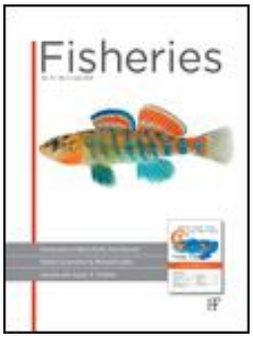

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CANADIAN AQUATIC RESOURCES SECTION

Climate Change Impacts on Freshwater Fishes: A Canadian Perspective

Mark S. Poesch
Department of Renewable Resources, University of Alberta, 751 General Services Building, Edmonton, AB, Canada T6G 2H1. E-mail: poesch@ualberta.ca

Louise Chavarie
Center for Systems Integration and Sustainability, Michigan State University, East Lansing, MI

Cindy Chu
Ontario Ministry of Natural Resources and Forestry, Peterborough, ON, Canada

Shubha N. Pandit
Terrestrial and Aquatic Applied Research and Management, Terraqua Inc., Entiat, WA

William Tonn
Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada

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 km^2. 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

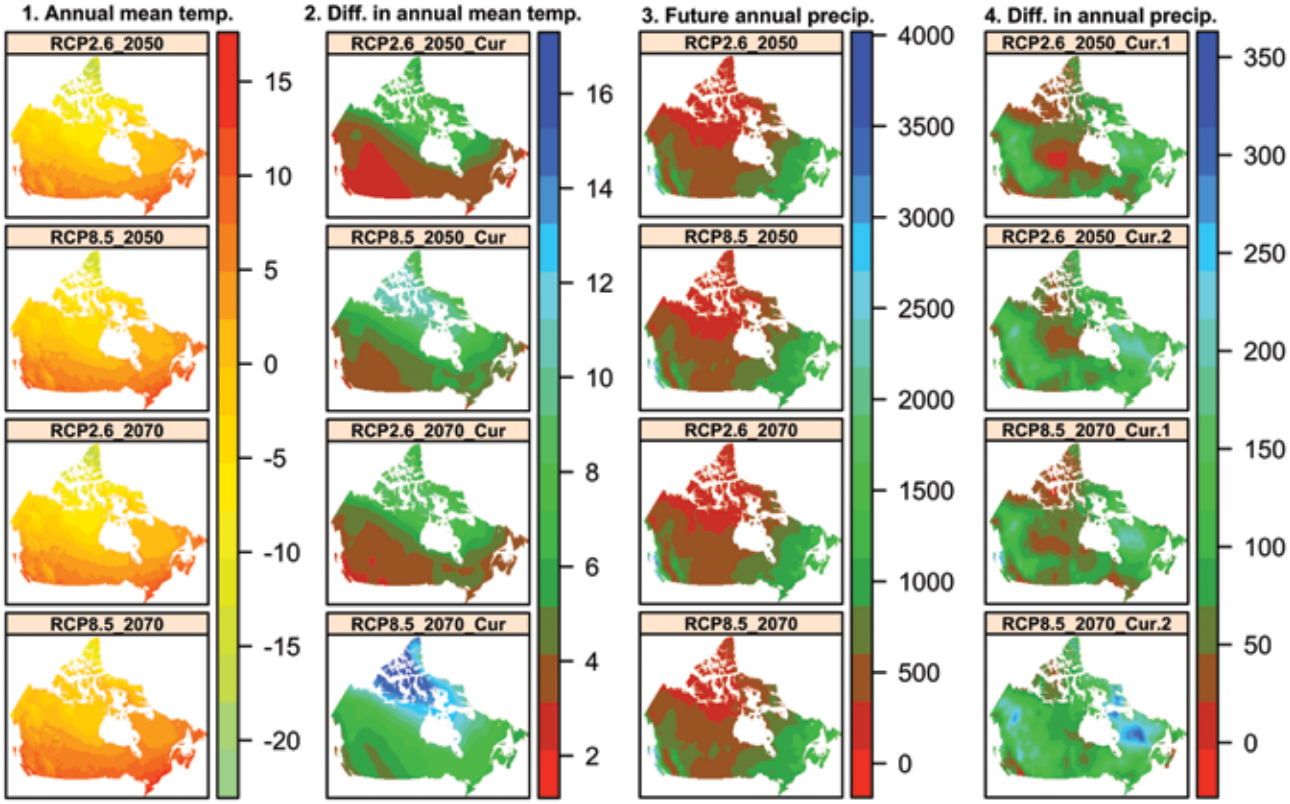

Figure 1. Projected (A)–(D) temperature (°C) and (E)–(H) precipitation (mm) in Canada for 2050s and 2070s under two Representative Concentrate Pathways (RCP 2.6 and RCP 8.5 of Geophysical Fluid Dynamics Laboratory's [GFDL] CM3). A1 and B1 are the difference in annual mean air temperature of 2050s from the current air temperature under RCP 2.6 and 8.5, respectively, whereas C1 and C2 are the difference in air temperature between 2070s and current under RCP 2.6 and 8.5, respectively. E1, F1, G1, and H1 are the difference in annual total precipitation between 2050s and current and 2070s and current under scenarios RCP 2.6 and 8.5, respectively. Note: This figure was generated using the data of 2013 generation General Circulation Model (GFDL CM3 at five-minute spatial resolution) projections with two greenhouse gas emission concentration scenarios (RCP 2.6 and 8.5) from the 5th Assessment Report of the IPCC. The data were accessed from Worldclim.org on February 20, 2016.

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 falvescencs* 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; Δ = change.

Expected changes	Environmental effects	Biotic effects
↑ frequency of extreme climate events	↑ permafrost degradation and Δ thermokarst processes	Δ quantity and access to critical habitat
Δ seasonal phenology	Δ drainage patterns	↑ mismatch of phenology and life history
↑ air temperature (especially winter)	Δ ice breakup processes and timing	Δ contaminant bioaccumulation
