A. Issue Statement

The earth's atmosphere and oceans are warming. Human activity, including burning fossil fuels and land clearing has contributed to rising atmospheric carbon dioxide concentrations. Ice cores revealed that present atmospheric carbon dioxide levels are 30 percent above levels experienced during the last 800,000 years, rising over the past approximately 250 years from estimated preindustrial levels of 280 ppm to current levels of 385 ppm (IPCC 2007). Concentrations currently are rising at about 2 ppm a year, a rate that has been increasing and is expected to continue doing so if current emission trajectories remain unchanged. By the end of this century, carbon dioxide concentrations could reach levels two to three times those prior to industrial times.

Global mean air temperatures have increased by approximately 0.6^{o}C during the past 100 years with accelerated warming trends from 1.4 to 5.8^{o}C predicted by the end of the 21st century (IPCC 2007). Other documented patterns and trends include changes in seasonal precipitation; increased precipitation shifts from snow to rain (USGCRP 2009); earlier onset of spring snowmelt and increased frequency of very heavy precipitation events. There has been a 0.1°C increase in ocean temperature from the sea surface to a depth of 700 m since 1961; an average of 1.7 mm per year rise in sea level during the 20th century (IPCC 2007; Domingues et al. 2008); a decline in arctic sea ice since 1978, with a steepened rate of decline since the turn of the 21st century (Earth Observatory 2009); and a change in ocean biogeochemistry as evidenced by a cumulative reduction of 0.1 pH units during the past 200 years (Hagen and Drange 1996). These trends are expected to continue during the coming century.

Impacts are projected to become more severe during the 21st century. Global average surface temperature is estimated to increase from 2 to 4.5°C, although substantially higher temperatures are possible (IPCC 2007). Sea level is projected to rise 1 to 3 m due to thermal expansion of oceans and glacier melt, and although the response of ice sheets to future climate change is uncertain, the potential for a more significant sea level rise due to ice sheet break up exists (the Greenland ice sheet contains enough ice to raise sea level by 23 m and the West Antarctic by 5-6 m) (ACIA 2004; NRC 2002; IPCC 2007). Storm events are likely to become more extreme, particularly in tropical and high-latitude regions. These regions are projected to experience overall increases in precipitation, with the heaviest downpours becoming heavier and precipitation during light events declining. Wildfire patterns will respond to changes in temperature and precipitation, making some areas, including the western United States, more susceptible to outbreaks (Krawchuk et al. 2009).

Paleoclimate evidence and ongoing global changes, many of which were noted above, imply that current carbon dioxide levels already may be too high to maintain the climate to which humanity, wildlife, and the rest of the biosphere currently are adapted (Hansen et al. 2008). Comprehensive efforts to reduce global carbon emissions were articulated in the 1997 Kyoto Protocol, which set targets for reducing greenhouse gas emissions over a five-year period (2008-2012). Despite the goals set in Kyoto, atmospheric carbon dioxide concentrations have continued to rise. Until recently, National governments in North America have failed to take substantive steps to reduce emissions. Further, reductions proposed under cap and trade legislation under consideration in the United States and Canada fall short of the IPCC (2007) recommended level of 25-40% reduction by 2020. Even after global emissions are cut substantially, atmospheric carbon present as a result of past emissions will continue to force climate change for several centuries. Efforts to prepare for the inevitable impacts of climate change (i.e., “adaptation”) only recently have begun to receive attention.

As a result of global climate change, fisheries that have sustained us in the past (whether through recreational, commercial, or subsistence means) will likely be different from the fisheries that will sustain us in the future. Vulnerability assessments will be required to understand which species, communities, and habitats are at risk so that appropriate adaptation measures can be designed. For success, adaptation policies must include long-term monitoring of sensitive ecosystem indicators, predictive modeling of ecosystem conditions, mitigation of local stressors and enhancement of ecosystem resilience, identification of irreversibly imperiled communities or habitats and shifts in focus to maintain ecosystem function, goods, and services which may include surrogate species communities. The uncertainty of impacts of climate change on communities and habitats necessitates that work should be carried out within an adaptive management framework where evaluation of policies and management action are strong components. Finally, education and outreach campaigns centered on informing policy-makers, and the public on the consequences of climate change for aquatic communities and habitats is needed to shape expectations for goods and services derived from marine and freshwater systems.

In the interest of sustaining marine and freshwater fisheries and their habitats, the American Fisheries Society encourages immediate reduction in greenhouse gas emissions and implementation of adaptation policies described above for fisheries communities and habitats. The purpose of the following discussion is not to provide extensive review of the literature regarding climate change but to focus on the current state of knowledge of observed and anticipated effects that warming trends would have on North American fisheries. Building upon a number of major syntheses (e.g., Arctic Climate Impact Assessment Report, ACIA 2004; Canada's 2nd National Climate Impact Assessment Report; U.S. Climate Action Report 2006; Union of Concerned Scientist's Confronting Climate Change in the Great Lakes Region, Kling et al. 2003) as well as AFS proceedings published since 1990 based on sessions dedicated to assessing climate change impacts on fisheries. We organized the following sections to describe climate effects within lakes and reservoirs, streams, estuarine and coastal, marine, arctic, and arid aquatic ecosystems. We end each section with a short discussion on information gaps that hinder effective policy and provide counteractive and proactive measures through adaptive management strategies. It is our plan that the document be used to build consensus among the fisheries disciplines and thus initiate action among ourselves, our stakeholders, and our policy makers.

B. Background

B.1. Lake Fishes, Fisheries and Habitats

Climate change will exacerbate the impacts from other landscape stressors

Through warming and altered precipitation patterns, climate change will exert indirect effects on lake habitats that will alter habitat suitability for many native and non-native species (Schindler 2001; Kling et al. 2003; Ficke et al. 2007; Table B.1). Further, many of these forces are synergistic, confounding our ability to determine cause and effect and strategies for lessening impacts on habitats and populations. Warmer air temperatures, besides bringing warmer water temperatures, will bring longer ice-free periods and growing seasons. Lake levels will decrease over the long-term due to higher evaporation. Greater frequency of storm events will increase runoff from surrounding watersheds and nutrient loading. The cumulative effects of these stressors on most lakes will be warmer, more nutrient enriched (i.e., eutrophic) waters with greater incidences of hypoxia through stronger and longer periods of stratification (Box B.1). Accordingly, climate stressors will exacerbate outcomes from other human stressors such as overexploitation of fish populations, runoff from impervious surfaces, feedlots, and crop fields, and removal of in-lake habitat such as aquatic plants and coarse woody habitat).

Nevertheless, some lakes will be more resilient to climate change than others including large deep lakes with relatively low ambient levels of nutrients and balanced food-webs (Beisner et al. 2003; Genkai-Kato and Carpenter 2005). Some species will adapt, some will be lost, and some will thrive as baseline ecosystem conditions shift with a net loss of native fish species. In general, many native species intolerant to disturbance will be replaced with fewer non-native or opportunistic species (Walther et al. 2009). Productive capacity of fisheries in the future will likely be reduced under future climate scenarios, but will ultimately depend on the interplay of losses native species and replacement by new species and losses from other non-climate human stressors (Minns 2009).

Fish species ranges will shift

A poleward migration of species ranges will occur due to changes in thermal habitat (Rahel 2002; Kling et al. 2003). With warming, production of warm-water species such as sunfish, black and striped bass will increase while production of cold-water species such as trout and whitefishes will decrease. Effects on cool-water species will be much more variable and strongly dependent on latitudinal or regional climate gradients. Cool-water species such as northern pike, walleye, and perch will likely decline near their southern range and increase throughout their northern range. Climate change will also have indirect effects on regional fish populations. In Ontario, increased smallmouth bass populations could extirpate native fathead minnow populations (Jackson and Mandrak 2002). In contrast, if climate change leads to greater connectivity and eutrophication in prairie pothole lakes, fathead minnow populations could expand (Herwig et al. 2009). Furthermore, effects on species will be strongly dependent on the system(s) of interest. Climatic variables were important predictors of the spread of smallmouth bass throughout central and southern watersheds of British Columbia (Sharma et al. 2007). In inland lakes inhabited by cold-water fish populations, water temperatures are predicted to go from cold to cool. Consequently, species such as lake trout, burbot, lake whitefish and herring are predicted to decline (Stefan et al. 1996; Mackenzie-Grieve and Post 2006). However, in parts of Great

Lakes Superior, Michigan, and Huron where waters will go from extremely cold to just cold, productivity of these species may actually increase (Magnuson et al. 1990). These cold-water species will be the ones to watch as early indicators of warming trends (Stapanian et al. 2009).

The frequency of winterkill in shallow lakes of northern biomes may increase in some regions while decreasing in others

Shallow lakes in northern biomes are stressful environments to fish due to oxygen depletion during winter. Extreme climate gradients characterize the upper Midwest (U.S.) and Great Lakes Basin (U.S. and Canada), and climate models run the gamut from predictions of warmer seasons and wetter summers with little snow in winter which would reduce winterkill (Fang and Stefan 2000) to warmer seasons with drier summers but greater snowpack in winters which would increase winterkill (Danylchuk and Tonn 2003). Reduced winterkill in historically fishless basins in the prairie pothole region has negative implications for water quality, aquatic plants and waterfowl habitat (Zimmer et al. 2003). Increased winterkill in shallow basins historically harboring fish populations will have negative implications on biodiversity in those systems (Danylchuk and Tonn 2003).

