importance in the handling of fish diseases, whether these conditions are due to infections, parasites, or the results of nutritional and developmental disturbances which lower vitality. A temperature above the optimum range increases the onset of symptoms and the rapidity of death. It lessens the general resistance of the fish and, in many bacterial and protozoan diseases, favors the multiplication of the invading organism. A high temperature is favorable for epidemics of bacterial disease. … The fish culturist who possesses an ample supply of cold water has one means of protection against bacterial disease since certain epidemics can be held in check by a low water temperature. (Belding 1928:105)

High latitudes where pathogen growth may be limited by cold temperatures, an increase in average water temperatures will permit pathogen development for a longer time period. For instance, increasing water temperatures are associated with higher prevalence of proliferative kidney disease in wild salmon in northern Europe, a response likely due to faster growth of the invertebrate host, accelerated parasite spore development in the host, and diminished immune responses in the fish (Sterud et al. 2007). Warmer waters can also reduce generation times of pathogens, allowing for faster replication within fish and other hosts and more life cycles to be completed within the year. For example, the salmonid ectoparasite *Argulus coregoni* can double the number of life cycles completed annually under warmer conditions (Hakalahti et al. 2006).

Many pathogens exhibit cycles of seasonal abundance, with highest levels occurring during warmer months. Warming temperatures could result in earlier peaks and longer “seasons” of maximum pathogen abundance. In addition to becoming more prevalent, some pathogens become more virulent at warmer temperatures, resulting in an expanded and more severe season of infectivity and disease. Temperature may also differentially affect different aspects of pathogen infectivity; in the case of some parasites, shedding rates and the abundance of infective stages may be increased at warmer temperatures, but the longevity of those same life stages may be reduced, giving them less time to find and successfully invade a fish or another host (Foott et al. 2007; Marcogliese 2008).

CONCLUSIONS

Despite the simplicity of the conceptual model illustrating the factors contributing to fish disease (Figure 1), the possible effects of climate change on this triad are complex. Abiotic and biotic attributes of the environment are likely to change in response to a changing climate. Increases in water temperature alone can directly affect fish and their pathogens; multifactorial environmental change may affect both in ways that are difficult to anticipate. The occurrence and severity of disease may increase, decrease, or merely shift in time or space, depending on the net effects on all three interrelated factors. Fish health professionals must consider each combination of fish–pathogen–environment as a unique scenario and use the tools available to them to minimize effects of altered thermal regimens on infectious disease in fish (e.g., temperature manipulations, invasive species control, timing of fish stocking to minimize pathogen overlap, improved fish culture practices, transitioning from flow-through to water reuse systems).

The American Fisheries Society Fish Health Section members, particularly the certified aquatic animal health inspectors and fish pathologists, will assist their fisheries colleagues and employers by helping to anticipate and address fish health challenges. Thorough inspections and biosecurity planning, rapid and accurate diagnoses, and—working with veterinarians as appropriate—effective disease treatment options are all essential services the fish health professional is called upon to provide. Increasingly, fish health professionals will also be asked to provide creative solutions to new challenges involving fish species not previously cultured; emerging pathogens or pathogens with altered virulence or emergence patterns; different, more intensive culture methods, such as recirculating aquaculture systems; and limited options for accessing vaccines and therapeutic drugs needed to provide effective and compassionate treatment when disease occurs.

Like climate change itself, the implications of a changing environment for fish health are complex and will require the knowledge of fish health experts as well as expertise in fish culture, fisheries management and ecology, physiology, water quality, and other disciplines. Fish Health Section members will serve the discipline, our fellow fisheries professionals, and aquatic resources through continued engagement in the broader fisheries community and a commitment to innovation and adaptation.

REFERENCES


INTRODUCTION

A range of perspectives is presented from the International Fisheries Section of the American Fisheries Society on climate change effects on inland fisheries from standing and flowing waters in Africa, Asia, Australia, Europe, and Latin America. Many of the world’s inland fisheries face common threats, such as eutrophication, overfishing, species introductions, and water development projects (Youn et al. 2014), which have essentially local solutions. However, most fisheries also face effects from the inherently global problem of climate change, which only can
be understood and ultimately managed from a truly international perspective. The potential extent and range of such effects were illustrated by Xenopoulos et al. (2005), who, assuming the A2 model for climate change, predicted a loss of 0% to 75% of the fish species in a variety of the world’s river basins but with an uncertain time lag (Tedesco et al. 2013). Here, we provide a range of perspectives from the International Fisheries Section of the American Fisheries Society on climate change effects on inland fisheries from standing and flowing waters in Africa, Asia, Australia, Europe, and Latin America.

**AFRICA**

Most tropical fishes are eurythermal and able to tolerate high temperatures, and most climate change scenarios predict little temperature increase in tropical Africa. Consequently, relatively small effects might be expected. However, many tropical fishes live in waters with low dissolved oxygen levels, where temperature fluctuations approach upper lethal limits (Ficke et al. 2007). Thus, temperature increases of only 1°C to 2°C are likely to affect swimming ability, growth rates, and reproduction, which in turn are likely to affect wild fish and aquaculture production. Fish species extinctions due to reduced water availability arising from climate change in arid and semi-arid regions of northern Africa are very likely before the end of this century (Tedesco et al. 2013).

Even large African lakes with considerable buffering capacities are likely to be affected by climate change. For example, the fishery catch of Lake Naivasha in Kenya is strongly correlated with water level (Hickley et al. 2002), and water level is likely to be affected by anticipated reductions in precipitation. Similar impacts of climate change are also anticipated in Lake Victoria (East Africa), where changes in interannual and interseasonal variability in rainfall and temperature could affect the survival of aquatic life, increasing the variability of fish catches (Johnson 2009; Sewagudde 2009).

**ASIA**

Climate change may affect the hydrology and fisheries of inland waters through increased precipitation, air temperature, and glacier melting in the Qinghai–Tibet Plateau (QTP). The QTP has many lakes and contains the glacier-fed headwaters of the Yangtze, Yellow, and Mekong rivers. The QTP has warmed in recent decades (e.g., Wang et al. 2015; Yang et al. 2015), stimulating increased glacial melting (Krause et al. 2010; Wang et al. 2013). In some QTP regions, increased precipitation may have affected runoff more than increased air temperature (e.g., Qian et al. 2014). In lakes, fish may need to adapt to habitat changes associated with rising lake levels and altered thermal stratification and mixing. In rivers, particularly the headwaters, increased discharge may change local habitat and deliver more terrestrial inputs downstream, with eventual effects on riverine fisheries.

The Caspian Sea is the world's largest inland sea, and a century-long shift in the abundance and composition of its fishery is correlated with a change in the local climate and sea environment. Specifically, increased air temperatures coupled with decreased precipitation and winter ice covers are associated with increased salinity and decreased sea level. From 1900 to 1933, annual fish catches in the Caspian Sea were often over 600,000 tons. Semi-anadromous (Vobla Rutulus caspicus, Common Bream Abramis brama, Pikeperch Sander lucioperca, Common Carp Cyprinus carpio) and anadromous (sturgeons, shads, Inconnu Stenodus leucichthys) fishes made up 79% and 16%, respectively, of the catch (Kuranova and Moiseev 1973). In the first years of the 21st century, catches of semi-anadromous and anadromous fishes declined dramatically and are significantly correlated with reduced Volga River discharges into the sea, lower sea levels, and higher salinities (Zhidovinov et al. 1985; Katunin and Strubalina 1986).

Inland fisheries occur across most areas of the Asian part of Russia and are particularly important, susceptible to climate change, and well-studied in Lake Baikal (Siberia). The most important fisheries species in this lake is Baikal Omul Coregonus migratorius, where catches increase 4 to 5 years after high water levels (Smirnov et al. 2015). There is a strong negative correlation between ice cover in the Arctic Ocean in the second half of August and Baikal Omul catches (Figure 1). During periods of low winter temperatures and long ice cover, conditions for Baikal Omul production improve because of increases in river flow, lake level, and subsequent juvenile survival (Smirnov et al. 2015).

**AUSTRALIA**

Australia is a large, dry continent that spans tropical to temperate zones. Its freshwater fishes and their habitats have suffered considerable degradation in many regions, leading to range reductions and reduced and fragmented populations. Consequently, a large proportion of Australia’s endemic freshwater fishes are of conservation concern. Rainfall and river discharge patterns are highly variable with increasingly unpredictable intense droughts and floods forecasted (Hobday and Lough 2011). Such changes combined with other pressures pose serious threats to fishes and fisheries.

Though climate change may affect fishes directly (e.g., effects of increased temperatures on reproduction and early life stages), changes in water availability and reliability alter freshwater habitats and indirectly affect fishes and fisheries (Morrongiello et al. 2011). Changes in fish distributions are predicted (Bond et al. 2011), but there are limited opportunities for species to move upstream to cooler higher altitudes because Australia has few high mountains.

![Figure 1. Square of Arctic Ocean ice cover in the second half of August as a percentage deviation from the mean for 1925 to 1976 (upper panel) and annual Baikal Omul commercial catches in feeding areas as a percentage deviation from the mean for 1925 to 1966 (lower panel). Lines 1 and 3 are 5-year means, and lines 2 and 4 are annual means (after Smirnov et al. 2015).](Image)
Climate-driven changes to popular recreational fisheries may have significant economic and social impacts, as well as indirect effects causing unexpected outcomes (Koehn et al. 2011). This complexity presents considerable challenges for water resource management (Kingsford 2011; Lester et al. 2011), within which prioritization must be given to the most vulnerable species, locations, and ecosystems (e.g., Barred Galaxias *Galaxias fuscus*; Crook et al. 2010). There is still considerable work to do in adapting management to the changed climate regime of Australia. The management of freshwater fishes under climate change must be undertaken in conjunction with existing stressors, including fisheries management and reforms to water extraction (Koehn 2015).