↑ water temperature	Δ freshet timing, duration, and magnitude	Δ population structure (e.g., age and size classes)
Δ precipitation (amount and form)	Δ groundwater levels	Δ demographic parameters
Δ ice cover duration	Δ evaporation, surface water levels, and habitat connectivity	Δ phenotype and genotypes
Δ ice thickness	Δ timing and magnitude of nutrient and dissolved organic carbon (DOC)	Δ ecosystem productivity and relative contributions from terrestrial, pelagic and benthic sources
Δ wind patterns	Δ ecosystem productivity	Δ geographical range limits of northern and southern species
Δ atmospheric pressure	Δ turbidity and light regime	Δ community composition and relative abundance (predators, prey, competitors, parasites)
↑ human population and activities	Δ sedimentation	
Δ drainage patterns	Δ carbon source/sinks/availability	
Δ ice breakup processes and timing	Δ mixing/stratification patterns, oxygen, and thermal profiles	
Δ freshet timing, duration, and magnitude	↑ mobilization and toxicity of contaminants	
Δ groundwater levels	Δ contaminant catchments (air and water)	
Δ evaporation, surface water levels, and habitat connectivity	↑ industrial activities and infrastructure	
Δ timing and magnitude of nutrient and DOC	↑ resource exploitation (commercial, recreational)	
Δ ecosystem productivity	↑ contaminant export from the south via long-range atmospheric transport	
Δ turbidity and light regime		
Δ sedimentation		
Δ carbon source/sinks/availability		
Δ mixing/stratification patterns, oxygen, and thermal profiles		
↑ mobilization and toxicity of contaminants		
Δ contaminant catchments (air and water)		
↑ industrial activities and infrastructure		
↑ resource exploitation (commercial, recreational)		
↑ contaminant export from the south via long-range atmospheric transport		
↑ mismatch of phenology and life history		
Δ contaminant bioaccumulation		
Δ population structure (e.g., age and size classes)		
Δ demographic parameters		
Δ phenotype and genotypes		
Δ ecosystem productivity and relative contributions from terrestrial, pelagic and benthic sources		
Δ geographical range limits of northern and southern species		
Δ community composition and relative abundance (predators, prey, competitors, parasites)		

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 Sasketchewan, 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 *Oncorhyunchus 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 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.