Adaptive strategies for management of fishes and fisheries in lake and reservoir systems

Adaptation strategies for fisheries managers, policy makers, and stakeholders should be considered to lessen the impact of climate change. Holding all other impacts constant, current trends in climate change will stress natural resilience mechanisms that maintain water quality and diverse native fish communities in lake systems. If the current resilience of lake habitats is reduced by other human impacts, it could eventually lead to a shift to a new highly resilient regime dominated by pollution tolerant fish species and turbid water (Scheffer and Carpenter 2003). Indeed, the threat of “tipping points” behooves policy makers and managers to take aggressive action to lessen the impact of human stressors and enhance desirable ecosystem resilience (Glick et al. 2009; Mawdsley et al. 2009). Examples of prudent actions may include:

- Controlling sources of nitrogen and phosphorus (e.g., manure containment, improved wastewater management, consider management alternatives for fertilizers in agricultural crops to reduce nutrient input) to avoid excessive nutrient input (Carpenter 2008)
- Increasing local infiltration and absorption of rain water (e.g., wetland preservation/restoration, low-impact development, vegetation buffers; Glick et al. 2009)
- Minimizing human destruction of shoreline and aquatic vegetation. (e.g., public education campaigns, “carrot and stick” policies for lakeshore owners)
- Maintaining or restoring balanced food-webs and self-sustaining fish communities (Beisner et al. 2003)
- Identifying, designating, and protecting aquatic refugia for sensitive habitats and populations that may withstand predicted outcomes of climate change (Mawdsley et al. 2009; e.g., see Box B.1).
- Restoration of natural hydrologic flow regimes (e.g., removing connections from systems historically isolated, restoring connections from systems historically connected)

- System-level management that prioritizes enhancing ecosystem function and services over preserving native species assemblages that may be irreversibly imperiled (Glick et al. 2009; Mawdsley et al. 2009)

Table B.1. Hypothesized effects of climate change on physical and biological properties and processes in lake and reservoir systems. Actual effects will depend on the system and regional heterogeneity of climate regimes.

Physical Ecosystem Properties

- Summer water temperatures will be greater and longer in duration.
- Increasingly severe drought and flooding will alter lake levels.
- Stronger and longer lake stratification will alter sediment processes (i.e., oxidation/reduction).
- Lakes will experience increased eutrophication.
- Increasing acidification will result in greater bioavailability of contaminants.
- Ultra-violet radiation will increase and penetrate further.
- Lakes will experience shorter duration of ice-cover.

Community and foodweb responses

- Elevated summer temperatures will shift composition of thermal guilds.
- Altered predator-prey dynamics resulting in habitat becoming more suitable for non-native species.
- Fish biodiversity will decline.
- Invasive non-native species will proliferate.

Box B.1. Case Study: *Effects of climate change and adaptation responses of Cisco in northern temperate lakes*

Populations of the stenotherm cisco are the most common coldwater lentic fish in Minnesota and are present in 648 lakes throughout the state. Minnesota is the southern part of the species range. Thus, the species is potentially vulnerable to climate change. Extended periods of stratification (an outcome of climate warming) and eutrophication can reduce hypolimnetic oxygen in deep lakes and thus impact cisco populations (De Stasio et al. 1996; Stefan et al. 1996). Indeed, historical records at the Minnesota Department of Natural Resources (DNR) show that cisco numbers have been declining statewide since 1975. Presumably, the declines are due to climate-driven stressors since these lakes have not experienced significant cultural eutrophication.

Adaptation measures that mitigate the effects of climate change on coldwater fish such as cisco are being developed by the Minnesota DNR. Specifically, deep lakes with exceptional water quality will represent important sanctuaries for coldwater fish in a warmer Minnesota. Refugia lakes are being identified to establish protection of the surrounding watershed. Protection efforts will include land purchase, easement protection, and implementation of best management practices throughout the watersheds. Despite successful watershed protection measures, climate change will undoubtedly reduce the number of lakes that sustain cisco throughout the state. Appropriate adaptation responses will identify imperiled lakes slated for protection to help shape agency and public expectations.

B.2. River and Stream Fishes, Fisheries and Habitats

Shifts in flow regimes will disrupt life cycles of river and stream fish assemblages

The effects of climate change on precipitation are complex and less predictable than anticipated changes in air temperature, but altered precipitation patterns will ultimately lead to changes in stream discharge regimes. Precipitation is variable in time and space and long-term records are sparse and unreliable. Thus, accurate prediction of global trends is difficult. In general, regional differences will be directly related to variation in intensity, frequency, duration, and amounts of precipitation (Trenberth et al. 2003). Warming trends have resulted in documented shifts in peak flow from snowmelt from late spring to late winter and are related to increased precipitation as rain (Leung and Wigmosta 1999). Earlier snow melt is occurring as spring temperatures increase (Stewart et al. 2005). Further, because melting snow sustains groundwater flows in the late summer months, shifting runoff patterns can result in water supply reductions during baseflow periods that often limit habitat availability and production to lotic fishes.

Direct effects on fish distribution, given reductions in water availability, may be exacerbated by social conflicts associated with competing demands for an increasingly scarce water supply. Because many life-history characteristics of lotic fish assemblages are tightly linked to the natural flow regime (Poff et al. 1997), there may also be indirect effects related to altered discharge patterns. For example, in many areas supporting coldwater fish, the discharge regime is currently characterized by a peak associated with spring snowmelt. Stream discharge patterns altered by diminishing snowpack and increasing evaporation associated with increasing air temperatures (Field et al. 2007) will likely diminish the spatial distribution and size of coldwater fish population in concordance with changes in the magnitude, frequency, duration, timing, and rate of change of discharge patterns (Jager et al. 1999).

Uncharacteristic winter flooding may also be a substantial stressor for some stream fishes (Hamlet and Lettenmaier 2007; Williams et al 2009). This factor has received less attention but changes from snow-dominated winter-precipitation regimes to transient watersheds where both rain and snow occur in winter may substantially increase the probability of winter floods. In systems where the life-history of native fishes are tightly linked to these annual patterns, winter floods may substantially increase overwinter mortality and reduce the probability of persistence, especially in small, isolated watersheds.

Habitat for stenothermal fish species will be altered in river and streams

Water temperature fundamentally influences the structure and processes that define aquatic ecosystems. The distribution, reproduction, fitness, and survival of fishes are inextricably linked to the thermal regime of the environment. Climate change may be the most critical factor affecting the persistence of stenothermal fish species such as trout because of existing threats posed by invasion of non-native fishes and habitat degradation. Water temperature increases 0.6-0.8 °C for each degree rise in air temperature; thus, a 3-5°C increase in air temperatures will yield a 2-3°C increase in water temperature (Morrill et al. 2005). Historically, research has focused on defining the lethal thermal limits of trout (Brett 1971; Eaton et al. 1995; Selong et al. 2001; Todd et al. 2008); however, water temperature is known to be important in biological processes at a variety of spatial scales and levels of biological organization (Rahel and Olden 2008; McCullough et al 2009). For instance, trout are affected directly by water temperature through feeding, metabolism, and growth rates, and indirectly by factors such as prey availability and species interactions (Wehrly et al. 2007; Rahel and Olden 2008). When growth rates of bull trout and brook trout were experimentally compared at a range of water temperatures from 8°C to 20°C, bull trout grew slower in the presence of brook trout than without brook trout, but brook trout actually grew slower when bull trout were absent (McMahon et al. 2007).

Changes in water temperature associated with climate change will alter the distribution of habitats suitable for stenothermal fish species, and current habitat space can be expected to shift up in elevation and northward in latitude. Unfortunately, the ability of stream fishes to simply migrate northward or upstream is likely to be constrained by river basin characteristics (e.g., east-west flowing drainages, steep channel gradients in headwater habitats). As a result, severe contraction of thermally suitable habitat is predicted under future warming scenarios (Meisner 1990; Eaton and Scheller 1996; Rahel et al. 1996; Hari et al. 2006). For example, Keleher and Rahel (1996) predicted an increase in water temperature from 1°C to 5°C would result in a 7.5-43.3% decline in the length of stream occupied by the coldwater guild of fishes in Wyoming. Furthermore, model projections suggest a reduction of 70% of suitable warm-season habitat for the threatened Gila trout (Kennedy et al. 2008). Thermally suitable natal habitat of bull trout is predicted to decline by 18–92% and large habitat patches (>10,000 ha) are predicted to decline 27–99%. Rieman et al. (2007) argued that over the range of anticipated changes, population-level effects of climate warming may be disproportionate to the simple loss of habitat area.

Coldwater fish assemblages in tail water releases below dams will be less likely to suffer the effects of warming as long as the water is released from the hypolimnion. Another possible mitigating factor is that streams with high groundwater discharge may be less sensitive to climate change than streams with low groundwater discharge (Chu et al. 2008). Moreover, several researchers have documented high-elevation areas without fishes where cold temperatures currently limit trout recruitment (Harig and Fausch 2002; Coleman and Fausch 2007). Although warmer stream temperatures could facilitate expansion of fish into high altitude habitats, the overall distribution of coldwater fish will probably decline (Keleher and Rahel 1996; Williams et al. 2009).

Abiotic and biotic interactions will be detrimental to fishes in rivers and streams

Climate change will shift abiotic variables (i.e., temperature and discharge) important to stream fishes and will most likely have negative health implications. For example, elevated water temperatures and altered flow regimes can significantly increase susceptibility of fish to disease and parasitism (Marcogliese 2001; McCullough et al. 2009). Disease is not the result of a single event, but the result of multiple interactions between the fish, the pathogen, and the aquatic environment. Thus, the cumulative effects of multiple stressors can be lethal to fish even if the effect of each individual stressor may not be lethal (Barton and Iwama 1991). If the duration and/or severity of the stressor exceed the tolerance limits of the fish, compensatory physiological changes become maladaptive. Adverse physiological responses, such as stunted growth, altered behavior, and increased susceptibility to disease are likely consequences (Snieszko 1974; Wedemeyer et al. 1984). An increased incidence of temperature-dependent Proliferative Kidney Disease in brown trout was observed when the habitat became marginal as a result of regional warming trends (Hari et al. 2006). The spread of other important trout diseases, such as whirling disease, may be influenced by climate change as well (Marcogliese 2001; Blazer et al. 2003). DuBey et al. (2007) demonstrated greater susceptibility of Rio Grande cutthroat trout to whirling disease when compared to rainbow trout and such differences may be exacerbated by additional environmental stress associated with elevated water temperature.