**EUROPE**

Europe contains great variability in climates and hydrological regimes, from northern alpine to southern Mediterranean; those regions are expected to be affected differently by climate change (Arnell 1999). A general reduction of annual discharge in the southern regions and an increase in the northern and higher altitude regions are anticipated. The duration, frequency, and intensity of floods and droughts will be exacerbated in the south (Figure 2), and runoff increases in winter and flow decreases in spring will be more frequent in northern and higher altitude areas (Arnell 1999; Christensen and Christensen 2003; Filipe et al. 2013a).

Fishes are expected to be affected strongly by climate change, tending toward local extirpations or displacements to higher elevations and more northern latitudes (Filipe et al. 2013a; Pletterbauer et al. 2016). This implies a decrease in local species richness and major changes in the structure of assemblages for some regions, with the most favored species being those that are alien or common and having low conservation or commercial importance (Buisson et al. 2008). For one of the most threatened species, Brown Trout *Salmo trutta* (Freyhof 2010), distribution forecasts for the Elbe, Elbe, and Danube river basins indicate that 64% of stream reaches will become unsuitable by the 2080s, with the highest risk of extirpation in the Elbe Basin (Filipe et al. 2013b). The greatest changes in fish assemblages are expected for the southern regions by the 2050s and 2080s, whereas boreal assemblages will change less over the same periods (Tedesco et al. 2013; Pletterbauer et al. 2015).

Fisheries provide important food sources and recreational opportunities throughout most of Europe and undoubtedly will be affected by climate change. Such changes will be particularly intense in areas such as the southern regions, which host many endemic and threatened fishes that already are under great stress from a range of anthropogenic pressures (Smith and Darwall 2006). Those pressures must be successfully managed along with restoration of stream connectivity, establishment of conservation areas, and improved water infrastructure planning (Hermoso et al. 2015a, 2015b).

Climate change effects also are likely in the European part of Russia, including the Great Lakes of Ladoga, Onega, Ilmen, and Peipsi, where fisheries target whitefishes (Coregonidae), Burbot *Lota lota*, European Perch *Perca fluviatilis*, Northern Pike *Esox lucius*, Roach *Rutilus rutilus*, and other species (Kudersky and Ivanov 2011). Catch dynamics depend on climatic factors associated with increasing frequencies of W- and E-types of atmospheric circulation over the North Atlantic (Dubravin and Pedchenko 2010; Pedchenko 2011). In particular, more frequent E-type atmospheric circulation (low winter temperatures and long ice cover) is consistent with the dynamics of the total fish catch (Pedchenko, in press). Similar species are exploited in Rybinsk Reservoir, together with European Smelt *Osmerus eperlanus* and the invasive Black and Caspian Sea Sprat *Clupeonella cultriventris* (Gerasimov 2015). Since 1995, freezing-over has shifted from early November to late December (Litvinov and Roshchupko 2010), coinciding with a decline of coldwater species including Burbot and European smelt and an increase in Black and Caspian Sea Sprat. Growth rates of Burbot and other coldwater species have decreased, and warming-induced lowered oxygen availability has reduced benthic species such as Ruff *Gymnocephalus cernuus* (Wrona et al. 2006; Rijnsdorp et al. 2009). Like the Caspian Sea, the Azov Sea has been affected by increased air temperatures, decreased precipitation and winter ice covers, increased salinity, and decreased level, resulting in reduced commercial catches of Pikeperch and Common Bream (Guptaev et al. 1991).

In central Europe, the transnational Lake Constance of Germany, Switzerland, and Austria has a long history of inland fisheries, particularly for European Whitefish *Coregonus lavaretus* and European Perch. Over the last 40 years, water temperature has increased by about 1.5°C (Jeppesen et al. 2012), and populations of several species including European Whitefish (Thomas et al. 2010) and European Perch (Eckmann et al. 2006) have changed. Recently, fisheries yields have decreased drastically (Rösch 2014), and in 2015 yield fell by approximately 50% from the already low yield of 2014.

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**Figure 2.** The Ardila River in the Guadiana Basin, southern Portugal, in which the hydrological regime is highly seasonal and expected to become even more strongly affected by extreme floods and droughts. The two photographs were taken less than 1 day apart. Photo credit: Patricia Tiago.
Since about 2014, pelagic expansion of the lake’s unexploited Threespine Stickleback *Gasterosteus aculeatus* has occurred and comprised more than 80% of pelagic fish in 2015, increasing the possibility of competition with European Whitefish for zooplankton and predation on larval European Whitefish and European Perch. Although corresponding information is not available for European Whitefish, preliminary data indicate that the 2014 year class of European Perch is extremely weak. The reason for this expansion of Threespine Stickleback into the pelagic zone is uncertain, but its recent observation in Lake Constance suggests that it may result at least in part from climate change.

In the United Kingdom, investigations of climate change effects have centered on the glacial lake of Windermere for three main reasons: co-occurrence of coldwater salmonids and warmwater cyprinids (Winfield et al. 2006), 70 years of fish population studies (e.g., Craig et al. 2015), and diverse fisheries, including historical commercial fisheries, which are rare in U.K. inland waters (Winfield 2016). As Windermere has warmed since the late 1980s, Arctic Charr *Salvelinus alpinus* has declined to the detriment of a traditional recreational fishery for this native salmonid (Figure 3), whereas introduced Roach has expanded to the benefit of angling for this warmwater cyprinid (Winfield et al. 2008). Similar declines in Arctic Charr have occurred in other U.K. lakes and are thought to have resulted in part from climate change (Winfield et al. 2010). Warming also has changed Windermere’s Northern Pike population by shifting the length structure of this top predator toward an increased proportion of medium-sized individuals (Vindenes et al. 2014). Climate change also has had wider impacts on the Windermere ecosystem. Expansion of a pathogen of European Perch into the lake has acted synergistically with warming to induce a regime shift within its European Perch–Northern Pike interaction, triggering a trophic cascade (Edeline et al. 2016). Trophic levels have responded differently to warming such that Windermere’s phytoplankton, zooplankton, and timing of European Perch spawning have become desynchronized (Thackeray et al. 2013). Finally, age–size truncation of European Perch induced by the pathogen has altered the consequences of this phenological mismatch for fish survival (Ohlberger et al. 2014).

Further north, the Arctic region has experienced more and faster climatic changes (warming waters and shorter durations of ice cover) than other European regions. Unlike temperate regions, warming in the Arctic is projected to improve conditions for anadromous and diadromous fishes such as Atlantic Salmon *Salmo salar* and Arctic Charr, as long as there is sufficient water in spawning and rearing streams (Nordeng 1983; Nielsen et al. 2013).

**LATIN AMERICA**

Even more than Europe, Latin America contains great variability in climates and hydrological regimes, including alpine, desert, savannah, and tropical rainforest. Tropical parts of South America are likely to experience climate change effects similar to those already described above for tropical Africa, whereas alpine regions are expected to follow patterns similar to Europe. Reductions in annual precipitation are predicted for semi-arid regions, as well as in humid basins such as the Amazon Basin (Saatchi et al. 2012; Oberdorff et al. 2015). Semi-arid and humid regions are predicted to experience increased incidence of extreme precipitation periods (droughts, floods), meaning less predictable water bodies and artisanal fisheries (Marengo et al. 2013; Castello and Macedo 2016). Nonetheless, Xenopoulos et al. (2005) and Oberdorff et al. (2015) predicted very few losses of Amazon drainage fish species.

In Mexico, Mendoza-Portillo (2014) conducted a fish faunal inventory in the Sierra Madre Occidental and related current distributions of 16 endemic species to current environmental conditions. Based on those relationships and future climate scenarios, she projected species distributions in 2020, 2050, and 2080. Precipitation seasonality, elevation, and minimum temperature of the coldest period explained most of the variability in current species distributions. Future climate (temperature and precipitation) predictions indicated a reduction of viable ranges for 10 of the 16 endemic species, displacement of viable range to the north for one species, and increased viable ranges for two species by 2080. She proposed making the Yaqui, San Pedro, Nazas, Santiago, and Bravo catchments priority conservation areas or refuges because they support the greatest fish faunal diversity in the Sierra Madre Occidental and have the greatest probability of suitable sites and the greatest potential for species migrations.

Reduction in rainfall and increase in temperature due to climate change will affect recruitment of migratory fishes in the Rio São Francisco (RSF), Minas Gerais, Brazil, with significant implications for fisheries. Aggregation of young migratory fishes occurs annually in the tailrace of Três Marias Dam on the RSF (Godinho and Kynard 2006). The number of fish involved varies yearly (Prado et al., in press); usually there are low numbers (<3 fish per cast net, i.e., 162 fish in 80 casts), but in some years there are large numbers (up to 27 fish per cast net, i.e., 878 fish in 33 casts). Since 2005, large aggregations have occurred only twice, and Prado et al. (in press) determined that those occurred only after two consecutive years of major floods (>5,000 m³/s), which allowed for successful floodplain rearing and escape back to the river by young-of-the-year fish. Large aggregations did not occur in years of major flood preceded and/or followed by years of low or medium flood. Two consecutive years of major flood also increased the fish catch of RSF artisanal fishers from 3 kg/fisher/d to 25 kg/fisher/d only after two consecutive years of major flood (Godinho, unpublished data). Three kilograms of fish per day is insufficient for providing a livelihood for artisanal fishers. Marengo et al. (2012) predicted a 25% reduction in summer (fish spawning season) rainfall and annual mean temperature increase of 2.8°C for the RSF Basin by 2041–2070. Such reduction in summer rainfall will increase the recurrence.
interval of two consecutive years of major flood from 2 years to 10 years. Higher temperatures may increase mortality of young-of-the-year migratory fishes because of reduced nursery habitat area due to evaporation. Both climate changes suggest a drastic reduction in migratory fish recruitment to a level that will not support the thousands of professional fishers along the middle RSF.