Species	Optimum temperature (growth; °C)	Lower/ upper range for survival	Salinity tolerance	Colonization potential	Current/projected status	References
Atlantic Salmon	16–19	0–(23.3–26.7)	Euryhaline	Populations in Ungava Bay (QC) but never colonized habitat outside of their native range to date	Large range of temperature tolerance but least tolerant to low temperatures of *Salmo* species, northern tip of Québec may be a migration barrier	Scott and Crossman (1973); ACIA (2010); Elliott and Elliott (2010); Hasnain et al. (2010); Nielsen et al. (2013)
Chinook Salmon	14.8–20	0.8–(24.7–26.2)	Euryhaline	Pacific salmon have been documented in the Arctic for over 100 years	Since 2003, only seven observations reported	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); Dunmall et al. (2013); Nielsen et al. (2013)
Coho Salmon	15–17	1.7–(25.8–28)	Euryhaline	Pacific salmon have been documented in the Arctic for over 100 years	Since 2003, only one observation reported	Brett (1952); Scott and Crossman (1973); Jobling (1981); Wismer and Christie (1987); Sullivan et al. (2000); ACIA (2010); Hasnain et al. (2010); Dunmall et al. (2013); Nielsen et al. (2013)
Chum Salmon	12–14	−0.5 to (23.2–25.8)	Euryhaline	Chum Salmon juveniles are presumed relatively tolerant of low freshwater temperatures, spend less time postemergence in freshwater, and grow rapidly in marine habitats	Chum Salmon have been harvested annually since 1997 and abundant harvests are becoming more frequent. Spawning populations are reported in the Upper Mackenzie	Brett (1952); Scott and Crossman (1973); Jobling (1981); ACIA (2010); Hasnain et al. (2010); Sullivan et al. (2000); Dunmall et al. (2013); Nielsen et al. (2013)
Pink Salmon	15.5	0–23.9	Euryhaline	Pink Salmon juveniles are presumed tolerant of the low freshwater temperatures, spend less time postemergence in freshwater, and grow rapidly in marine habitats	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	Brett (1952); Scott and Crossman (1973); Wismer and Christie (1987); Jobling (1981); Sullivan et al. (2000); ACIA (2010); Hasnain et al. (2010); Dunmall et al. (2013); Nielsen et al. (2013)
Sockeye Salmon	15	3.1–(23.5–25.8)	Euryhaline	Pacific salmon have been documented in the Arctic for over 100 years	Since 2003, only 10 observations reported	Brett (1952); Scott and Crossman (1973); Jobling (1981); Wismer and Christie (1987); Sullivan et al. (2000); ACIA (2010); Hasnain et al. (2010); Dunmall et al. (2013); Nielsen et al. (2013)
Lake Whitefish	12–16.8	0.1–26.6	Stenohaline	Whitefish have expanded northward into to the low Arctic, up to Cambridge Bay (NU)	Whitefish yields are projected to increase threefold	Scott and Crossman (1973); Jobling (1981); Christie and Regier (1988); Wismer and Christie (1987); Minns and Moore (1992); Reist et al. (2006); ACIA (2010); Hasnain et al. (2010)
Smallmouth Bass	25–29	(1.6–10.1)–35	Stenohaline	Not present currently in Arctic	Lakes in the Arctic are predicted to be thermally suitable by 2100	Horning and Pearson (1973); Scott and Crossman (1973); Jobling (1981); Wismer and Christie (1987); Jackson and Mandrak (2002); Chu et al. (2005); Reist et al. (2006); Sharma et al. (2007, 2009); Hasnain et al. (2010)
Northern Pike	23	0.1–(28.4–34)	Stenohaline	Temperate center of distribution but ranges widely into the Arctic, up to coastal area of Arctic Ocean	Northern Pike yields in Arctic/Subarctic are projected to increase threefold	Scott and Crossman (1973); Jobling (1981); Wismer and Christie (1987); Christie and Regier (1988); Minns and Moore (1992); Casselman (1996); Hillman et al. (1999); Reist et al. (2006); ACIA (2010); Hasnain et al. (2010)
Walleye	18–22	<4–(29–35)	Stenohaline	Temperate center of distribution but ranges into southern Arctic, extending to the Mackenzie River delta	Walleye yields in Subarctic are projected to increase tenfold	Scott and Crossman (1973); Kitchell et al. (1977); Jobling (1981); Wismer and Christie (1987); Christie and Regier (1988); Minns and Moore (1992); Armour (1993); Hillman et al. (1999); Chu et al. (2005); Reist et al. (2006); Zhao et al. (2008); ACIA (2010); Hasnain et al. (2010)
Yellow Perch	21–24	1.1–(29.2–32.3)	Stenohaline	Temperate center of distribution but ranges into Subarctic (Great Slave Lake)	Northward range extensions of 2° to 8° latitude are projected	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)