Complex behavioral responses to shifts in water temperature and precipitation may also affect persistence of stenothermal fishes. Understanding the effects of climate change on interactions among sympatric fishes, or those residing in close proximity, is especially important for determining future management options (Rahel and Olden 2008). For example, changes in water temperature may preferentially facilitate the colonization of existing habitat by cool-water and warm-water fish species and increase the interactions between native and non-native fishes (Taniguchi et al. 1998; Buisson et al. 2008). In the western U.S., one of the greatest threats to the persistence of native cutthroat trout species is hybridization with introduced rainbow trout (Seiler and Keeley 2009; Muhlfeld et al. 2009). Henderson et al. (2000) reported that the probability of introgression could increase if migration cues are altered by changing hydrological patterns. Other interspecific interactions, including competition and predation with introduced brown trout and brook trout (McHugh and Budy 2005; McGrath and Lewis 2007; Rodtka and Volpe 2007; Peterson et al. 2004) may be modified as the result of changing physical conditions.

Fragmented or isolated fish populations will have the greater risk of extirpation and extinction

Many native trout species persist in highly isolated, fragmented populations. In some cases, these populations remain isolated by unsuitable downstream habitat. With climate change, fragmentation of these populations will likely increase (Flebbe et al. 2006). Isolated and fragmented populations may solely exist through active fisheries management (e.g., establishment of artificial barriers) to limit detrimental interactions with downstream nonnative fish species (Novinger and Rahel 2003). Importantly, fragmentation of stream habitats can increase extirpation risk by reducing effective habitat area and connectivity (Fagan 2002; Guy et al. 2008). Specifically, spatially restricted trout populations may not have access to a sufficient diversity of habitat types to complete their life cycle, and restricted genetic diversity may reduce the probability of persistence in isolated populations (Hilderbrand and Kershner 2000; Horan et al. 2000). Finally, severely isolated trout populations are at increased risk of loss from stochastic events (e.g., flooding, wildfire), because recolonization following the event may be precluded (Propst et al. 1992; Gresswell 1999; Brown et al. 2001).

Environmental processes such as wildfire will increase risk of extirpation or extinction of stream fishes

Factors related to a changing climate (e.g., earlier snowmelt, higher summer temperatures, longer fire season) are positively associated with increased wildfire activity in recent decades (Running 2006; Westerling et al. 2006; Littell et al. 2009). The effects of wildfire on stream habitats are diverse and complex (Gresswell 1999; Dunham et al. 2003; Rieman et al. 2003). For example, the direct effects of wildfire are increases in stream temperature (Hitt 2003) and changes in aquatic chemistry can approach lethal toxicity thresholds for fishes (Spencer and Hauer 1991). Indirect effects include the loss of streamside vegetation, resultant increases in stream temperature from increased solar radiation and increased sedimentation (Gresswell 1999). Although some stream fishes such as trout are commonly well adapted to the effects of moderate wildfire (Gresswell 1999), severe wildfire in small isolated headwater streams can result in extirpation of resident stream fishes and long-term alterations within the forage base (Rinne 1996). As noted above, recolonization of trout into locally extirpated burned areas was largely a function of the proximity and connectivity to potential migrants (Gresswell 1999).

Unfortunately, fragmented fish populations are at the greatest risk to effects of fire. Thus climate change will not only increase the potential for catastrophic wildfire, but increase the chances of extirpation and extinction of tenuous fish populations.

Adaptive strategies for management of fishes and fisheries in river and stream systems

The cumulative impact that climate change will have on stenothermal fish populations will require coordinated development and implementation of conservation and management strategies that will most likely have complex societal and political ramifications (Schindler 2001). Limited resources will require difficult decisions when selecting species and populations for continued conservation based on potential for long-term persistence (e.g., ability to maintain stream migration corridors that facilitate movement among sub-populations; Williams et al. 2009). However, isolated populations on the periphery of distributions may also be of great conservation interest, as these populations contain genetic information that may prove valuable in the re-establishment or expansion of populations as climate change proceeds (Williams et al. 2009). As coldwater habitat contracts, headwater streams may represent the last stop for stenothermal fish. More refined predictive capabilities are needed to anticipate thermal changes in these habitats to better anticipate management needs or alternatives. Thus, long term monitoring of water and air temperature to determine potential thermal loading at high elevations is imperative because these changes are on a smaller spatial scale than the resolution of current global climate change models (Kennedy et al. 2009). Certainly, land managers should attempt to minimize anthropogenic stressors (i.e., logging, water diversion) that negatively affect stream hydrology and water temperatures, as well as be proactive by limiting the spread of introduced species and disease. Adaptive strategies should include but not be limited to:

- Restore/preserve geomorphological integrity of streams and rivers when management activities such as fish restoration are planned
- Provide historic flow regime where possible. It is likely that natural flow regimes will more likely support native fish assemblages and be less likely to provide conditions suitable to non-native fishes accustomed to other biotic and abiotic conditions
- Provide connectivity of habitat to disparate populations. Removal of structures that act as barriers to native species dispersal such as diversion dams and culverts will aid in connectivity and thus resilience. This improves the chances of species persistence and population connectivity as well as facilitates opportunity to conserve genetic integrity of species
- Maximize local infiltration and absorption of rain water (e.g., wetland preservation/restoration, low-impact development, vegetation buffers)
- Provide incentives for flood plain, riparian or watershed protection to build resiliency of the aquatic water bodies (e.g., reduce stressors such as grazing by native and non-native ungulates, recreational impacts of off-road vehicles and camping, drilling, and consumptive harvesting of forest or woodland products)
- Incorporate prescription wildfire in long-range management plans for forested areas

Table B.2. Hypothesized effects of climate change on physical and biological properties and processes in river and stream systems. Effects will depend on the system and regional heterogeneity of climate regimes.

Physical Ecosystem Properties

- Summer water temperatures will be greater and longer in duration.
- Higher minimum water temperature will occur in winter.
- Rain-on-snow and winter-spring flooding will increase in frequency.
- Earlier spring snow melt will be followed by lower summer flow.
- Ultra-violet radiation will increase and penetrate further.
- Drought will increase in frequency and severity.
- Acidification will increase.

Community and Foodweb Responses

- Macroinvertebrate community structure will shift in response to all the above.
- Fish biodiversity will decline in response to altered macroinvertebrate structure.
- Invasive non-native species will proliferate.
- Increased strain on predator-prey relationships will result in altered community structure and stability.

Box B.2. CASE STUDY: *Anadromous salmon in the Pacific Northwest and Southern British Columbia will experience cumulative effects of climate change as increasing temperatures and altered precipitation patterns uncouple the timing of life history benchmarks for migratory riverine species*

While models for the Pacific Northwest project relatively modest overall precipitation changes, the timing of these changes will be crucial (ISAB 2007). Summer precipitation is expected to decrease and winter precipitation to increase in the form of rainfall rather than snow. Snowpack will diminish, altering stream flow timing, while peak river flows are expected to increase (ISAB 2007). Eggs of fall and winter spawning fish (i.e., coho, chum, sockeye and Chinook salmon) will be lost to high flows (Jager et al. 1999) while eggs of spring-spawning cutthroat trout will be lost to sedimentation and dewatering. Throughout, water temperatures will be linked to hydrological changes as lower summer flows will result in streams and rivers becoming more responsive to increased air temperatures. Species with extended freshwater rearing will experience higher water temperatures during egg incubation, emergence, freshwater rearing and smoltification. Elevated temperatures would result in earlier emergence of smaller fry. The mismatch between availability of food and timing of fry emergence will be compounded as elevated temperatures redirect energy from growth to maintenance. Warmer temperatures and earlier snowmelt may result in earlier smolting and emigration to the estuary and ocean where survival is contingent upon the timing of ocean upwelling for delivery of needed nutrients for the young salmon food base (Scheuerell and Williams 2005). Thermal stress of juvenile salmonids will not only increase chances of predation as shown by Petersen and Kitchell (2001), but reduce the chances of a successful emigration through dams and diversions. Warming ocean surface temperatures and shifts in wind-driven upwelling events will alter the fish’s behavior and migrational patterns potentially forcing salmon further from their home streams in search of ocean feeding areas. Increased temperatures will increase energetic demands that require increased forage time and feed requirements. Increased energetic demands will also increase density-dependent competition within species and among species such as with hatchery-reared fish for limited food. Ultimately, this would delay time to maturity and migration to natal streams.

B.3. Coastal and Estuarine Fishes, Fisheries and Habitats

Sea levels will rise along ocean shores with implications to coastal and estuarine habitats that support diverse ecosystems and dependent coastal economies

Sea level, driven mostly by ocean water levels but strongly influenced by watershed hydrology, is expected to rise as global climate warms. Estimates of sea level rise between 0.18 and 0.59 m by the end of the 21st century (IPCC 2007) will profoundly affect environmental conditions in the coastal fringe that include shallow waters, inter-tidal zone, and immediate upland areas. Most projections expect the net effect of these changes to include a net shift of habitats inland as waters rise, a net loss of ecosystem capacity in certain habitats as that inland movement is truncated by engineered structures such as seawalls and buildings or existing habitats are fully submerged and a net loss of environmental capacity to sustain healthy fish populations and support commercial and recreational fisheries. Shallow coastal waters are expected to cope best with rising waters and migrating shorelines but, where water levels rise most quickly, ecologically sensitive inter-tidal habitats, submerged reefs and aquatic vegetation beds, and emergent salt marshes will not have the time to shift spatially or adapt genetically to meet the projected pace of rising waters and associated physical pressures from sediments, water, and temperature. Except where coastal lands and waters may be replaced further inland (which is likely to occur along the least developed shores representing a small percentage of coastal North America), these changes portend a complicated and negative effect on coastal areas as we know them. Societal services such as fishery production are likely to decline with few options for mitigation. The socio-economic consequences are likely to be huge: estuarine waters in the United States (a subset of the larger coastal waters that are likely to bear the brunt of rising waters) support about 68% of the value of marine commercial harvests and 80% of the fish caught by salt-water recreational anglers (Lellis-Dibble et al. 2008).

Shallow ocean habitats will be directly affected by upstream, watershed, and air shed events

Coastal rivers draining into estuaries have a profound influence on fishes and their habitats (Najjar et al. 2000). Fisheries managers will need to consider changing contributions of water nutrients and materials from upland sources when modeling fish populations into the coming decades and centuries. Water cycles may include similar volumes but different pulses, with net effects on water quality, migratory behavior, reproductive success, and overall fish population health. In some cases, fish distributions may shift as river flows and estuaries yield to climate change. In addition, increased severity and frequency of storm and drought events are predicted (Houghton et al. 2001). If this prediction holds true, coastal habitats are likely to be affected by both chronic water rise and more significant but infrequent change in overall hydrologic cycles.