The Furnas Reservoir is the fourth in a series of 12 dams on the Rio Grande, Minas Gerais, Brazil. Becker (2010) sampled fish from 1996 to 2009, which encompassed a severe drought in 1998 and 1999 that reduced the reservoir volume by 75% from 1999 to 2002. Annual catch per unit effort was negatively correlated with reservoir volume, and total species richness declined after the drought. However, the species richness and abundance of alien species increased during and after the drought, and the fish assemblage composition was significantly different following it. If predicted reductions in rainfall for the Rio Grande Basin and other Brazilian basins occur (IPCC 2015), similar fish assemblage changes are likely in other reservoirs.

Climate change in Argentinean inland waters will affect fish assemblages and most relevant target species and related fisheries. In Patagonia, predicted air temperature increase and precipitation reduction will reduce salmonid recreational fisheries because of reduced abundance and distribution of salmonids (Aigo et al. 2008). In turn, in the shallow Pampean lakes located in the east-central region of the country, Pejerrey Odontesthes bonariensis populations support very important recreational fisheries that could be affected because that species displays a temperature-dependent sex determination. Finally, in the La Plata Basin, increased water temperatures will promote the movement of Brazilian species southward and colonization by alien species currently inhabiting the upper basin. Flow augmentation and controls in response to increased temperatures and droughts are likely to have impacts on important artisanal and recreational fisheries mainly based on migratory species (Baigún 2015).

CLOSING REMARKS

The preceding sections amply illustrate the diverse and pervasive effects of climate change anticipated and in many cases already experienced by inland fisheries around the world. The long-term studies of lake and river fisheries described above demonstrate the value of such studies for teasing out the mechanisms of fish and fisheries losses, whereas the spatially extensive studies demonstrate their importance for estimating the extent of predicted changes. Moreover, it is now known that our global climate temperatures and precipitation patterns will continue to change even if carbon emissions decline or cease altogether (IPCC 2015). Therefore, it is imperative that other anthropogenic pressures on inland fisheries (such as migration barriers, land use/abuse, fisheries overexploitation, excessive and poorly planned stocking of hatchery fish, alien species introductions, and physical and chemical habitat alteration), which are driven by continued human population and economic growth (Limburg et al. 2011), be limited to the maximum degree possible. In fact, Tedesco et al. (2013) reported that such pressures apparently explained more fish taxonomic biodiversity losses than did reduced habitat availability from climate change. Nonetheless, Xenopoulos et al. (2005) predicted greater taxonomic biodiversity losses from climate change than from water withdrawal in many rivers. However, in other rivers the reverse was predicted, for example in the Euphrates (Iraq), Kura (Azerbaijan), Murgab (Afghanistan), Murray-Darling (Australia), and Rio Grande (United States). Examining functional versus taxonomic diversity, Buisson et al. (2013) reported that climate change is expected to yield substantial declines in the functional diversity of fish assemblages. Clearly, the combined effects of climate change and existing anthropogenic pressures are major challenges to freshwater fish biodiversity and fisheries in much of the world (Travis 2003; Dudgeon et al. 2006), and the scope of this challenge necessitates both local and international solutions.

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Pedchenko, A. P. 2011. Dynamics of Baltic Sea stocks under condi- tions of climatic changes. 150 Years of Russian fisheries science. Abstracts of Scientific Conference. VNIRO, Moscow (in Russian.).
The coming decades are expected to bring unprecedented climatological changes, with profound implications for inland fishes (Lynch et al., this issue), including for the many established nonnative (NN) species and new ones to invade (Diez et al. 2012; Sorte et al. 2013). Of interest are the effects of climate change on water resources: higher temperatures; changes to the timing, type, and intensity of precipitation; and alterations to extreme climates. For North American aquatic ecosystems, this translates to warmer waters, increased evapotranspiration, reduced ice cover, wetter conditions in the northern regions, drier conditions in the south, altered hydrological regimes, and changes to the frequency, timing and severity of extreme events, such as droughts and storms (Rahel and Olden 2008; Karl et al. 2009; Garcia et al. 2014). From the perspective of the Introduced Fish Section, major questions surrounding climate change center on (1) how will these changes tip the balance of fish invasions (i.e., under what conditions will NN species be favored) and (2) how do NN invasions interact with other anthropogenic stressors to affect native fish diversity?

**LOCAL VS. REGIONAL EFFECTS OF CLIMATE CHANGE ON FISHES**

Changes to climate averages and extremes will present major challenges to native biodiversity, affecting habitat suitability at both local and regional scales (Garcia et al. 2014). Locally, these changing conditions will affect the physiology, morphology, and behavior of fishes and ultimately cascade to demographic parameters and the strength of interactions with other species (Garcia et al. 2014; Lynch et al., this issue). For instance, temperature is a “master” variable, with an overarching effect on physicochemical and biological processes in aquatic systems, particularly for ectothermic taxa such as...
fishes (Ficke et al. 2007). Warming will increase physiological stress or, at minimum, physiological rates and reduce habitat suitability for many species (e.g., decreased thermal habitat for coldwater species), while simultaneously providing opportunities for invasion and range expansion for others (e.g., warm- and coolwater fishes; Ficke et al. 2007; Comte et al. 2013). These gradual effects will be punctuated by extreme floods and droughts that will constitute another major source of physiological stress and mortality for fish populations, and thus an important agent of selection under future scenarios.

At larger scales, the regional availability of climates will change, including the emergence of novel climatic conditions (Garcia et al. 2014). For example, southern latitudes will experience unprecedented high temperatures, beyond baseline variability (1960–1990s), which will affect the distribution of suitable habitats in both space and time. For fishes, their ability to respond to these regional changes and track suitable habitat conditions will depend on hydrological connectivity and the degree of habitat modification (e.g., dams, canals, water control structures). Thus, we expect fishes to experience higher vulnerability to habitat and hydrological modifications and to the synergistic effects emerging from the interaction of climate change and these human-induced modifications.

A third dimension of the response of fishes to changing local and regional climate is phenological effects, or effects to the timing of life history events such as migration and spawning. For fishes, these effects are better documented than distributional range shifts (Lynch et al., this issue), but data remain scant for NN species. Regardless, human-induced alterations to natural hydrological regimes and connectivity will interfere with the ability of both native and NN fishes to respond to climate change via latitudinal and/or altitudinal distributional changes in space, as well as via phenological shifts in time. In fact, a key concern is that stress on water resources will increase water development (e.g., construction of reservoirs, increased infrastructure for water withdrawal), with further negative effects on both connectivity and habitat suitability (Rahel and Olden 2008) and, as a consequence, on the ability of fish to track regional climate suitability. For NN fishes, this could present an advantage over native taxa. The natural flow paradigm predicts that human-modified flows favor NN species (Propst et al. 2008; Gido et al. 2013). As an example, Kiernan et al. (2012) showed that restoration of natural flows and associated temperature regimes in California streams favored locally-adapted native species and suppressed NN fishes.

**EFFECTS OF CLIMATE CHANGE ON INVASION OPPORTUNITIES**

Climate change may translate into invasion opportunities for many species as habitat suitability and thus the invasibility of ecosystems increases (Rahel and Olden 2008; Sorte et al. 2013). One key outcome is that climate change may result in a new wave of “native invaders” or species that become invasive in their own native range (Carey et al. 2012) or as these native ranges respond to climate change. As species distributions expand, contract, or change placement, native fishes could become invasive and exhibit the types of harmful ecological and socioeconomic impacts typically associated with NN species. Without doubt, the existence of these native “climate” invaders will bring a suite of new challenges to NN mitigation and control practices, in light of potentially conflicting societal vs. resource management concerns.

Beyond redefining invasiveness, climate change can affect NN invasions in a variety of other ways. Climate change may alter the pathways of invasion, the climatic constrains or filters experienced by NN taxa, their distributional patterns and impacts on native taxa, and the effectiveness of management actions (Hellmann et al. 2008). For instance, climate change can create new or more effective vectors of invasion (e.g., ones with higher survivorship), whereby propagate pressure and thus the likelihood of successful invasion increases. Rahel and Olden (2008) pointed to the simple fact that more of North America will become suitable for aquaculture practices and thus more successful introductions may be anticipated. Van Zuiden et al. (2016) forecasted that warmwater nonnative fish will expand their range northward into new lakes faster than originally anticipated as thermal filters disappear, with major implications for co-occurrence and competition with native coolwater fishes, biotic homogenization, and the profitability of fisheries.

Similarly, a recent meta-analysis on gradual climate change (higher temperatures, higher CO₂ levels, and altered precipitation) showed that climate change can favor NN species, particularly in aquatic systems (Sorte et al. 2013). Although fish were underrepresented in the study, climate change inhibited the survival, growth, and fecundity of native taxa to a greater extent that those of NN taxa. The authors also showed that, interestingly, NN tended to respond more strongly, both positively and negatively, to the effects of climate change. Similarly, for extreme climate events, Dize et al. (2012) pointed to the fact that extreme events can result in abrupt stressful conditions for native species that can reduce biotic resistance (or the ability of a community to fend off invasion), create resources pulses, and thus provide “invasion windows” for opportunistically and broadly tolerant NN species.