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.

REFERENCES

Abell, R., and coauthors. 2008. Freshwater ecoregions of the world: A new map of biogeographic units for freshwater biodiversity conservation. BioScience 54:403–414.

AESRD (Alberta Environment and Sustainable Resource Development). 2005. Status of the Arctic Grayling (*Thymallus arcticus*) in Alberta. Alberta Environment and Sustainable Resource Development, Edmonton, Alberta, Canada.

——. 2009. Status of the Athabasca Rainbow Trout (*Oncorhynchus mykiss*) in Alberta. Alberta Environment and Sustainable Resource Development, Edmonton, Alberta, Canada.

——. 2012. Bull Trout conservation management plan 2012–17. Alberta Environment and Sustainable Resource Development, Edmonton, Alberta, Canada.

Alofs, K. M., D. A. Jackson, and N. P. Lester. 2014. Ontario freshwater fish demonstrate differing range-boundary shifts in a warming climate. Diversity and Distributions 20:123–136.

Angers, B., E. Castonguay, and R. Massicotte. 2010. Environmentally induced phenotypes and DNA methylation: how to deal with unpredictable conditions until the next generation and after. Molecular Ecology 19(7):1283–1295.

Armour, C. L. 1993. Evaluating temperature regimes for protection of Walleye. U.S. Fish and Wildlife, Resource Publication 195, Washington, D.C.

Beauchamp, M., A. A. Assani, R. Landry, and P. Massicotte. 2015. Temporal variability of the magnitude and timing of winter maximum daily flows in southern Quebec (Canada). Journal of Hydrology 529:410–417.

Boyer, C., D. Chaumont, I. Chartier, and A. G. Roy. 2010. Impact of climate change on the hydrology of St. Lawrence tributaries. Journal of Hydrology 384(1):65–83.

Bradford, M. J., and J. R. Irvine. 2011. Land use, fishing, climate change, and the decline of Thompson River, British Columbia, Coho Salmon. Canadian Journal of Fisheries and Aquatic Sciences 57(1):13–16.

Brander, K. 2010. Impacts of climate change on fisheries. Journal of Marine Systems 79(3–4):389–402.

Brett, J. R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. Journal of the Fisheries Board of Canada 9(6):265–323.

CAFF (Conservation of Arctic Flora and Fauna). 2013. Arctic biodiversity assessment: status and trends in Arctic biodiversity. Conservation of Arctic Flora and Fauna, Akureyri, Iceland.

Carl, L. M., C. Hunt, and P. E. Ihssen. 1994. Rainbow Trout of the Athabasca River, Alberta: a unique population. Transactions of the American Fisheries Society 123(2):129–140.

Casselman, J. 1996. Age, growth and environmental requirements of pike. Pages 69–101 *in* J. F. Craig, editor, Fisheries in a changing climate. Pike: biology and exploitation. Chapman and Hall, London.

——. 2002. Effects of temperature, global extremes, and climate change on year-class production of warm water, cool water, and coldwater fishes in the Great Lakes Basin. Pages 39–59 *in* N. A. McGinn, editor. American Fisheries Society, Symposium 32, Bethesda, Maryland.

Christie, G. C., and H. A. Regier. 1988. Measures of optimal thermal habitat and their relationship to yields for four commercial fish species. Canadian Journal of Fisheries and Aquatic Sciences 45(2):301–314.