Against this background, efforts to protect and restore habitats to recover depleted fisheries that rely on estuarine areas should be a priority. Restoration can provide some mitigation for climate change, but habitat deterioration associated with changes in stream flows will make fish population recovery targets hard to meet. For example, all species of Pacific salmon spend some time in estuaries during their transition to the ocean. Estuaries will experience altered sediment transport and deposition as well as altered salinity at the saltwater and freshwater interface.

Adaptive strategies for management of fishes and fisheries in coastal and estuarine systems

Increased shifts in ecological range are anticipated. This suggests that resource managers may need to expand the geographic scope of their efforts to include those areas that might be habitats of the future and to consider a broader range of human activities that might affect future habitat management options. Public and private institutions often limit their technical contributions to issues with immediate relevancy, both in time and space. For example, government agencies might comment on proposed actions in coastal waters or focus on impacts to habitats in their current state. Such approaches warrant renewed scrutiny since habitats may shift geographically with resulting challenges to government jurisdictions whose roles hinge on the boundaries of specific habitats. A major objective when considering future scenarios should be to retain options for habitats to shift and resources to adapt. These adaptive measures will ‘hedge our bet’ that innate resilience will enable fishes and fisheries to persist during times of environmental change. If we cannot use adaptive management to avoid impacts, can we give serious consideration to some actions that could minimize impacts and preserve options?

Climate change and associated impacts should be considered when establishing goals for or funding of habitat protection and restoration activities. Care must be taken to ensure that environmental investments will yield expected results in the face of significant ecological transitions. The changes mentioned above must be considered in societal decisions to protect or restore fish habitat. Major efforts to protect existing or potential habitat, or to invest in habitat restoration must consider not only historical ecological conditions but also a reasonable suite of likely future scenarios. Will a place or project survive as waters rise? Will local citizens seek to entrench at the current shoreline to protect upland investments or support retreat that might enable coastal habitat to migrate inland? Harris et al. (2006) offered logical considerations in societal decisions such as these, each with major financial and ecological implications. Experience shows that predictive models can support long-range conservation plans at regional to larger scales (Lassalle et al., 2008). With care, society can plan now at scales appropriate for this challenge.

Societal implications of projected changes in sea level, inundation, habitat loss, ecological implications, and economic impacts should prompt planning for adaptive management. The key to preemptive adaptive management strategies for coastal and estuarine areas is careful planning. The following adaptive strategies should include but not be limited to:

- Assess the likelihood of impacts using risk-based modeling approaches
- Characterize the full range of responses by coastal and large inland lake resources
- Manage imperiled habitats for horizontal space to migrate inland as waters rise, salinity encroaches, and coastal habitats give way to open waters
- Work with legislative governance to develop flexible state and federal policies
- Revisit financial incentives such as flood and hazard insurance
- Educate stakeholders and citizens of the potential effects climate change will have on the unique and sensitive nature of coastal and estuarine resources

Table B.3. Hypothesized effects of climate change on physical and biological properties and processes in coastal and estuarine habitats. Effects will depend on the system and regional heterogeneity of climate regimes.

Physical ecosystem properties

- Waters will encroach further inland.
- Water encroachment will impose physical pressures that shift key habitat types inland, however, uncertainty is high regarding whether fish stocks can maintain pace.
- Altered freshwater flow (total amount and pulse in weather events) from coastal watersheds will increase levels of complexity.
- Temperature change will alter fish use of habitat throughout various life stages.
- Increased storm frequencies will affect habitat use by fish species.
- Reduced habitat diversity will occur as coastal habitats are truncated by roads, buildings, utility lines, flood protection features, or other engineered structures that limit habitat migration inland.

Community and food web responses

- Shifting waters will compromise coastal communities with negative effects on ecosystem resilience.
- Potential for tropic dynamics to favor opportunistic or invasive species.
- New stress on species already pressured by over-harvest and other human activities but now facing the need to develop coping strategies.

Box B.3. CASE STUDY: *The impacts of climate change on coastal fish habitat and commercial fisheries*

Climate change is expected to decrease harvests in wild-caught fisheries of stocks that depend on coastal habitats. Along the Texas shore, for example, rising sea levels will alter estuaries by inundating marshes, shifting salinity regimes, and eroding mudflats, with a net loss of habitats supporting economically important fishes and shellfish. In an area where most commercial fish harvests (97% by weight and 93% by value during 2000-2004) depend on estuaries, impacts to coastal habitats will profoundly affect the fishing industry and coastal communities (Lellis-Dibble et al., 2008). And since these same areas are already losing valued habitats to a mix of human and natural pressures (Stedman and Dahl, 2008), the additional effects of climate change will have detrimental effects to the ecology and economies of these coastal areas. Those challenges are even more daunting since coastal habitat loss and physical processes are difficult to mitigate within a realistic timeframe.

These dire prospects might be moderated with careful and timely planning. One anticipatory tactic could be to protect lands inland and adjacent to the current shoreline so coastal habitats such as wetlands and mudflats have space to migrate as waters rise. Without the ecological freedom to move inland, these coastal habitats will be pinched between the ocean and various types of coastal infrastructure (e.g., seawalls, roads, buildings, utility corridors). This approach has costs but also benefits. In the Gulf of Mexico, where rising waters could inundate estuarine habitats, at-risk habitats support about $3.6 billion of commercial harvests, fully 31% of the United States harvest during 2000-2004 (Lellis-Dibble et al., 2008).

B.4. Marine Fisheries and Habitats

Ecosystem-level changes will extend to offshore waters

Since 1900, waters in the Pacific Northwest have warmed 1.0^{o}C (about 50% more than the global average warming over the same period). That warming rate during the next century is projected to increase an average of 0.3^{o}C per decade (Salathé et al. 2007). The impact of climate change to estuaries and coastal rivers (described previously) will have cumulative effects throughout offshore waters supporting marine species and multi-billion dollar fishing industries. Climate change will also manifest itself through new regimes for ocean water temperature, salinity, wind stress, local precipitation, and cloud cover, all with implications to ocean features such as the water circulation and nutrient shifts. Murawski (1993) described an early indication of climate change would result in fish species responding differently to changing thermal regimes with potential consequences for trophic dynamics and fisheries yields. Marine water temperature changes could benefit some species and harm others (IPCC 2001). Temperature appears to be a major determinant in several aspects of fish ecology and recruitment seems to be significantly better in warmer years than in colder years; the same is true for growth (Loeng 1989). Fogarty et al. (2007) discussed how ocean features could lead to a significant shift in distributions of key species with associated economic implications. Since that analysis, recent oceanographic changes associated with climate change in the Northeast of the United States continental shelf ecosystem have caused a change in the spatial distribution of 36 fish stocks (Nye et al. 2009). Under the influence of climate warming, the southern limits of subarctic fishes and the northern limits of subtropical fishes are both likely to shift northwards (Rosentrater and Ogden 2003). Within the temperate zones, major geographic shifts have been reported (Nye et al. 2009).

Physical variables that are broadly understood to affect fish populations in freshwater and marine environments include temperature, precipitation, river discharge, ocean salinity, winds, currents, water levels, ocean upwelling, ice coverage, pH, oxygen levels and UV-B radiation. Recent predictions from global circulation models suggest changes to any one of these variables may interact with limiting factors operating in regional areas will elicit changes at all levels of biological organization from individuals to ecosystems. For example, interactions between riverine discharge and coastal upwelling/downwelling processes affect delivery of limiting nutrients and biological production in coastal food-webs. Although the net influence of climate change on these interactions is unknown, future yields of migratory and resident fish could be affected.

Given variable atmospheric and oceanic effects on different production domains, fish stocks response to climate change will vary greatly among ecosystems. As example, semi-enclosed seas such as the Georgia Strait will react differently than open water systems such as the California Current (coastal upwelling zone west of Vancouver Island) and the Alaska Current and transitional zone of Queen Charlotte Basin and offshore Gulf of Alaska waters.

Net effects at the population level could disturb ecosystem structure and processes with significant implications to multi-billion dollar fishing industries

Climate change will manifest itself through new regimes for ocean water temperature, salinity, wind stress, local precipitation, and cloud cover, all with implications to ocean features such as the water circulation and nutrient shifts. Fogarty et al. (2007) discussed how ocean features could lead to a significant shift in distributions of key species with associated economic implications. Fish that tend to aggregate near gyres or fronts may move significant distances to find those edges. Fish stocks that are constrained by water temperature are likely to retract north while new species are likely to arrive from southern waters (Rosentrater and Ogden 2003). Another example could be the ecological effects of melting sea ice on fisheries distribution and health as well as their susceptibility to harvest.

Some examples from the Pacific Northwest offer insights into changes we would expect around all North American coasts. Along the northeastern rim of the Pacific, halibut, herring, sardines, hake and salmon have supported major fisheries since the late 1800's. Salmon fisheries have been dominant from a socioeconomic perspective for much of the past century. The historic highs of salmon catch in the 1980's followed by extreme lows in the 1990's (Beamish and Noakes 2004) was due to changes in marine productivity (Hare and Mantua 2000), management agency objectives and reduced economic value of wild salmon due to market competition from aquaculture.

Salmon live for 1-4 years in offshore Gulf of Alaska waters. Warming trends associated with climate change could result in thermal stratification, altered nutrient delivery, and lower primary production which would reduce salmon production due to their increasing displacement from the Gulf of Alaska to the Bering Sea (Welch et al. 1998). The ultimate consequences of such complex changes are unknown but likely place southern fisheries rather than northern fisheries (Pacific Northwest, southern B.C.) at greater risk of future losses than northern fisheries (northern B.C. and Alaska). Vulnerability to climate impacts varies greatly for short-lived versus long-lived fish species. The former (e.g., shrimp, salmon, herring or sardines) respond quickly to temperature change. The result can be a collapse in fisheries or recovery without warning (e.g., sardines, Hargreaves et al. 1994; herring, Schweigert 1993). Climate or fishery-induced production trajectories of longer-lived species (e.g., geoduck clams, ocean perch, and halibut) change more slowly (decadal or longer scale).