Chief among climate change concerns for NN are the fact that (1) climate change can remove the filters or constraints that keep NN fishes in check (Rahel and Olden 2008) and (2) NN species may be better poised to take advantage of the loss of such filters (Sorte et al. 2013). Climate change may loosen the effect of climatic, environmental, and/or biotic factors that limit the geographic range and local abundances of NN fishes, preventing them from becoming dominant, and have large negative impacts on native biota. In south Florida, episodic cold spells can reduce the abundance and limit range expansion of tropical NN fishes, but predicted changes in the frequency and severity of cold events will lessen this “natural” control mechanism (Rehage et al. 2016). In colder areas, climate change will reduce or eliminate the occurrence of winter hypoxia associated with ice cover. Winter hypoxia can limit the establishment of NN piscivores and maintain assemblages of small-bodied fishes and amphibians that do not coexist well with NN predators (Rahel and Olden 2008).

Second, NN species have already succeeded at invading novel environments during an invasion and may be better equipped for dealing with the challenges of range expansion under climate change than native taxa (Sorte et al. 2013). Nonnative species are often characterized by their strong dispersal abilities, rapid population growth rates, broad environmental tolerances, and high phenotypic plasticity. These traits allow NN species to cope well with novel conditions and environmental variability, permitting them to commonly outperform natives. We would expect that these same traits would give NN a competitive advantage relative to natives when tracking changing climate conditions in both space and time.
We conclude by highlighting that aquatic systems may be particularly vulnerable to invasion as climate change proceeds (Rahel and Olden 2008; Sorte et al. 2013). Climate change may interact with other environmental stressors, particularly altered hydrologic regimes, to benefit NN fishes and negatively impact native fish diversity. Reducing or mitigating the impact of these other stressors and ensuring hydrological connectivity to allow for distributional shifts will be key components of climate adaptation to protect native fishes. Lastly, climate change and invasions may interact synergistically, exacerbating effects on native fish diversity and ecosystem structure and function. This will likely result in increased variability in inland fisheries, which may not be fully captured using extant management models. To ensure that fisheries resources can weather these stresses, it will be necessary for managers to adopt adaptive conservation strategies that allow stressed populations to respond to the interplay of climate change effects and NN species. Importantly, these effects, along with the trajectories of the ecosystems of the future, will be conditional on human responses to climate change, particularly those related to water resources.

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MARINE FISHERIES SECTION

Methodology for Assessing the Vulnerability of Marine and Anadromous Fish Stocks in a Changing Climate

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The National Oceanic and Atmospheric Administration’s (NOAA) National Marine Fisheries Service (NOAA Fisheries) works with our partners to sustainably manage U.S. marine and anadromous fisheries and to conserve and protect marine mammals, sea turtles, and species listed under the Endangered Species Act. NOAA Fisheries also recognizes that climate-related changes are affecting the nation’s valuable living marine resources and the people, businesses, and communities that depend on them. NOAA Fisheries recently released a National Climate Science Strategy (Link et al. 2015) that outlines the
agency’s approach to tackling the science needs for managing fisheries and protected species in a changing climate. A primary goal of the science strategy is to better understand which species are more or less vulnerable to environmental changes and the factors driving the vulnerability. NOAA Fisheries has developed a methodology (Morrison et al. 2015) for assessing the relative vulnerability of marine and anadromous fish and invertebrate species to climate change. Implementing the methodology will help identify areas for in-depth analysis and assist fisheries and protected species decision makers in considering how to prepare for and respond to climate-related changes. We have implemented the methodology for 82 fish and invertebrate species off the northeastern United States, including a mix of exploited, protected, and forage species (Hare et al. 2016).

Similar assessments are currently underway for the Bering Sea and California Current ecosystems. The methodology is being modified in the California Current to better account for the vulnerability of Pacific salmon, an important anadromous protected species. NOAA Fisheries intends to replicate this process in other regions, depending on needs and available resources. In addition, NOAA Fisheries is in the process of creating a similar analysis for marine mammals and sea turtles.

The methodology is designed to generate three key results for each species: a relative vulnerability rank (based on exposure and sensitivity), an indication of a species’ propensity for shifting distribution (based on a subset of the sensitivity attributes), and an overall directional effect (do experts expect the species to respond positively or negatively to expected climate changes). NOAA Fisheries designed the methodology to be applicable across tropical, temperate, and high-latitude marine systems and address a wide range of fish and invertebrate life history characteristics. The vulnerability rank is a combination of a species’ expected exposure to environmental change and its biological sensitivity to that change. The methodology assumes that current biological parameters are an indicator of the relative sensitivity of a species. The exposure variables may vary between different regions (e.g., extent of sea ice will be important in some but not all regions). However, the 12 life history attributes used to determine a species’ sensitivity to climate change are consistent across regions and include habitat requirements, prey requirements, physiological tolerances, reproduction requirements, ability to change distributions, and other stressors. A subset of the life history attributes can be used to determine whether a species is likely to respond to changes in climate by shifting distributions, which could have a large impact on some fishing communities and on the overlap among fisheries and with protected species.

The methodology uses expert elicitation to rank multiple species at the same time. Experts assign scores based on four well-defined scoring bins (low, moderate, high, very high) to ensure that the scores are consistent across species. Each expert is asked to independently score the exposure and sensitivity of the species using species profiles, scientific literature, and general knowledge. Later the experts are asked to review their scores compared to the other experts and discuss the results and are allowed to adjust their scores based on those discussions. Using both individual and group expert elicitation practices helps minimize bias and increases precision of the results.

The results from a climate vulnerability assessment can be used to identify (1) species with high relative vulnerability that may need additional research or monitoring, (2) species that have a propensity to change distribution in response to a changing climate, (3) species that may be positively impacted by projected change, and (4) a list of major data gaps identified during the assessment. The assessment does not predict or quantify the scale or magnitude of expected change for a species in the future. We recommend that the results, along with other relevant information, be summarized for each species in a short species narrative that provides an easily accessible resource that can be used by scientists, fishery managers, or the public. Scientists can use these results to identify research priorities, such as identifying stock assessments that can benefit from explicit consideration of climate vulnerability and species that could benefit from increased monitoring. Managers can use the results to help identify specific attributes that make a particular species more or less resilient to climate change and to craft management measures that account for those differences among species.

Summary of the results from Hare et al. 2016. Approximately half the species assessed are estimated to have a high or very high vulnerability to climate change in the Northeast U.S. Continental Shelf Large Marine Ecosystem. In general, diadromous fish and benthic invertebrate species are predicted to be more vulnerable to climate effects in the ecosystem, and pelagic species are predicted to be the less vulnerable.
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PHYSIOLOGY SECTION

From the Equator to the Poles, a Physiology Section Perspective on Climate Change

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Anthropogenic climate disruption over the past century has driven significant physical, chemical, and biological changes in freshwater systems that directly affect fishes at all biological levels. Changes in temperature, precipitation, water flow, acidification, oxygen availability, and the food web are among climate-driven impacts on freshwaters. According to the Intergovernmental Panel on Climate Change (IPCC 2013), continued trends of greenhouse gas emissions and deforestation could produce global temperatures in excess of 3°C higher than pre-industrial values by the end of this century. Fifteen of the 16 hottest years recorded have all been this century, with 2015 being the hottest year ever. Furthermore, 2011–2015 was the hottest five-year period ever recorded. Under this rapidly changing climate, aquatic ecosystems are predicted to get warmer and become regionally more acidic and hypoxic. Patterns of precipitation and water flow are also predicted to change dramatically in many areas (Döll and Müller-Schmied 2012). Thus, aquatic organisms will have their homeostatic coping mechanisms pushed to their limits, and fish physiologists will be the ones to elucidate what those limits are.

Normally, natural selection would favor a close match between local environmental conditions and animal physiological performance capacity, through either maintenance of sufficient phenotypic plasticity or evolutionary adaptation. How effective these processes are at compensating for rapid environmental change will depend heavily on each species’ physiology in addition to ecological factors such as generation times and population size. Presently, a species’ response to climate change is predicted from correlative distribution models. These models correlate environmental factors (e.g., temperature and precipitation) with current distributions of species to predict future species’ distributions by assuming a species will follow this same “climate niche” as climate changes. These models are inherently flawed because they do not incorporate any knowledge of the species’ physiological capacity to compensate or to adapt through natural selection. A clear view of the future of fish will require substantial input from fish physiologists and their collaborations with geneticists to provide this vision.

Temperature is a well-known controller of physiological and ecological processes in fishes and can also influence potential fitness determinants as diverse as morphology, life history, and behavior. The past 70 years of fish physiology research has produced a wealth of data to help predict temperature change effects on fishes. But a changing thermal regime is not the only factor that fishes will have to successfully respond to as climate changes. Water availability, quality of that water, and magnitude of flow are all factors that can change a fish’s biology and distribution. Accurately predicting how a species will respond to climate change will require knowing its capacity for physiological response not only to temperature but to this suite of coincidently changing environmental variables as well as its ability to evolve and/or migrate to more amenable environments. Again, predicting this will require not only physiologists but collaborations with ecologists and evolutionary biologists.