Chu, C. 2015. Climate change vulnerability assessment for inland aquatic ecosystems in the Great Lakes Basin, Ontario. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, Ontario, Canada.

Chu, C., N. E. Mandrak, and C. K. Minns. 2005. Potential impacts of climate change on the distributions of several common and rare freshwater fishes in Canada. Diversity and Distributions 11(4):299–310.

Chu, C., C. K. Minns, N. P. Lester, and N. E. Mandrak. 2014. An updated assessment of human activities, the environment, and freshwater fish biodiversity in Canada. Canadian Journal of Fisheries and Aquatic Sciences 72(1):135–148.

Culp, J. M., and coauthors. 2012. Developing a circumpolar monitoring framework for Arctic freshwater biodiversity. Biodiversity 13(3–4):215–227.

DFO (Department of Fisheries and Oceans Canada). 2013. Survey of recreational fishing in Canada 2010. Government of Canada, Ottawa.

Dobiesz, N. E., and N. P. Lester. 2009. Changes in mid-summer water temperature and clarity across the Great Lakes between 1968 and 2002. Journal of Great Lakes Research 35:371–384.

Dove-Thompson, D., C. Lewis, P. A. Gray, C. Chu, and W. Dunlop. 2011. A summary of the effects of climate change on Ontario's aquatic ecosystems. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, Ontario, Canada.

Dunmall, K., and coauthors. 2013. Pacific salmon in the Arctic: harbingers of change. Responses of Arctic marine ecosystems to climate change. Alaska Sea Grant, University of Alaska Fairbanks.

Elliott, J., and J. Elliott. 2010. Temperature requirements of Atlantic Salmon *Salmo salar*, Brown Trout *Salmo trutta* and Arctic Charr *Salvelinus alpinus*: predicting the effects of climate change. Journal of Fish Biology 77(8):1793–1817.

Ficke, A. D., C. A. Myrick, and L. J. Hansen. 2007. Potential impacts of global climate change on freshwater fisheries. Reviews in Fish Biology and Fisheries 17(4):581–613.

Flannigan, M. D., and C. E. Van Wagner. 1991. Climate change and wildfire in Canada. Canadian Journal of Forest Research 21(1):66–72.

Friedland, K. D., D. G. Reddin, J. R. McMenemy, and K. F. Drinkwater. 2003. Multidecadal trends in North American Atlantic Salmon (*Salmo salar*) stocks and climate trends relevant to juvenile survival. Canadian Journal of Fisheries and Aquatic Sciences 60:563–583.

Gleeson, J., P. Gray, A. Douglas, C. J. Lemieux, and G. Nielsen. 2011. A practitioner's guide to climate change adaptation in Ontario's ecosystems. Ontario Centre for Climate Impacts and Adaptation Resources, Sudbury, Ontario, Canada.