Ocean currents will shift and alter present-day temperature regimes, triggering ecological ramifications with economic implications

Climate change is expected to have a profound effect on ocean hydrological regimes with implications to fish and the ecosystems that support them. Future oceans could have different mixing depths that distribute nutrients differently. Increased ocean temperatures could increase ocean stratification, which could lead to nutrient shortages and less robust marine food chains (Litchman et al. 2009). This cycle could begin with diatoms and algae and cascade up to ocean predators, and become more acute if future conditions select for smaller organisms that sequester less carbon than the current mix. Among the effects of these changes are local species extinctions in sub-polar, tropical, and semi-enclosed areas and species invasions to occupy vacant niches. Those projections show a possible change of perhaps 60% from current biodiversity (Cheung et al. 2009). In a separate study, Cheung et al. (2008) used macro-ecological theory to predict changes in maximum catch potentials for about 1,000 species in commercial fisheries worldwide. Despite inherent uncertainty, ocean temperature and circulation changes are predicted to decrease harvest in many important fisheries, although a simple geographic shift and expanded fishery opportunities may be the short-term result (Hare and Able 2006). Biodiversity losses are expected to shift other ecological services at local, regional, and global scales (Worm et al. 2006). While marine perturbations affected ecosystem health, the authors' survey of marine reserves and fishery closures revealed that ecosystems could reverse impacts of decreased biodiversity and lower productivity.

Water chemistry will change as more carbon dioxide is sequestered in ocean waters

Increased acidity will affect micro- and macro-fauna with calcium carbonate structures. Our oceans' capacity to absorb carbon and buffer some effects of increased atmospheric carbon dioxide levels is expected to translate into more acidic waters that will become increasingly hostile for organisms with a calcium-based shell or exoskeleton. Shallow and deep corals, mollusks, crustaceans, urchins, diatoms, and other species with significant ecological roles would be at great risk in oceans with lower pH levels, with implications to marine biodiversity and ecosystem services. Fish harvests could decline for species directly affected (crabs, lobsters, clams, oysters) or stressed by food chain disruptions (benthic feeders, filter feeders). Approximately 51% of the U.S. commercial harvest (about $2 billion by value in 2008) is crustaceans and bivalves (Doney et al. 2009; Feely et al. 2008). And for salmon that depend largely on calcium-containing food sources, a 10% increase in water temperature is predicted to lead to a 3% drop in mature salmon body weight (physiological effect) while a 10% decrease in planktonic food could lead to 20% drop in mature salmon body weight (Doney et al. 2009). Based on those projections and for those species, calcium in the food chain may be a more important variable than water temperature in influencing population health and size.

Fishery managers have observed how natural climate patterns such as the Pacific decadal regime shifts can affect the abundance of marine fishes. Now there is some concern that climate change will decrease cloud cover and raise ocean temperatures, which could affect regime shifts and affect production of some pelagic species that thrive in areas of coastal upwellings (Clement et al. 2009). The resulting shifting currents, chemistry, and temperature could affect structural features of shallow coral reefs, deep coral assemblages, and shellfish beds with implications to fish populations that depend on these for survival.

Marine biodiversity will decrease and/or change at a regional scale and reach entire basins with implications to ecosystem services such as fish harvests and the health of reefs and shellfish beds that help define ecosystem structure

Regional species diversity could be affected by local extinctions of sedentary species like corals and scallops, major relocations (by latitude or depth) among mobile species like migratory fish, and invasions by opportunistic species colonizing vacated niches. Populations of commercially and recreationally important species could suffer when ocean conditions shift in response to climate change. Populations already impaired by overfishing and other human activities could become more susceptible to even greater impacts from climate change. Since many U.S. harvested stocks are at sub-optimal population levels (NMFS, 2009) (see: http://www.nmfs.noaa.gov/sfa/statusoffisheries/2009/firstquarter/q1_2009_fssi_summary_changes.pdf), these additional pressures can be expected to lower harvest, decrease economic benefits, and impose social costs on industries and coastal communities. Ecosystem structures such as shellfish beds and coral reefs could suffer from ocean acidification, with secondary impacts to harvested species. These changes in stock health and ecosystem integrity will invite opportunistic species. Each new species shifts the environmental baseline, thereby complicating efforts for native species to survive and thrive. Although the focus has been on harvested species, many protected species such as whales and sea turtles could also be affected by these types of ecosystem changes on a regional scale.

Adaptive strategies for management of fishes and fisheries in marine systems

Ecosystem-based fishery management, which would include existing policy tools such as area closures or harvest allocation strategies, would provide the comprehensive approach needed to balance the multiple stresses of climate change on our oceans and species (Kling and Sanchirico 2009). Harvest allocation schemes, established in advance of anticipated impacts, would add predictability and reduce waste associated with natural instincts to increase fishing pressure on stocks already coping with ecosystem disruption. These types of ecosystem approaches offer promise but little prior experience.

Another adaptation could be to shift harvests or ocean uses to offset possible losses in capture fisheries. Kling and Sanchirico (2009) suggest that an investment in offshore aquaculture could provide protein lost when ocean conditions no longer support key fisheries. A shift from affected species, such as shellfish and mollusks, to more resilient migratory species could reduce the effects of change on the fishing industry and seafood consumers. Shifting ocean conditions, ranging from ocean acidification to local extinctions, should prompt adaptive management strategies. Adaptive strategies should include but not be limited to:

- Characterize and rank by ecological and economic importance the short term and long term effects of climate change in marine systems
- Characterize the range of responses of marine systems
- Apply principles of adaptive management to avoid or minimize impacts and preserve future options

Table B.4. Hypothesized effects of climate change on physical and biological properties and processes in ocean habitats. Effects will depend on the system and regional heterogeneity of climate regimes.

Physical ecosystem properties

- Water chemistry will change markedly (i.e., water temperature will increase, pH will decrease as marine waters absorb carbon, coastal salinities will fluctuate as coastal run-off occurs)
- Higher water temperatures and ice melt will alter circulation patterns
- New physical oceanographic features will redistribute species away from important ecological features like canyons or events like upwellings that support them

Community and food web responses

- New stress on species already pressured by over-harvest and other human activities will affect productivity
- Tropic dynamics will favor opportunistic or invasive species
- Biodiversity will decrease as some species fail to compete in new conditions

---

Box B.4. CASE STUDY: *The effect of climate change on offshore fish populations and implications to commercial fisheries*

Environmental changes prompted by shifting climates are expected to influence the size and health of marine fish populations both near and far from the coast. Offshore finfish will face different stressors than estuarine shellfish but the net effect could be significant. For example, Atlantic cod are an iconic species with mythical status in New England that have declined substantially in recent years (Fogarty et al. 2007). Overfishing has clearly been a major factor but an analysis of north Atlantic cod stocks suggests that increased mean annual water temperatures are depressing population levels, reducing harvests, and limiting the cod's long-term potential to recover to healthier stock sizes. These implications of the loss of "thermal habitat" (Fogarty et al. 2007) are likely to increase if present levels of carbon dioxide emissions persist through this century.

The fishing industry and coastal communities dominated by fishing interests can expect to feel the social, economic, and cultural effects of depressed cod populations. Economic disaster declarations in New England states were followed by further reductions in fishing efforts; however, little change in the health of the cod stock was observed due to competition with other species and loss of nursery habitat throughout the Georges Bank.

Offshore species might gain some resilience to climate change due to distance or depth. But the options to ameliorate impacts to offshore stocks might be fewer than in estuaries. Reducing fishing pressure could protect genetic diversity and overall population fitness, with benefits as the pressures of shifting ocean conditions build over the decades. New gear could allow harvest but reduce habitat impacts, with benefits to struggling populations. Redirecting fishers to other fisheries, gear types, or occupations could provide other benefits.

Similar changes are expected in the Pacific. Salmon, herring, and resident hake assemblages that dominate western Vancouver Island pelagic communities during cool La Nina conditions are replaced by migratory hake and "southern exotics" such as mackerel, tuna, and even Humboldt squid during warm El Nino conditions. Experience to date suggests that socioeconomic gains from harvest of larger quantities of migratory hake (Ware and McFarlane 1995), sardine (McFarlane and Beamish 1999) and tuna under a "warmer regime" will not immediately offset losses from collapses of higher value salmon fisheries.

B.5. Arctic and Sub-arctic Fisheries and Habitats

Persistent freshwater sub-Arctic fisheries may initially increase in total productivity as the temperature of freshwater systems increase; however, drying of aquatic habitats, increased sedimentation and permafrost loss will offset this increase in productivity

As evidence of global climate change continues to accumulate throughout the world, the most profound and stark effects are in Arctic and Sub-arctic regions. This region has warmed rapidly in the last 50 years, with temperature increases nearly twice the rest of the world (0.45^{o}C, or 0.81^{o}F per decade). This amplification of warming is the result of positive feedback effects related to heat absorption due to reduced reflective ice and snow cover with a larger fraction of the thermal energy resulting in warming rather than evaporation. For freshwater fish in the region, three responses are likely: 1) local or widespread extirpation as habitat conditions extend beyond the tolerance limits of the species; 2) northward shift in the distribution of species, tracking preferred thermal habitats (requires that routes for dispersal exist); and 3) changes in the phenotypic expression of species in response to thermal shifts, either through natural selection or phenotypic plasticity (Reist et al. 2006).

Evidence of climate change in the Arctic precedes the turn of the 20th century. Paleolimnological records throughout the Arctic reflected large-scale ecosystem reorganization triggered by climate change as early as 150 years ago (Smol et al. 2005). The authors demonstrated that water bodies throughout the Canadian High Arctic had experienced unidirectional shifts in diatom taxa representative of longer growing seasons and expanded habitats. These high latitudinal lakes are very responsive to warming (less than 0.5^{o}C). The consequence of decreased ice cover is lake stratification that promotes primary productivity. Thus, warming trends throughout the Arctic will result in shifts in species composition of aquatic food webs and limnological communities that affect higher trophic levels.