Physiology Section Perspective on Climate Change

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Anthropogenic climate disruption over the past century has driven significant physical, chemical, and biological changes in freshwater systems that directly affect fishes at all biological levels. Changes in temperature, precipitation, water flow, acidification, oxygen availability, and the food web are among climate-driven impacts on freshwaters. According to the Intergovernmental Panel on Climate Change (IPCC 2013), continued trends of greenhouse gas emissions and deforestation could produce global temperatures in excess of 3°C higher than pre-industrial values by the end of this century. Fifteen of the 16 hottest years recorded have all been this century, with 2015 being the hottest year ever. Furthermore, 2011–2015 was the hottest five-year period ever recorded. Under this rapidly changing climate, aquatic ecosystems are predicted to get warmer and become regionally more acidic and hypoxic. Patterns of precipitation and water flow are also predicted to change dramatically in many areas (Döll and Müller-Schmied 2012). Thus, aquatic organisms will have their homeostatic coping mechanisms pushed to their limits, and fish physiologists will be the ones to elucidate what those limits are.

Normally, natural selection would favor a close match between local environmental conditions and animal physiological performance capacity, through either maintenance of sufficient phenotypic plasticity or evolutionary adaptation. How effective these processes are at compensating for rapid environmental change will depend heavily on each species’ physiology in addition to ecological factors such as generation times and population size. Presently, a species’ response to climate change is predicted from correlative distribution models. These models correlate environmental factors (e.g., temperature and precipitation) with current distributions of species to predict future species’ distributions by assuming a species will follow this same “climate niche” as climate changes. These models are inherently flawed because they do not incorporate any knowledge of the species’ physiological capacity to compensate or to adapt through natural selection. A clear view of the future of fish will require substantial input from fish physiologists and their collaborations with geneticists to provide this vision.

Temperature is a well-known controller of physiological and ecological processes in fishes and can also influence potential fitness determinants as diverse as morphology, life history, and behavior. The past 70 years of fish physiology research has produced a wealth of data to help predict temperature change effects on fishes. But a changing thermal regime is not the only factor that fishes will have to successfully respond to as climate changes. Water availability, quality of that water, and magnitude of flow are all factors that can change a fish’s biology and distribution. Accurately predicting how a species will respond to climate change will require knowing its capacity for physiological response not only to temperature but to this suite of coincidently changing environmental variables as well as its ability to evolve and/or migrate to more amenable environments. Again, predicting this will require not only physiologists but collaborations with ecologists and evolutionary biologists.
An unparalleled diversity of fish species inhabit tropical freshwaters, where they are often endemic to narrow geographical ranges and where they have very specific ecological niches. These niches will not be solely determined by environmental variables but will have involved coevolution with biological resources, the microbial community, competitors, predators, and parasites. All of these are subject to change as species with different thermal, oxygen, water, ion, and pH requirements drop in and out of changing ecosystems. In the Amazon, for example, it is foreseen that part of the region will experience a “savanzation” (Cândido et al. 2007), with profound effects on existing water bodies and the niches of the local fish species they encompass. It has been demonstrated that organisms, including freshwater fishes, from thermally stable environments such as the tropics tend to be thermal specialists (Campos et al. 2016). The Amazon is already experiencing extreme floods and droughts predicted by climate change models, particularly during El Niño–influenced years. The physicochemical characteristics of the waters of the Amazon define the distribution of many fish species across the biome. Recent unpublished analyses indicate, for example, that only a small portion of the fish species existing in the region occur simultaneously in all three types of water of the region (white, black, and clear water), and only a few migratory fish species swim back and forth between types of water (E. J. G. Ferreira, Brazilian National Institute for Research of the Amazon, unpublished data). This suggests that a species highly adapted to a specific type of water would face a size reduction of their habitat due to persistent drought that will likely occur in some parts of the region. The effects of these altered flows and water availability on fish biology and reproduction need to be understood. Without this information, nothing can be done regarding mitigation—more fodder for fish physiologists.

Moving to a part of the planet where climate is changing most rapidly, Arctic freshwaters, the problem is somewhat different. Fish diversity is far less, but large populations of predatory fishes that have sustained important fisheries for millennia and ecosystems for far longer are imperiled. Many of these coldwater fishes are also stenothermal and are threatened directly by warming planetary waters. Current climate projections predict not only temperature increases for most polar waters but also flow regimes that are more stochastic (Döll and Müller-Schmied 2012). Lotic and anadromous fish populations may have to deal with both unprecedented flows as well as the risk of their stream drying up. Lentic fishes may face longer and more stable stratification as well as contraction of their water body. Functional relationships between morphology and the magnitude of water flow have been reported frequently in freshwater fishes, yet physiological and performance traits driven by occupying different flow environments have only been studied rarely (Nelson et al. 2015). Understanding how these fish will cope with the altered flow regimes and water supply will be essential to predicting their futures. Thus, fish physiologists need to start addressing our lack of knowledge concerning how fish are able to respond to changes in flow and lacustrine dynamics.

Temperature influences on fish metabolism have been studied for over 100 years now (Ege and Krogh 1914), and we have long had temperature/swimming performance curves for a variety of fishes (Brett 1964) and similar temperature/function curves for many subordinate physiological processes (Taylor et al. 1996). Presently, the ability of animals to shift those performance curves as climate changes, through either plasticity or natural selection, is a subject of much interest and a place where fish physiologists are already contributing mightily to the climate change conversation (e.g., Pörtner 2010; Clark et al. 2013). Additionally, because all fish require oxygen to complete their life cycle, the predicted climate change reduction of dissolved oxygen in many waters may be more critical to future fish success than temperature changes alone. Many tropical fish species are obligatory air breathers; others facultatively breathe air, but the great majority are gill breathers and depend on dissolved oxygen. The gill breathers include species that are hypoxia resistant and those that are not. In many cases, closely related species use different strategies to maintain oxygen transfer to tissues. Therefore, though air breathers, both obligatory and facultative, would face climate change–driven challenges from increased time at the water–air interface (e.g., increased ultraviolet exposure, predation, etc.), gill breathers may be directly excluded from habitats as the water oxygen level falls below their ability to compensate. In addition, we are also learning that even if hypoxia is not outright lethal to a given fish species, there are many sublethal effects of hypoxia exposure that can compromise Darwinian fitness (Domenici et al. 2012). As dissolved oxygen decreases, the difference between an animal’s maximum metabolic rate and resting routine metabolic rate often decreases, limiting an animal’s capacity to engage in metabolically expensive activities such as swimming and digestion (Claireaux and Chabot 2016). Even a short (<1 h) exposure to hypoxic water can produce a metabolic disturbance that lasts for many hours in some fish (Plambeck et al. 2013). Reduced swimming ability, reduced growth, compromised immune system function, disorientation, and reduced ability to respond to stimuli have all been reported as outcomes of mild hypoxia exposure (reviewed by Chapman and McKenzie 2009; Diaz and Breitburg 2009). These sublethal effects of hypoxia exposure can influence survival and the ability to carry out routine biological functions and therefore Darwinian fitness, but even more alarming is that hypoxia can also act as an endocrine disruptor, including sex reversal, that could lead to a rapid demise of populations (Wu et al. 2003; Cheung et al. 2014). Many Physiology Section members are currently studying how fish deal with these lower oxygen levels; their experiments, especially their collaborations with geneticists, will help predict the future for the many fish species that will see their environmental oxygen levels diminish over the coming years.

In summary, physiologists can contribute to our understanding of climate change impacts by directly gauging the capacity of fish to respond to future environments. Physiologists can also use historic records and species distribution patters to find populations from extreme environments that will help infer the capacity of a species to respond to climate change through natural selection. Furthermore, collaborations with geneticists and ecologists will greatly improve our power to predict climate disruption’s effects on fishes. Many fisheries scientists are already reporting declines in fish populations that they attribute to climate change. By analyzing the functional and mechanistic responses of fish to climate-driven stressors, this “conservation physiology” practiced by members of the Physiology Section will help illuminate the future of freshwater fishes.

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**STUDENT SUBSECTION**

**Climate Change and Fisheries Education**

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Climate change is predicted to affect aquatic ecosystems in diverse ways with implications for management of inland fishes and fisheries. For example, the frequency of weather events that alter the availability and movement of water (e.g., droughts, heavy precipitation, heat waves) is predicted to increase with climate change (Saha et al. 2006). Rising sea levels are predicted to cause saltwater intrusion (i.e., replacement of freshwater by saltwater) in coastal aquifers (Iyalomhe et al. 2015), which may alter habitat suitability for freshwater and marine fishes.

Warmer air temperatures resulting from climate change are expected to increase water temperatures, with effects on growth, reproduction, and survival of fishes and their prey (Woodward et al. 2010; Hershkovitz et al. 2015; Kanno et al. 2015). Moreover, climate change is predicted to alter species interactions, the timing of important life history events (e.g., migration, spawning), and the spatial distribution of fish populations (Lynch et al., this issue). On a physiological level, effects of climate change on individual fish include reduced immune function, decreased cardiovascular performance, and changes in reproductive investment (Whitney et al., this issue).