Government of Quebec. 2012. Québec in action greener by 2020. 2013–2020 Government strategy for climate change adaptation. Available: mddelcc.gouv.qc.ca/changements/plan.../stategie-adaptation2013-2. (March 2016).
Hansen, J., and coauthors. 2006. Global temperature change. Proceedings of the National Academy of Sciences 103(39):14288–14293.
Hasnain, S. S., C. K. Minns, and B. J. Shuter. 2010. Key ecological temperature metrics for Canadian freshwater fishes. Ontario Forest Research Institute, Ontario, Canada.
Hauer, F. R., and coauthors. 1997. Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. Hydrological Processes 11(8):903–924.
Heller, N. E., and E. S. Zavaleta. 2009. Biodiversity management in the face of climate change: A review of 22 years of recommendations. Biological Conservation 142(1):14–32.
Hillman, T., M. Miller, and B. Nishitani. 1999. Evaluation of seasonal-cold-water temperature criteria. BioAnalysts, Inc., Boise, Idaho.
Horning, W. B., II, and R. E. Pearson. 1973. Growth temperature requirements and lower lethal temperatures for juvenile Smallmouth Bass (*Micropterus dolomieui*). Journal of the Fisheries Research Board of Canada 30(8):1226–1230.
Jackson, D. A., and N. E. Mandrak. 2002. Changing fish biodiversity: predicting the loss of cyprinid biodiversity due to global climate change. Pages 89–98 *in* N. A. McGuinn, editor, Fisheries in a changing climate.. American Fisheries Society, Symposium 32, Bethesda, Maryland.
Jobling, M. 1981. Temperature tolerance and the final preferendum—rapid methods for the assessment of optimum growth temperatures. Journal of Fish Biology 19(4):439–455.
Jonsson, B., and N. Jonsson. 2009. A review of the likely effects of climate change on anadromous Atlantic Salmon *Salmo salar* and Brown Trout *Salmo trutta*, with particular reference to water temperature and flow. Journal of Fish Biology 75:2381–2447.
Karl, T., J. Melillo, and T. Petersen, editors. 2009. Regional climate impacts: Alaska. *In* Global climate change impacts in the United States. Cambridge University Press, New York.
Kitchell, J. F., D. J. Stewart, and D. Weininger. 1977. Applications of a bioenergetics model to Yellow Perch (*Perca flavescens*) and Walleye (*Stizostedion vitreum vitreum*). Journal of the Fisheries Board of Canada 34(10):1922–1935.
Kurylyk, B. L., C. P.-A. Bourque, and K. T. B. MacQuarrie. 2013. Potential surface temperature and shallow groundwater temperature response to climate change: an example from a small forested catchment in east–central New Brunswick (Canada). Hydrology and Earth System Sciences 17:2701–2716.
Linnansaari, T., R. A. Cunjak, K. Storey, and K. Tanino. 2012. Fish: freshwater ecosystems. Temperature adaptation in a changing climate: nature at risk. CAB International Publishing, Climate Change Series 3:80–97.
Lynch, A. J., B. J. E. Myers, C. Chu, L. A. Eby, J. A. Falke, R. P. Kovach, T. J. Krabbenhoft, T. J. Kwak, J. Lyons, C. P. Paukert, and J. E. Whitney. 2016. Climate change effects on North American inland fish populations and assemblages. Fisheries 41: 346–361.
Maitland, B. M., M. Poesch, A. E. Anderson, and S. N. Pandit. 2016. Industrial road crossings drive changes in community structure and instream habitat for freshwater fishes in the boreal forest. Freshwater Biology 61:1–18.
McCullough, D. A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook Salmon. Environmental Protection Agency, EPA 910-R-99-010, Seattle, Washington.
Milner, A. M., L. E. Brown, and D. M. Hannah. 2009. Hydroecological response of river systems to shrinking glaciers. Hydrological Processes 23(1):62–77.
Minns, C. K., and J. E. Moore. 1992. Predicting the impact of climate change on the spatial pattern of freshwater fish yield capability in eastern Canadian lakes. Climatic Change 22(4):327–346.
Minns, C. K., and J. E. Moore. 1995. Factors limiting the distributions of Ontario's freshwater fishes: the role of climate and other variables, and the potential impacts of climate change. Canadian Special Publication of Fisheries and Aquatic Sciences 121:137–160.
Nielsen, J. L., G. T. Ruggerone, and C. E. Zimmerman. 2013. Adaptive strategies and life history characteristics in a warming climate: salmon in the Arctic? Environmental Biology of Fishes 96(10–11):1187–1226.