However, if there are increases in overall productivity of freshwater sub-Arctic fisheries, these may be offset by decreases in the southern ranges of native species as temperatures move beyond upper threshold limits for some cold-water fishes (Reist et al. 2006). Northern pike, walleye, and lake whitefish populations are expected to increase in yield and distribution as these fishes move into previously unsuitable areas. In contrast, the Arctic grayling is at its most northern limit and would not survive an increase in summer temperatures of only a few degrees. Similarly, Arctic char could be eliminated from most of their range in the western and central Arctic where harvest studies indicate this species constitutes 45% (by number caught) of the top 15 harvested species of fish and wildlife reported from 1996-2001 (NWMB 2004).

Finally, changes in lake and river hydrology, thermal regimes, and sediment regimes in the Arctic could have widespread, but variable effects on aquatic communities. Smith et al. (2005) compared historic and current satellite imagery records and documented widespread decline of arctic lake abundance since 1973. Thaw and breaching of permafrost was driving the disappearance of these lakes below the subsurface once they thawed. This loss of available habitat for freshwater fish in the Arctic could represent a severe decline in freshwater fish productivity. Although cold temperatures are often assumed to limit fish species at high latitudes, seasonal warming can also limit sensitive Arctic and subarctic fishes, particularly in locations of the Alaska interior, where summer air temperatures can exceed 30°C. For example, recent observations of fish kills In the Yukon Flats National Wildlife Refuge in Alaska suggest that high summer temperatures can impact resident whitefish populations (Personal communication: R. Brown, U.S. Fish and Wildlife Service, Fairbanks, Alaska Fisheries Field

Office). Finally, loss of permafrost can result in large hill slope failures and catastrophic input of sediment into important riverine habitats such as gravel beds that are critical spawning grounds for migratory species, such as the Inconnu (*Stenodus leucichthys*).

Anadromy is likely to decrease in Arctic fisheries as freshwater systems increase in overall productivity

Approximately 1/3 of Arctic fish species are diadromous while the majority are anadromous (Reist et al. 2006). Arctic habitats are a complex mosaic upon which salmonids and other species complete their life histories. If Arctic systems experience a shift in habitat conditions, rare life history forms or small portions of salmonid populations in peripheral habitats could become disproportionately important for the long-term survival and resilience of populations in the region.

Climate change may initially increase production for some anadromous fishes. An increase in temperature trends will initially improve spawning success and frequency in the longer lived anadromous fishes (> 10-15 years) resulting in recruitment and abundance in these stocks. In contrast, the shorter lived fishes (< 10 years) will experience greater variability in year-to-year climate change resulting in variable recruitment and abundance. The benefits of facultative anadromy in diadromous fishes are evident as fish move from nutrient poor Arctic lakes to nutrient rich coastal waters for growth and survival. As warming trends occur, facultative anadromy in species such as Arctic char, brown and brook trout will reduce in frequency southward if the benefits of remaining in freshwater outweigh the benefits of migrating to coastal areas for feeding and maturation.

Adaptive strategies for management of fishes and fisheries in freshwater Arctic systems

Proximate effects of fishing pressure with climate change will exacerbate declining salmon returns and necessitate a shift to reliance on local fish species such as whitefish and northern pike (Koskey et al. 2007) by indigenous people. Understanding risks to fishery resources under climate change scenarios requires a better understanding of how native fishes and the people who rely on these fisheries respond to physical changes in their environment. This requires that we continue to study the ecological, life-history, and physical mechanisms that contribute to fish population resilience and persistence in this extreme environment. Extreme conditions typified by the Arctic ecosystem reflect that certain habitats (e.g., winter refugia, rearing habitat, clearwater spawning habitat) are limited in their availability. Thus certain areas of this northern landscape will become disproportionately more important for the persistence and productivity of fish populations region wide.

Table B.5. Hypothesized effects of climate change on physical and biological properties and processes in Arctic freshwater and marine fisheries. Effects will depend on the system and regional heterogeneity of climate regimes.

Physical ecosystem properties

- Air and water temperature will continue to increase.
- Onset of spring snowmelt will occur sooner with an increase in minimum winter temperatures.
- Winter flows will be enhanced and summer flows reduced.
- Shortened ice season will reduce ice-cover thickness.
- Open water will stratify.

Community and food web responses

- Greater primary productivity in Arctic systems will give rise to increased fish dispersal, invasion of non-native fishes, and reduced incidence of anadromy.

Box B.5. CASE STUDY: *Climate change will have complex positive and negative effects on anadromy of Arctic char*

The distribution and life history traits of the anadromous Arctic char are complex. The effects of year-to-year environmental variation (i.e., precipitation and temperature) of this long-lived and large-bodied fish is often not seen until well after recruitment (Power et al. 2000). Important considerations yet to be understood include whether climate change will have more profound effects on the earlier critical life stages in freshwater, or, on growth and attainment of reproductive readiness in marine waters. While elevated spring and summer water temperatures may increase growth rates in earlier life stages, elevated temperatures may also accelerate smoltification (see review by Reist et al. 2006). The energetic costs of earlier smoltification would take its toll on survival during migration to the sea. A reduction in overall size and age at maturity of the marine life stage would result from a decrease in overall average duration of marine residence.

B.6. Arid-land Fishes and Their Habitats

Outside of the Arctic, the four arid and semi-arid regions within North America (Great Basin, Sonoran, Mohave, and Chihuahuan Deserts) are the result of local mountain ranges that cast a rain shadow. Although each region differs in temperature (varying in latitude) and seasonal precipitation (varying in longitude), each is influenced by when the majority of the water gained from precipitation is lost through evapotranspiration (i.e., loss of water to the atmosphere by evaporation and plant transpiration). Thus, the arid nature of these regions is defined by overall average annual precipitation from 0 to 200 mm/year when the potential evapotranspiration ranges from 2,000 to 4,000 mm/year. The western arid regions of the U.S. rely heavily on snow pack as the primary mechanism by which moisture is carried through to the summer when the majority of annual precipitation occurs. Despite summer precipitation, deposition is patchy and not reliable for recharge of surface and ground water systems. While the harsh climate of arid systems results in a relatively low biomass of plant and animals, species richness and endemism is high. The maintenance of biodiversity in these arid systems is ultimately centered on the timing, quantity and quality of water.

Warming trends will result in the extirpation of native fish populations due to loss of habitat from drying and/or fire, geographic restrictions northward, and competition with non-native fishes

A broad consensus among climate models indicate that the arid regions will become more arid during the 21st century with a projected aridity that will be further intensified by La Nina events beyond any experienced in recent human record (Seager et al. 2007). An increase in warming trends with a lengthening of the freeze-free season has been recorded in the Sonoran Desert throughout the 20th century and is expected to continue through the 21st century (Weiss and Overpeck 2005). Warming trends will reduce endemic fish populations due to the east-west geographic restriction of streams throughout the Great Plains and the Southwest (Mathews and Zimmerman 1990). Habitat connectivity throughout and among stream systems is important to dispersal and re-colonization of extirpated fish populations (Fagan et al. 2002). Thus, the result will be a shift toward more thermally tolerant fish assemblages that can survive an era of fragmented habitats. The response of aquatic ecosystems to warmer and drier climate will result in greater fire severity and frequency. Increasing temperatures and new precipitation patterns will alter the landscape such that when a wet year is followed by a dry year, a surge in forest fuel loads will increase risk to wildfire. Fire within watersheds fragments aquatic habitats (Rieman and Clayton 1997). High severity fires can alter stream temperatures, fish species composition erosion patterns water yield and hydrologic processes (Bozek and Young 1994). Reduced flow and fragmented habitats which impede re-colonization, in concert with non-native fish species, will affect persistence of native fishes (Propst et al. 2008).

North American deserts will likely become drier

Drought is a frequent climatic feature of the arid regions throughout western North America. Moreover, since the 1940's, many of these areas have experienced unprecedented human population growth which makes the prospects of competition for limited water resources a concern for policy makers, municipalities, hydroelectric utilities, farmers, ranchers, and natural resource managers (U.S. Population Census Bureau 2006; Lemmen et al. 2008). While drought may be a relatively common occurrence in the west, as indicated by 1200 years of tree-ring data, current climate models indicate that the combined effects of natural climate variability and human-induced climate change would result in severe longer-lasting periods of drier weather that could exceed the mega-drought of the U.S. dust bowl era (Seager et al. 2007). Snow pack is a crucial resource in mountain fringed areas of the west. Warming trends will likely result in the proportion of precipitation that falls as rain with earlier snow melt at the onset of spring with an amplification of precipitation events (Allen and Soden 2008). Thus, the diminished snow pack, increased evaporative losses, and reduced runoff will translate into less water available for fish in the cooler season. Paradoxically, climate models indicate that amplification of extreme rainfall events will occur in warm wet seasons (Karl et al. 2009). One can anticipate that vegetation die-off from drought and fire will reduce the flood-buffering capacity of landscapes. Thus, if extreme rainfall occurs, then the outcome will most likely be severe flooding that will alter the course of streams and rivers. In addition to this physical change will be loss of suitable fish habitat and the reshuffling of fish communities.

Competition will increase for over-allocated water resources

Water is a valuable commodity in arid lands. Desert areas of the west experienced explosive rates of population growth in the latter half of the 20th century and growth is expected to continue into the 21st Century. For example, the U.S. southwest's population is expected to increase by 13.5 million people by 2025 (Southwest Regional Assessment Group 2000). Human populations have adapted to the hot, dry climate of the west through irrigation resulting in highly modified and regulated rivers. Thus, one of the impacts that climate change will have in arid lands of North America will most likely be acute increases in competition for limited water supplies to meet the needs of natural resources (fish and wildlife) and human populations (municipal, industrial, agricultural). For example, the Colorado Compact of 1920 allocated Colorado River water among the seven U.S. states through which it flows. At the time of the compact, the region had experienced a short term wet period that has subsequently reverted to drier conditions more representative of the long term mean for this region (www.globalchange.gov/usimpacts). Currently, the Colorado River lacks sufficient water to meet agreed-upon allocations resulting in conflicts between extractive user demands and maintenance of aquatic ecosystems for federally-listed endangered fish species.