As leaders of the Student Subsection of the Education Section (Student Subsection), we recognize the importance of understanding how climate change will affect inland fisheries and making this knowledge meaningful for fisheries students and young professionals. The Student Subsection serves to facilitate interactions between fisheries professionals and students by providing member services consistent with the mission of the American Fisheries Society (AFS), for which professional development is a primary goal. To prepare students and young professionals for rewarding careers in fisheries conservation, it is our duty as Student Subsection leaders to anticipate issues and trends that are relevant for future fisheries professionals. As climate change intensifies, we believe that it is imperative that students and young professionals acquire basic and applied knowledge of climate change as it relates to inland fisheries. Not only must students and young professionals understand the process of climate change, they must develop skills to apply this knowledge for fisheries conservation. How can fisheries professionals ensure that students have climate change know-how as they prepare for their careers? We describe five action items that we believe will enable fisheries students and young professionals to tackle the challenges imposed by climate change.
1. Incorporate climate change into university fisheries programs, particularly undergraduate courses. All graduates should have a working knowledge of climate change and its ecological and sociological effects on fisheries management. Design education programs so that students are prepared to think critically about the implications of climate change, identify knowledge gaps, and develop research projects to address unanswered questions.

2. Foster undergraduate and graduate research opportunities on how climate change is affecting (and will affect) inland fishes and fisheries management. Provide resources (e.g., fish sampling equipment, water temperature loggers, geographic information systems) that students need to conduct research and thereby fill knowledge gaps. Research will enable students to increase their understanding of climate change complexities and advance the state of fisheries science relative to climate change. In addition, ecological studies, research on fisheries stakeholders (e.g., anglers, boaters, commercial fishers) should be conducted, allowing students to understand the social effects of climate change and ultimately apply this knowledge as fisheries professionals.

3. Enable students to share climate research findings through existing and yet-to-be established forums. Traditional avenues such as Fisheries “Student Angles” and research articles enable students and young professionals to convey their results to other fisheries professionals. In addition, creating and enhancing nontraditional communication mechanisms such as blogs, discussion boards, Facebook pages, podcasts, and webinars will allow students to describe their research findings in less formal settings and develop skills for communicating with non-scientists.

4. Solidify the nexus between climate change and fisheries stakeholders by equipping future fisheries professionals with public engagement skills for conveying the projected effects of climate change to resource users and the general public. Fisheries professionals need skills to effectively communicate realistic expectations for future fisheries to stakeholders. Students and young professionals can develop these skills by preparing written documents for stakeholders that describe fisheries in a changing climate; coordinating meetings with angling groups, watershed associations, and other organizations; and enrolling in courses and directed training programs focused on communicating science to the public.

5. Encourage established professionals in fisheries and other fields to share their perspectives regarding present and future effects of climate change on fisheries and the fisheries profession. This can be achieved by inviting researchers, managers, biologists, and human dimensions specialists to speak at universities, research conferences, AFS Student Subunit meetings, and other events. By sharing their professional wisdom on climate change, established professionals will provide students and young professionals with valuable information for applying climate change knowledge in their careers. For example, a human dimensions specialist could describe the strategies used to convey climate change science to general audiences and thereby help future fisheries professionals bridge the gap between climate change and fisheries stakeholders.

As climate change continues to affect inland fisheries, it is our responsibility as Student Subsection leaders to work with the broader fisheries community to ensure that the fisheries professionals of tomorrow have basic and applied knowledge of climate change. By enhancing climate change education, research opportunities, communication mechanisms, public engagement training, and intergenerational information flow, we believe that the professional fisheries community will be better equipped to face the current and future challenges imposed by climate change. Adding climate change know-how to the toolboxes of students and young professionals will benefit the fisheries profession now and in the future.

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Anticipated Water Quality Changes in Response to Climate Change and Potential Consequences for Inland Fishes

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INTRODUCTION

Healthy freshwater ecosystems are a critical component of the world’s economy, with a critical role in maintaining public health, inland biological diversity, and overall quality of life. Globally, our climate is changing, with air temperature and precipitation regimes deviating significantly from historical patterns. Healthy freshwater ecosystems are a critical component of the world’s economy, with a critical role in maintaining public health, inland biological diversity, and overall quality of life. Globally, our climate is changing, with air temperature and precipitation regimes deviating significantly from historical patterns. Changes anticipated with climate change in the future are likely to have a profound effect on inland aquatic ecosystems through diverse pathways, including changes in water quality. In this brief article, we present an initial discussion of several of the water quality responses that can be anticipated to occur within inland water bodies with climate change and how those changes are likely to impact fishes.

WATER TEMPERATURE INCREASE IN SURFACE WATERS

As global surface temperatures increase with climate change, associated increases in water temperature have the potential to significantly shift the variety of aquatic thermal environments that assemblages of fish occupy (Buisson et al. 2008). The distribution, reproduction, fitness, and survival of fishes are all inextricably linked to the thermal regime of their environment. Diverse laboratory studies highlight the direct effects that increasing water temperatures can have on fish, including increased lethality as thermal limits are exceeded (Seleng et al. 2001; Zeigler et al. 2013), changes in feeding behavior, metabolism, and growth rates; and altered reproductive success (Pankhurst and Munday 2011). Indirect effects may result from uncoupled trophic interactions (Winder and Schindler 2004), shifting prey availability, interspecies competition (Buisson et al. 2008), and increased susceptibility to disease and parasitism (Marcogliese 2001; Hari et al. 2006).

Many recent studies have predicted significant shifts in thermally suitable fish habitat under climate change scenarios. These scientific predictions have been particularly bleak for stenothermal fish species (e.g., trout and salmon), with anticipated widespread contraction of suitable salmonid habitat remaining largely within higher elevations and northern latitudes (Eaton and Scheller 1996; Isaak et al. 2012). Moving forward, studies that systematically document realized fisheries impacts would enable us to ground truth laboratory- and model-based climate change predictions (Kovach et al. 2016).

Importantly, one significant ecological consequence resulting from the loss of lower elevation mainstem habitats to warming is the increased fragmentation and resultant isolation of remaining thermally suitable habitats in colder headwater streams. Fishes in these isolated, fragmented streams typically have a much higher risk of extirpation due to an insufficient quantity and diversity of habitat to complete life cycles (Hilderbrand and Kershner 2000), increased vulnerability to genetic diversity issues resulting from inbreeding within functionally smaller populations, and increased risk of loss through stochastic events (Brown et al. 2001).

In small, shallow, and low-gradient streams, water temperature increase may have severe impacts on aquatic biota (Chen et al. 2015). For instance, many small streams in the Mississippi River Basin (Figure 1) have very poor habitat conditions (e.g., no clear poor riffle-run pattern, no in-stream or riparian vegetation, single sediment particles dominant such as silt), which may exacerbate the water temperature stress, and fish and other aquatic organisms that do not have natural shelters to escape the heat stress.

Compared with lotic waters, water temperature increases in lentic waters (e.g., lakes, ponds) may persist longer and have larger potential impacts on aquatic biota because of longer periods of stratification (Wetzel 2001). Increased water temperature in these seasons would have strong impacts on aquatic biota, especially on those surface dwelling organisms. Moreover, organisms in small (e.g., less than 0.1 ha) and shallow (e.g., less than 0.5 m deep) ponds (Figure 2) may be impacted more by the increased water temperature than those in larger and deeper lakes, because the former do not have space to escape the added heat stress.
DISSOLVED OXYGEN PROBLEMS IN STATIC WATERS AS WATER TEMPERATURE INCREASES

As surface water temperatures increase with predicted climate change, the solubility of dissolved oxygen (DO) in those waters will decrease (Ficke et al. 2007; Solheim et al. 2010). Examples of potential widespread outcomes may include (1) a general 10% decrease in DO availability, dropping concentrations below survival thresholds for resident aquatic organisms (e.g., native indicator species in the California Sierra Nevada) by 2100 (Ficklin et al. 2013); (2) native fish biodiversity may also change with habitat loss for coldwater fish as increased water temperatures and lower DO concentrations occur, leading to a northern range expansion of nonindigenous species (Sharma et al. 2011); (3) elevated air temperatures would create deeper and longer lasting thermoclines in lentic water bodies, leading to greater metabolic activity in the hypolimnion, further reducing DO (Schindler et al. 1996); (4) decreased surface water mixing may decrease direct DO inputs and increase sediment metabolic activity in the isolated hypolimnion, further reducing DO to harmful or lethal levels for freshwater fish (Ficke et al. 2007); (5) decreased DO may lead to increased sediment solubility and availability of nutrients (Blumberg and Di Toro 1990) and other compounds, potentially increasing toxicity to fisheries from pollutants (Ficke et al. 2007); and (6) increased algae growth during daytime but more DO consumption during the night, especially in shallow, small static water bodies, such as a fish pond where low DO problems usually occur during nights and early morning hours (Farrelly et al. 2015).

HYDROLOGY-RELATED WATER QUALITY CHANGES

Increased air temperature and changes in precipitation patterns are likely to alter stream and river discharge regimes (Clow 2010; Leppi et al. 2012). In ice- or snow-covered regions, increasing air temperatures will hasten snowmelt, altering hydrological regimes by increasing adjacent stream flow earlier and creating deficits later in the season (Stewart et al. 2005). Importantly, these late season deficits leave less water in the channel to be warmed during the warmest months of the year.

Though chemical concentrations are likely to be diluted during high flows, the total contaminant load may increase (Novotny 2003; Grigas et al. 2015). During low flows, chemical concentrations (and water temperatures) will increase, but the total load may decrease as well. For instance, in the Mississippi River Basin, runoff of agricultural nutrients (e.g., nitrogen and phosphorus) and sediment would have relatively higher concentrations but low total loads. In some extreme conditions, high flow can cause high concentrations of these agricultural pollutants as well (Reba et al. 2013). This similar flow–chemical concentration/load pattern has been observed in urbanized watersheds as well (e.g., Grigas et al. 2015).