NRCan (Natural Resources Canada). 2010. The atlas of Canada. Available: www.nrcan.gc.ca/earth-sciences/geography/atlas-canada. (March 2016).
Power, G. 1990. Warming rivers. Atlantic Salmon Journal 39(4):40–42.
Prowse, T. D., and coauthors. 2011. Effects of changes in Arctic lake and river ice. Ambio 40(1):63–74.
Raleigh, R. F., W. J. Miller, and P. C. Nelson. 1986. Habitat suitability index models and instream flow suitability curves: Chinook Salmon. U.S. Fish and Wildlife Service, Report 82(10.22), Washington, D.C.
Reist, J. D., and coauthors. 2006. General effects of climate change on Arctic fishes and fish populations. Ambio 35(7):370–380.
Reist, J. D., M. Power, and J. B. Dempson. 2013. Arctic Charr (*Salvelinus alpinus*): a case study of the importance of understanding biodiversity and taxonomic issues in northern fishes. Biodiversity 14(1):45–56.
Reist, J. D., C. D. Sawatzky, and L. Johnson. 2015. The Arctic "Great" Lakes of Canada and their fish faunas—an overview in the context of Arctic change. Journal of Great Lakes Research. DOI: 10.1016/j.jglr.2015.10.008
Robillard, M. M., and M. G. Fox. 2006. Historical changes in abundance and community structure of warmwater piscivore communities associated with changes in water clarity, nutrients, and temperature. Canadian Journal of Fisheries and Aquatic Sciences 63(4):798–809.
Russell, I. C., and coauthors. 2012. The influence of the freshwater environment and the biological characteristics of Atlantic salmon smolts on their subsequent marine survival. ICES Journal of Marine Science 69(9):1563–1573.
Salinas, S., S. C. Brown, M. Mangel, and S. B. Munch. 2013. Non-genetic inheritance and changing environments. Non-Genetic Inheritance 1:38–50.
Schindler, D. W., and coauthors. 1990. Effects of climatic warming on lakes of the central boreal forest. Science 250(4983):967–970.
Schindler, D. W., and W. F. Donahue. 2006. An impending water crisis in Canada's western prairie provinces. Proceedings of the National Academy of Sciences 103(19):7210–7216.
Scott, W. B., and E. J. Crossman. 1973. Freshwater fishes of Canada. Fisheries Research Board of Canada, Bulletin 184, Ottawa.
Sharma, S., D. A. Jackson, and C. K. Minns. 2009. Quantifying the potential effects of climate change and the invasion of Smallmouth Bass on native Lake Trout populations across Canadian lakes. Ecography 32(3):517–525.
Sharma, S., D. A. Jackson, C. K. Minns, and B. J. Shuter. 2007. Will northern fish populations be in hot water because of climate change? Global Change Biology 13(10):2052–2064.
Shuter, B., A. Finstad, I. Helland, I. Zweimüller, and F. Hölker. 2012. The role of winter phenology in shaping the ecology of freshwater fish and their sensitivities to climate change. Aquatic Sciences 74(4):637–657.
Shuter, B., and J. Meisner. 1992. Tools for assessing the impact of climate change on freshwater fish populations. GeoJournal 28(1):7–20.
Solomon, S. 2007. Climate change 2007—the physical science basis: Working group I contribution to the fourth assessment report of the IPCC, volume 4. Cambridge University Press, Cambridge, UK.
Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a business as usual climate change scenario. Climatic Change 62(1–3):217–232.
Sullivan, K., D. J. Martin, R. D. Cardwell, J. E. Toll, and S. Duke. 2000. An analysis of the effects of temperature on salmonids of the Pacific Northwest with implications for selecting temperature criteria. Sustainable Ecosystems Institute, Portland, Oregon.
Tarnocai, C. 2009. The impact of climate change on Canadian peatlands. Canadian Water Resources Journal 34(4):453–466.
Vincent, W. F., and coauthors. 2011. Ecological implications of changes in the Arctic cryosphere. Ambio 40(1):87–99.
Whitney, J. E., R. Al-Chokhachy, D. B. Bunnell, C. A. Caldwell, S. J. Cooke, E. J. Eliason, M. Rogers, A. J. Lynch, and C. P. Paukert. 2016. Physiological basis of climate change impacts on North American inland fishes. Fisheries 41:332–345.
Wismer, D. A., and A. E. Christie. 1987. Temperature relationships of Great Lakes fishes. Great Lakes Fishery Commission, Special Publication 87-3, Ann Arbor, Michigan.
Zhao, Y., B. J. Shuter, and D. A. Jackson. 2008. Life history variation parallels phylogeographical patterns in North American Walleye (*Sander vitreus*) populations. Canadian Journal of Fisheries and Aquatic Sciences 65(2):198–211. AFS