Adaptive strategies for managing fishes and fisheries in arid lands

Adaptation strategies for fishery managers throughout the arid southwest should include support of more efficient irrigation measures and a shift in agricultural commodities to reduce or compensate for the climate-driven increases in water demand. Municipal coping strategies could include desalinization, water banks, and pricing water for its real value. One key adaptive strategy to managing fisheries in arid lands systems will be to reduce the user conflict.

Table B.6. Hypothesized effects of climate change on physical and biological properties and processes in arid-lands aquatic systems. Effects will depend on the system and regional heterogeneity of climate regimes.

Physical ecosystem properties

- Air and water temperature will increase markedly
- Increase in aridity will occur
- Onset of spring snowmelt will occur sooner with an increase in minimum winter temperatures
- Increase in occurrence and severity of wildland fires will occur

Community and food web responses

- Conversion of forest lands to grasslands and grasslands to desert in association with decreased rainfall will occur. This will result in increased losses of forests due to epidemic infestations by insects and disease, increased frequency and magnitude of wild-fire
- Biodiversity will decline due to drought, fire, connectivity, and competition with non-natives and human population needs
- Conflict and competition between human and fish will increase over limited water quality and availability

Box B.6. Case Study: *Rio Grande cutthroat trout persistence in Arid-lands*

The 2008 decision to list Rio Grande cutthroat trout under the Endangered Species Act of 1973 listed the possible effects of climate change as a threat to the species long term persistence (U.S. Federal Register 2008). The subspecies once occupied 9,700 km of stream and is currently restricted to 1,300 km (Alves et al. 2008). The majority of the remaining populations are confined to small headwater stream segments between 2,590 and 3,352 m in elevation (Alves et al. 2008). The narrow range and genetic isolation in less than optimal habitats has increased its vulnerability to climatic and anthropogenic effects. The species’ southern distribution places it within the upper range of thermal limits for most salmonids. More than half of the species can be found in small isolated populations scattered throughout north-central New Mexico. Thus, the predicted effects of climate change on Rio Grande cutthroat trout will be through elevated water temperature and loss of thermally suitable habitat. This will have profound effects on the hydrology and ecology of the intermountain region (Hauer et al. 1997). Anticipated hydrological changes would reduce winter snow pack and alter timing of spring runoff (Meisner 1990). The earlier snow melt will reduce base flow and result in loss of habitat sooner. Rio Grande cutthroat trout will face increased competition for suitable thermal habitat as non-native fishes are forced into higher elevations. The subspecies is at the southern most range for cutthroat trout and will most likely experience the greatest effects of warming trends due to population fragmentation resulting in introgression, increased competition for limited resources, miss-match between emergence of young and food availability, increased disease susceptibility, and decreased growth rate and reproduction. Thus, if this species is to persevere, then long term monitoring of temperature, establishment of metapopulations, and protection from non-native fishes throughout the species range is essential.

C. “Adaptation” to Climate Change

Regardless of whether we are successful in these endeavors, fisheries that have sustained us in the past (whether through recreational, commercial, or subsistence means) will likely be different than the fisheries that will sustain us in the future. To slow these changes, managers and policy makers must recognize factors contributing to ecosystem resilience and take proactive measures to enhance this resilience (Mawdsley et al. 2009). Fisheries management agencies should conduct vulnerability assessments for species and habitats and adapt management policies accordingly. Large education and outreach efforts will be needed to shape public expectations for local and marine fisheries. Successful adaptation also requires long-term monitoring of sensitive indicators, predictive modeling, and adaptive management, whereby the consequences of climate change and other stressors are detected early and appropriate responses or adaptations can be implemented and continually evaluated.

With a changing climate, managers of threatened fisheries will be faced with challenging management decisions. Should at-risk fish populations be translocated to higher elevations and/or northward? Such a strategy might risk the marginalization of existing ecosystems within those habitats (Magnuson 2002), and place the population at greater risk of extirpation from genetic isolation and/or stochastic events (Peterson et al. 2008). At what point does the view of invasive species shift from a scourge to a surrogate because they are better suited to altered habitats and provide some ecological or recreation benefit that would otherwise be lost. In summary, adaptive measures should:

- Include water conservation measures and support wise and sustainable use
- Encourage decisions in which water priorities are constructed through careful evaluation of market demands weighed against the potential impacts to sustainability of fisheries and aquatic habitats
- Encourage continued research and monitoring of climate change
- Support captive propagation of imperiled native fish species
- Enhance resiliency of aquatic ecosystems, thereby increasing their ability to withstand the many stressors associated local impacts
- Incorporate an adaptive management framework to cope with uncertainty, policy and management decisions using precautionary principles (e.g., decisions that are deliberately conservative) and carry them out within an adaptive management framework that includes a strong evaluation component

D. Information Gaps

- Uncertainties exist due to the scarcity of climate data coverage and the lack of balanced data among geographic areas

- The concept of manual translocation of fish populations by fisheries managers from impacted systems to new refuge habitats remains a topic of debate

E. Policy Statement

1. Do not delay emission reductions. Encourage reductions in anthropogenic sources of carbon dioxide and other greenhouse gases.

2. Encourage economic mitigation options that indirectly or directly assist with water conservation practices and watershed protection of policies and laws that support wise and sustainable use.

3. Integrate efforts to manage for both fish and wildlife habitat. Develop partnerships with overlapping interests on shared concerns will increase overall effectiveness and temper uncertainty of difficult decisions.

4. Restore historic hydrologic regimes that facilitate historic fish dispersal patterns. Do not support assisted migration or translocation of fish species as a standard operating policy, but consider this tool on a case-by-case basis carefully evaluating possibilities of unintended consequences. In landlocked “island” systems with imperiled or extirpated species, assisted migration may be the only viable management alternative for maintaining ecosystem function.

5. Encourage education efforts aimed at federal and state agencies and the private sector about the general effects of climate change to our aquatic ecosystems. This ensures transparency of the principles and practices employed for either mitigation or adaptation responses to climate change in fisheries.

6. Encourage implementation of national, regional, and local monitoring programs to evaluate the effects of climate change in fisheries. The continuation of long term monitoring (i.e., biological, hydrological, climatic) will be essential in addressing trends.

7. Encourage management and research activities that reduce ecosystem stressors to include but not be limited to: metapopulation expansion through careful consideration (i.e., use or removal) of barriers, prescribed fire in watershed to reduce chances of catastrophic fires, pollution preventive measures, biodiversity protection, and land use practices to mitigate changes to disturbances in hydrology of riparian areas and ameliorate temperature fluctuations for protection of coldwater refugia of trout, salmon, and whitefish.

8. Encourage research activities to characterize climate effects in marine, arctic and freshwater systems, reduce ecosystem stressors, and optimize harvest quota for commercial fisheries stocks.

9. Support provisions of dedicated funding for climate legislation that would provide for conservation of fish, water and other natural resources affected by climate change.

(This policy will expire in 20xx)

Contributors and Members of the Resource Policy Sub-Committee for Climate Change (Alphabetically)

The article represents the views of the American Fisheries Society and not the authors' organizations or agencies.

Thomas Bigford, NOAA Fisheries

Colleen A. Caldwell, U.S. Geological Survey

David Fluharty, University of Washington

Robert E. Gresswell, U. S. Geological Survey

Kim Hyatt, Fisheries and Oceans Canada

Doug Inkley, National Wildlife Federation

Don MacDonald, MacDonald Environmental Sciences, Ltd.

Anne Mullan, NOAA Fisheries

Andrew Todd, U.S. Geological Survey

Cindy Deacon Williams, National Center for Conservation Science and Policy

Amanda Rosenberger, University of Alaska-Fairbanks

Ray Valley, Minnesota Department of Natural Resources

Literature cited

Allan, R.P. and B.J. Soden. 2008. Atmospheric warming and the amplification of precipitation extremes. Science 321:1481-1484.

Alves, John E. Kirk A. Patten, Daniel E. Brauch, and Paul M. Jones. 2008. Range-Wide Status Report of Rio Grande Cutthroat Trout (*Oncorhynchus clarki virginalis*): 2008.

Arctic Council and the International Arctic Science Committee (ACIA). 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press.

Barton, B.A. and G.K. Iwama. 1991. Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. Annual Review of Fish Disease 1:3-26.

Battin, J., M.W. Wiley, M.H. Ruckelshaus, R.N. Palmer, E. Korb, K.K. Bartz, and H. Imaki. 2007. Projected impacts of climate change on salmon habitat restoration. Proceedings of the National Academy of Science 104:6720-6725.

Beamish, R.J. and D.J. Noakes. 2004. Global warming, aquaculture, and commercial fisheries. Pages 25-47 *in* K.M. Leber, S. Kitada, and H.L. Blankenship and T. Svasand, editors. Stock enhancement and sea ranching: developments, pitfalls and opportunities. Blackwell Scientific Publications, Oxford, UK.

Beisner, B.E., C.L. Dent, and S.R. Carpenter. 2003. Variability of lakes on the landscape: roles of phosphorus, food webs, and dissolved organic carbon. Ecology 84:1563-1575.

Blazer, V.S., T.B. Waldrop, W.B. Schill, C.L. Densmore, and D. Smith. 2003. Effects of water temperature and substrate type on spore production and release in eastern *Tubifex tubifex* worms infected with *Myxobolus cerebralis*. Journal of Parasitology 89:21-26.

Bozek, M.A. and M.K. Young. 1994. Fish mortality resulting from delayed effects of fire in the Greater Yellowstone ecosystem. Great Basin Naturalist 54:91-95.

Brett, J.R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). American Zoologist 11:99-113.

Brown, D.K., A.A. Echelle, D.L. Propst, J.E. Brooks, and W.L. Fisher. 2001. Catastrophic wildfire and number of populations as factors influencing risk of extinction for Gila trout (*Oncorhynchus gilae*). Western North American Naturalist 61:139-148.

Buisson, L., W. Thuiller, S. Lek, P. Lim, and G. Grenouillet. 2008. Climate change hastens the turnover of stream fish assemblages. Global Change Biology 14:2232-2248.