Similarly, many components of rock weathering and solute transport are influenced either directly or indirectly by the local climate. Local hydrology, which is directly linked to climate, governs the subsurface flow of oxygen and water, as well as the surface and subsurface transport of weathering products (Nordstrom 2011). Further, both temperature and hydrology have a strong influence on watershed geochemical reaction rates and, as such, define resultant water chemistry in waterbodies draining those watersheds. As such, significant change in climate conditions (e.g., thermal and hydrological regimes) within mineralized areas has the potential to change watershed chemistry (Rogora et al. 2003).

Several studies have documented increases in rock weathering solutes (e.g., dissolved sulfate) over the last several decades and have attributed these increases to climate warming (Lami et al. 2010; Mast et al. 2011). One recent study has documented a concomitant increase in concentrations of
dissolved metals known to be both products of pyrite weathering and toxic to freshwater fishes (e.g., Zn, Cu, Cd; Todd et al. 2012). In this study, it was concluded that observed increases of instream toxic metal concentrations were likely attributable to a number of climate-influenced factors, including increased rock weathering, new subsurface flow and weathering pathways resulting from loss of frozen surface ground, and a decreasing groundwater table (Todd et al. 2012). Importantly, if such water chemistry changes cause downstream water quality to worsen, it may result in exceedances of toxicity thresholds, extending fisheries impacts downstream.

DISSOLVED ORGANIC CARBON AND METAL PROBLEMS AS AIR EMISSIONS CHANGE

Air emission of CO₂, SO₂, and NOₓ can affect water quality through the change in precipitation chemistry. For instance, when the emission of SO₂ is increased, more SO₄²⁻ will be available in receiving water bodies, reducing pH in the water. One chemical within water bodies that appears to be increasing as a result of a combination of declines in acidification, as well as increasing temperatures, is dissolved organic carbon (DOC; Evans et al. 2005). Increasing pH and decreasing aluminum in water bodies recovering from acidification also have been accompanied by increasing DOC (Lawrence et al. 2013), which partially offsets pH increases and complicates assessment of recovery from acidification. DOC change affects drinking water quality, metal and organic contaminant transport and toxicity, nutrient availability, and attenuation of solar radiation (Erlandsson et al. 2011).

In addition, there is concern with the link between DOC and mercury concentration in biota. For instance, Driscoll et al. (1995, 2007) have reported increasing concentrations of mercury in lakes and biota of the Adirondacks with increasing concentration of DOC. Other related studies have also shown that lake water chemistry, particularly pH and DOC, influence the bioavailability of mercury at the base of the aquatic food chain (Adams et al. 2009; Dittman and Driscoll 2009). Where atmospheric mercury deposition is a problem, the increased DOC can lead to increased tissue concentrations of mercury in aquatic organisms. In areas without a mercury point source, tissue concentrations may continue to climb resulting in new or sustained advisories for fish consumption.

CONCLUSIONS

In summary, global climate change is predicted to change air temperature; precipitation; emissions of CO₂, SO₂, and NOₓ; and other aspects. These changes are expected to lead to increased water temperatures (in most cases), decreasing dissolved oxygen concentration, altered water chemistry and chemical loads, and, in certain regions, create new water quality challenges including increased dissolved organic carbon and toxic metal loads. As fishery professionals, we suggest the need to be proactive and anticipate these changes to allow for adaptation in fisheries management and conservation.

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Leveraging BIG Data from BIG Databases to Answer BIG Questions

What is "big data?" This phrase has become so commonly used that Wikipedia has an entry for it (and not just for the music band). Big data is generally considered to be datasets that exceed the capacity of typical management and analytical software (Snijders et al. 2012). Most fisheries biologists do not use massive datasets on a regular basis; however, they do regularly collect similar types of data across agencies (e.g., fish records, water quality), which could be collated to create datasets with increased temporal and geographic coverage. Big fisheries datasets provide resources for managers, researchers, and stakeholders to address broader questions such as the potential effects of climate change, barrier installation or removal, or land use management on inland fisheries. As an example, many public and private sector fisheries biologists collect data that would be relevant for assessing impacts of climate change on inland fishes, including fish species distributions, population trends, water temperature and chemistry, and habitat composition. Much of this information languishes in office files, but an increasing amount is in electronic form which allows for easy sharing. Impediments to sharing data do exist (Loftus 2006, Midway et al., in press) with time, personnel, financial, and fear of misuse ranked as most important, followed by technical, legal, and policy (Table 1; Loftus 2006). However, electronic datasets are increasingly easy to compile, maintain, and share through technological advances at a decreasing time, personnel, and financial cost. The use of hand-held devices to enter data while in the field has increased dramatically over the past decade, and we can expect that trend to continue. For such big questions, going into the field and collecting data for these purposes often is not feasible, or even possible for assessing historical trends. By combining forces, we can leverage big data to address these big picture questions.

How can we address questions which require big data on small budgets? In these times of tightening budgets, sharing data provides the opportunity to stretch limited resources. Datasets collected for local uses could be dovetailed together across natural and political boundaries to address regional, national, and international questions. Accessing records collected over long periods of time or over large spatial extents can give insight into trends in inland fisheries such as documenting climate linked changes in distribution (Comte et al. 2012) or population size (Paukert et al., this issue). Data availability allows leveraging datasets in lieu of collecting new data, as McKenna et al. (2010) did when they utilized point temperature measurements from >3,000 stream sites to create a summer water temperature classification for New York streams that
was used by Schlesinger et al. (2011) to assess vulnerability of species at risk. Access to big data could better inform national initiatives such as the National Fish Habitat Partnership, better enabling resource managers, policy makers, and stakeholders to address questions that might otherwise not be answered working with data limited by source and scale. Practical examples such as these illustrate why having these datasets organized and available allows natural resource managers to act quickly without the need to commit substantial monetary and time investments in order to address important questions.

Throughout its existence, the AFS Fisheries Information and Technology Section (FITS) has advocated for the development of big data for purposes including analysis of climate change. The idea of using big datasets may sound intimidating to some, however tools could be developed that provide automation of data importation and analysis. Two examples are the Multistate Aquatic Resources Information System (MARIS) and the NorWeST project.

### MARIS

For nearly two decades FITS served as the coordinating body for the MARIS. MARIS began in the 1990s as an exploratory endeavor between state natural resources management agencies and federal resource agencies as a mechanism for distributing select information collected by state agencies to apply to the analysis of status and trends of fish populations over watersheds, ecoregions, and across jurisdictional boundaries (A. J. Loftus, MARIS coordinator, personal communication). Among the earliest discussions during the formation of MARIS was its application for tracking (at the macro level) the impact of climate change on the distribution of fish species (particularly those close to the edge of their ranges) and correlations with changes in water temperatures and watershed factors (Beard et al. 1998). MARIS has flourished, and now contains over 1 million fish sampling and water quality records for more than 1,000 fish species in 24 states with some data extending back 100 years. MARIS is being applied for many purposes directly or indirectly related to climate change studies, including:

- Compiling stream and river temperature time series records to relate to the fish community data.
- Fish passage studies to identify opportunities for barrier removal, thus opening additional habitat for species being pushed out of changing habitats.
- Investigating fish assemblages and distribution in southwestern and southeastern rivers related to human water uses and climate change.
- Historical occurrence of fish species in the specific drainages and changes in range over time.
- Invasive species tracking and distribution.
- Species occurrence in the past 10 years for populating third-party web query results for identifying species locations (A.J. Loftus, MARIS coordinator, personal communication).

### NorWeST

Another example of the application of big data is the NorWeST project, a collaboration across the American West by fisheries biologists and hydrologists from >100 agencies which has resulted in synthesis products that are directly applicable to the assessment of climate change to inland fishes (Isaac et al. 2011). In brief, the project began in the Pacific Northwest due to concerns about the effects of climate change on cold water fish species and grew organically to encompass all streams and rivers in the West by cleaning and organizing datasets into digital formats that make it easy for data contributors to access and use stream temperature information for many purposes. One important application has been the development of a stream temperature model that uses all the data with sophisticated spatial-stream network data mining tools (Ver Hoef et al. 2014) to create consistent sets of high-resolution climate scenarios, which are also available for download from the website. Many organizations now use the NorWeST scenarios for climate vulnerability assessments, and Isaak et al. (2016) provide a recent example for the Pacific Northwest. Similar big data applications for many types of stream data (e.g., habitat surveys, water quality parameters, biological samples) have also been made easier with toolsets provided through the National Stream Internet project so that biologists throughout the conterminous United States can use new stream network models in their local watersheds. As more data are compiled, organized, and shared, a proliferation of new information about stream resources will follow, and these efforts will be greatly accelerated by the collaboration of biologists and hydrologists working for dozens of agencies.

### FITS Fosters Data Sharing

For the past two decades, AFS and FITS have advocated for the sharing of datasets for the purpose of harnessing the wealth of information being collected by fisheries biologists every year. Since 1998, FITS has played an active role in hosting three national fisheries data summits with an underlying theme of facilitating access to existing datasets (see www.fishdata.org for summaries). These summits have incrementally provided a pathway toward the development of a National Fisheries Data Exchange Standard. More recently, FITS has hosted and co-hosted symposia focused on developing a National Fisheries Data Exchange Standard. The objective of this initiative is to provide common codes and metadata and data elements that can be used by freshwater fisheries biologists. This will facilitate

| Impediments to sharing agency fisheries data (N=62; Loftus 2006). |
| --- | --- | --- | --- |
| Very Important | Important | Somewhat Important | Not Important |
| Legal | 23% | 24% | 27% | 26% |
| Policy | 16% | 24% | 35% | 24% |
| Technical | 27% | 42% | 24% | 6% |
| Financial | 32% | 27% | 29% | 11% |
| Personnel | 48% | 39% | 10% | 3% |
| Time | 61% | 27% | 10% | 2% |
| Fear of misuse | 30% | 25% | 34% | 11% |
sharing and collating of datasets into the big data described above in a timely fashion to allow the use of current and relevant data in science and advance the goals of regional and national initiatives. Currently, the creation of large geographical and temporal datasets through the compilation of smaller datasets is hindered because the translations are excessively time consuming. A National Fisheries Data Exchange Standard will provide the benefits seen through programs like NorWeST and MARIS at a larger scale.

Through our newsletter and website we highlight tools which aid in the development of big data, opportunities for data sharing, and research which has leveraged big data and technology to address important questions in inland fisheries. The use of big data will be critical to addressing many of the questions pertinent to the impacts of climate change on inland fisheries, and we at FITS want to encourage the development and use of these data sources.

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FISHERIES MANAGEMENT SECTION

Effective Stewardship incorporates Expertise and Innovative Approaches to Aquatic Resource Management

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A professional position as a “fish biologist” or a “fisheries manager” suggests a singular focus on fish, which is a bit misleading. Modern fisheries management encompasses more than a fascination with these underwater evolutionary marvels. The long-held visualization of a three-legged stool consisting of habitat, fish and people symbolizes the entwinement of these components and the wisdom in managing them collectively rather than exclusively. Similarly, aquatic ecosystems include both the components and the forces (natural and anthropogenic effects) that have been at work through time to arrive at the current set of abiotic conditions (Ponomarenko 1996) and biotic communities (Infante et al. 2009; Wootton 1992) encountered today. Climate change is yet another force that further complicates our understanding as well as the long-term beneficial management of these aquatic ecosystems. Fortunately, training, continuing education, professional involvement and experience are available for biologists and managers to continually incorporate new information to aid in their stewardship responsibilities.

MANAGEMENT COMBINES AN UNDERSTANDING OF SYSTEMS WITH ACTIONS TO REACH A DESIRED GOAL

The discipline of fisheries management strives to attain a specific state or condition for the resource under stewardship (e.g., goals and strategies). Whether a recreational fishery, nature preserve or commercial fishing operation, to be an effective steward you need to not only have a solid grasp on how the current forces (natural and anthropogenic) are acting on communities within the system, but then must also be able to anticipate how changes (natural, induced, or prescribed) will influence existing system dynamics to predict future conditions. A new impoundment on a river can dramatically alter system connectivity, while changes to land use practices (e.g., no-till farming, phosphorus fertilizer bans, pet waste ordinances) can be much more subtle. Challenges faced by fisheries managers today, range from preserving genetic diversity of at-risk populations (Vrijenhoek 1998), to managing for sustainable yields of commercial harvest (Botsford et al. 1997), or providing...
unique recreational fishing opportunities (Neely et al. 2015; Pikitch et al. 2005). Changes to the underlying habitat condition complicate these challenges.

Beneficial management actions (or lack thereof) require an understanding of the forces already acting upon the resource, as well as knowledge of how a system will respond, ideally prior to prescribing an appropriate strategy. For example, a fisheries manager responsible for a healthy, intact and pristine system often takes a protectionist viewpoint and usually prescribes a very conservative suite of management tactics to minimize impacts to what is perceived as a system in good working condition. In contrast, the manager of a system that is highly altered and degraded, and comprised of numerous introduced or habitat-detrimental species, is likely to take a much more aggressive approach to purposefully nudge the existing system towards a more desirable state. Even if both the pristine and altered systems have identical goals, each approach requires substantially different levels of active management and system strategies, often referred to as resilience management (Pope et al. 2014). The recognition and application of appropriate tactics to meet a desired goal across a diverse range of systems and conditions, is the basic tenet of fisheries management (McMullin and Pert 2010).

AQUATIC SYSTEMS, LIKE TIME, NEVER STAND STILL

While many of the techniques used in fisheries management have been vetted, improved, and refined over time by the application of fisheries science, hard work, and experience, they have been developed for conditions encountered over the last century, but the real challenge will be developing the approaches and tools needed for future conditions (Paukert et al., this issue). Climate science is focusing on predicting rates of change while fisheries and resource professionals are applying this information to predict future system conditions and subsequent influence to dependent communities.

Fortunately, the management process is well suited to meet the challenges imposed by climate change. As more of the earth’s natural resources are exposed to anthropogenic (e.g., land use and pollution emissions) and climate change impacts (e.g., temperatures rise, precipitation patterns change), system forces will continue to alter making the prediction of future conditions even more uncertain. As our aquatic ecosystems serve as poor experimental units because of their scale and complexity and rates of general condition decline, this will necessitate an ever-increasing need for more active and enhanced management applications. But it will also further complicate our ability to evaluate and determine which actions were successful. Design and implementation of habitat rehabilitation and enhancements projects, forecasting future water conditions, stock assessment modeling and even recreational fishing (e.g., stocking and regulations) will need to consider these uncertainties and incorporate them into an adaptive management decision-making process that adequately considers multiple causal factors simultaneously (Hillborn 2016) to truly understand the system mechanics and adjust strategies accordingly to be successful.

To meet this challenge, communication of the science behind system influences and responses will be critical in determining the impact to our resources and more importantly how we respond to manage effectively in the wake of climate change (Essig, this issue). AFS will need to continue being the leading source for communicating fisheries science information and research, but that will not be enough. As fisheries professionals and resource stewards, it will be up to us to perform the due diligence needed to research and adapt techniques, the science and ultimately our management strategies to meet the challenges presented by climate change. AFS and the Fisheries Management Section must collaborate to provide continuing education and training opportunities, sponsor symposia and publish information on advanced management techniques and topics to train the next generation of “fish biologists” or “fisheries managers” for the challenges facing our next generation of aquatic ecosystems.

REFERENCES


Essig, R. 2016. Climate change: SWAPs and AFS. Fisheries 41: 327.


habitat management, fish dispersal, education, monitoring, research, funding, and management to reduce ecosystem stressors. AFS sent letters to President Obama in January 2013 and the U.S. Environmental Protection Agency administrator in June 2014 promoting the policy statement.

Climate change has been the subject of many symposia at Society and AFS Unit meetings in recent years. The 2015 Annual Meeting had sessions on ocean acidification and impacts of climate change on populations, distributions, and habitats. The 2016 Midwest Fish and Wildlife Conference, where the North Central Division meets, featured a session on climate science for state-level resource management. There will be symposia on drought and impacts of climate change on inland fish at the AFS 2016 Annual Meeting in Kansas City. Symposia like these provide an opportunity for researchers and managers to share the latest climate change science that is tailored to aquatic species and habitats.

AFS organized two Congressional Hill briefings in recent years where climate change was a major focus. The Society and its Potomac Chapter presented a briefing entitled “Climate Change and Fisheries” on May 9, 2013, with speakers from federal and state agencies, academia, and a Native American tribe. A March 19, 2015, briefing on marine fisheries management included a presentation entitled “Addressing Climate Change as a New Challenge to Fisheries Managers.”

AFS staff is currently working through Cornell University on a three-year project to review the work of the eight Department of Interior Climate Science Centers (CSCs) in the United States. The scientific goal of these reviews is to assess the contribution of each CSC in climate modeling, climate change impact assessments, vulnerability and adaptation analyses, and developing adaptation strategies. Review objectives also include evaluating partner engagement and graduate student training of the CSCs.

There are other ways that AFS is likely to engage in the climate change issue in the future. Sections like Fish Habitat and Water Quality are well positioned to work on the issue, and there has been discussion of forming a new AFS Climate Change Section. Through its Future of the Nation’s Aquatic Resources initiative, AFS is currently gathering information on important issues for the incoming U.S. Presidential administration that are very likely to include climate change.

Finally, this thematic issue of Fisheries is the most recent example of AFS involvement in climate change. It includes a cross section of articles organized by active members Craig Paukert and Abby Lynch that are sure to pique your interest. Please take some time to explore and enjoy the issue. Perhaps you can apply some of the science contained within to your current or future fisheries work.

To tackle these issues, and in conjunction with the United Nations World Water Day, the White House Water Summit was convened on March 22, 2016, to

- raise public awareness of water issues and potential solutions,
- catalyze ideas and actions to help build a sustainable and secure water future through innovative science and technology, and
- frame ideas for the next administration.

The summit focused domestically on the full range of topics relevant to aquatic systems, small communities, and metropolitan utilities. This event was livestreamed by the White House and is likely to be archived on that site.

The Association of Fish and Wildlife Agencies convened its own “Drought Forum” on February 29, 2016, to prepare for discussions at the National Fish Habitat Partnership’s board meeting mentioned above. And the discussion will continue at the American Fisheries Society Annual Meeting in Kansas City, where the Estuaries Section and Fish Habitat Section have joined forces on a special symposium on drought.

The momentum of these events, coupled with a snowy first day of spring covering my earliest-ever cherry tree blossoms, has me hoping for great success on all three goals for the Water Summit. Perhaps this discussion will expand from drought to the broader issues of flow because the water that doesn’t fall in parched watersheds will fall elsewhere. Our challenges just doubled!

Note: This column represents my personal opinions, as based on the comments of Ellen Gilinsky at the National Fish Habitat Partnership March 2016 Board Meeting. They do not necessarily represent those of the American Fisheries Society. Comments are invited at tbgilford@fisheries.org.

REFERENCES