Carpenter, S. R. 2008. Phosphorus control is critical to mitigating eutrophication. Proceedings of the National Academy of Sciences 105:11039-11040.

Cheung, W.W.L., C. Close, V. Lam, R. Watson, and D. Pauly. 2008. Application of macroecological theory to predict effects of climate change on global fisheries potential. Marine Ecology Progress Series 365:187-197.

Cheung, W.W.L., V.W.Y. Lam, J.L. Samiento, K. Kearney, R. Watson, and D. Pauly. 2009. Projecting global marine biodiversity impacts under climate change scenarios. *In* Fish and Fisheries. Blackwell Publishing, Ltd. pp. 1-17.

Chu, C., N.E. Jones, N.E. Mandrak, A.R. Piggott, and C.K. Minns. 2008. The influence of air temperature, groundwater discharge, and climate change on the thermal diversity of stream fishes in southern Ontario watersheds. Canadian Journal of Fisheries and Aquatic Sciences 65:297-308.

Clement, A.C., R. Burgman, and J.R. Norris. 2009. Observational and model evidence for positive low-level cloud feedback. Science 325:460-464.

Coleman, M.A. and K.D. Fausch. 2007. Cold summer temperature limits recruitment of age-0 cutthroat trout in high-elevation Colorado streams. Transactions of the American Fisheries Society 136:1231-1244.

Danylchuk, A.J. and W.M. Tonn. 2003. Natural disturbances and fish: local and regional influences on winterkill of fathead minnows in Boreal lakes. Transactions of the American Fisheries Society 132:289-298.

DeStasio, B.T. Jr., D.K. Hill, J.M. Kleinhans, N.P. Nibbelink, and J.J. Magnuson. 1996. Potential effects of global climate change on small north-temperate lakes: physics, fish, and plankton. Limnology and Oceanography 41:1136-1149.

Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453:1090-1093.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas. 2009. Ocean acidification: The other CO_2 problem. Annual Reviews of Marine Science 1:169-192.

DuBey, R.J., C.A. Caldwell, and W.R. Gould. 2007. Relative susceptibility and effects on performance of Rio Grande cutthroat trout and rainbow trout challenged with *Myxobolus cerebralis*. Transactions of the American Fisheries Society 136:1406-1414.

Dunham, J.B., M.K. Young, R.E. Gresswell, and B.E. Rieman. 2003. Effects of fire on fish populations: landscape perspectives on persistence of native fishes and nonnative fish invasions. Forest Ecology and Management 178:183-196.

Earth Observatory. 2009. Amount of Old Ice in Arctic Hits Record Low in February 2009. Posted April 10, 2009. Accessed June 29, 2009.

Eaton, J.G. and R.M. Scheller. 1996. Effects of climate warming on fish thermal habitat in streams of the United States. Limnology and Oceanography 41:1109-1115.

Eaton, J.G., J.H. McCormick, B.E. Goodno, D.G. O'Brien, H.G Stefany, M. Hondzo, and R.M. Scheller. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries 20:10-18.

Fagan W. F. 2002. Connectivity, fragmentation, and extinction risk in dendritic metapopulations. Ecology 83:3243–3249.

Fagan, W.F., P.J. Unmack, C. Burgess, and W.L. Minckley. 2002. Rarity, fragmentation, and extinction risk in desert fishes. Ecology 83:3250-3256.

Fang, X., and H. G. Stefan. 2000. Projected climate change effects on winterkill in shallow lakes in the northern United States. Environmental Management 25:291-304.

Feely, R.A., V.J. Fabry, and J.M. Guinotte. 2008. Ocean acidification of the North Pacific Ocean. PICES Press 16: 22–26.

Field, B., L.D. Mortsch, M. Brklacich, D. L. Forbes, P. Kovacs, J. A. Patz, S. W. Running and M. J. Scott. 2007. North America. Pages 617-652 *in* M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. Van der Linden, and C. E. Hanson, editors. Climate Change 2007: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

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

Flebbe, P.A., L.D. Roghairand, and, J.L. Bruggink. 2006. Spatial modeling to project southern Appalachian trout distribution in a warmer climate. Transactions of the American Fisheries Society 135:1371-1382.

Fogarty, M., L. Incze, R. Wahle, D. Mountain, A. Robinson, A. Pershing, K. Hayhoe, A. Richards, and J. Manning. 2007. Potential climate change impacts on marine resources of the northeastern United States. *In* "Confronting Climate in the U.S. Northeast: Science, Impacts, and Solutions," based on the Northeast Climate Impacts Assessment.

Genkai-Kato, M. and S. R. Carpenter. 2005. Eutrophication due to phosphorus recycling in relation to lake morphometry, temperature, and macrophytes. Ecology 86:210-219.

Glick, P., A. Staudt, and B. Stein. 2009. A new era for conservation: review of climate change adaptation literature. National Wildlife Federation.

Gresswell, R.E. 1999. Fire and aquatic ecosystems in forested biomes of North America. Transactions of the American Fisheries Society 128:193-221.

Guy, T. J., R. E. Gresswell, and M. A. Banks. 2008. Landscape-scale evaluation of genetic structure among barrier-isolated populations of coastal cutthroat trout *Oncorhynchus clarkii clarkii*. Canadian Journal of Fisheries and Aquatic Sciences 65:1749-1762.

Hamlet, A. F. and D. P. Lettenmaier. 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. Water Resources Research 43:W06427.

Hamlet, A.F., P.W. Mote, M.P. Clark, and D. P. Lettenmaier. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. American Meteorological Society 18:4545-4561.

Hare, S.R. and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-145.

Hargreaves, N.B., D.M. Ware, and G.A. McFarlane. 1994. Return of the Pacific sardine (*Sardinops sagax*) to the British Columbia coast in 1992. Canadian Journal of Aquatic Sciences 51:460-463.

Harig, A. L. and K. D. Fausch. 2002. Minimum habitat requirements for establishing translocated cutthroat trout populations. Ecological Applications 12:535-551.

Hari, R.E., D.M. Livingstone, R. Siber, P. Burkhardt-Holm, and H. Guttinger. 2006. Consequences of climatic change for water temperature and brown trout populations in alpine rivers and streams. Global Change Biology 12:10-26.

Harris, J.A., R.J. Hobbs, E. Higgs, and J. Aronson. 2006. Ecological restoration and global climate change. Restoration Ecology 14:170-176.

Hauer, F.R., J.S. Baron, D.H. Campbell, K.D. Fausch, S.W. Hostetler, G.H. Leavesley, P.R. Leavitt, D.M. McKnight, and J.A. Stanford. 1997. Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. Hydrological Processes 11:949-970.

Hagen, P.H. and H. Drange. 1996. Effects of CO_2 on the ocean environment. Energy Conversion and Management 37:1019-1022

Herwig, B.R., K.D. Zimmer, M.A. Hanson, M.L. Konsti, J.A. Younk, R.W. Wright, S.R. Vaughn, and M.D. Haustein. 2009. Factors influencing fish distributions and community structure in shallow lakes within prairie and prairie-parkland regions of Minnesota, USA. (Wetlands, In Revision).

Henderson, R., J. L. Kershner, and C.A. Toline. 2000. Timing and location of spawning by nonnative wild rainbow trout and native cutthroat trout in the South Fork Snake River, Idaho, with implications. North American Journal of Fisheries Management 20:584-596.

Hilderbrand, R.H. and J.L. Kershner. 2000. Conserving inland cutthroat trout in small streams: how much stream is enough? North American Journal of Fisheries Management 20:513-520.

Hitt, N.P. 2003. Immediate effects of wildfire on stream temperature. Journal of Freshwater Ecology 18:171-173.

Horan, D.L., J.L. Kershner, C.P. Hawkins, and T.A. Crowl. 2000. Effects of habitat area and complexity on Colorado River cutthroat trout density in Uinta Mountain streams. Transactions of the American Fisheries Society 129:1250-1263.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: Contribution of Working Groups III to the Third Assessment Report of the Intergovernmental Panel on Climate Change.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

ISAB 2007. Climate Change Impacts on Columbia River Basin Fish and Wildlife, May 11, 2007 document ISAB 2007-2. www.nwcouncil.org/library/isab/isab2007-2.htm

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. McGinn, editor. Fisheries in a Changing Climate. American Fisheries Society, Bethesda, MD.

Jager, H. I., W. Van Winkle, and B. D. Holcomb. 1999. Would hydrologic climate changes in Sierra Nevada streams influence trout persistence? Transactions of the American Fisheries Society 128:222-240.

Karl, T.R., J.M. Melillo, and T.C. Peterson (eds). 2009. Regional climate impacts: Southwest. *In* Global climate change impacts in the United States. Cambridge University Press. Pp. 129-134.

Keleher, C.J. and F.J. Rahel. 1996. Thermal limits to salmonid distributions in the Rocky Mountain region and potential habitat loss due to global warming: a geographic information systems (GIS) approach. Transactions of the American Fisheries Society 125:1-13.

Kennedy, T.L., D.S. Gutzler, and R.L. Leung. 2009. Predicting future threats to the long-term survival of Gila trout using a high-resolution stimulation of climate change. Climatic Change 94:503-515.

Kling, G.W., K. Hayhoe, L.B. Johnson, J.J. Magnuson, S. Polasky, S.K. Robinson, B.J. Shuter, M.M. Wander, D.J. Wuebbles, and D.R. Zak. 2003. Confronting climate change in the Great Lakes region: impacts on our communities and ecosystems. A report of the Union of Concerned Scientists and the Ecological Society of America. Online at http://www.ucsusa.org/greatlakes/glchallengereport.html

Krawchuk, M.A., M.A. Moritz, M-A. Parisien, J. Van Dorn, and K. Hayhoe. 2009. Global Pyrogeography: the Current and Future Distribution of Wildfire. PLoS ONE 4(4): e5102. doi:10.1371/journal.pone.0005102.

Lassalle, G., M. Beguer, L. Beaulaton, and E. Rochard. 2008. Diadromous fish conservation plans need to consider global warming issues: An approach using biogeographical models. Biological Conservation 141:1105-1118.

Lellis-Dibble, K.A., K.E. McGlynn, and T.E. Bigford. 2008. Estuarine fish and shellfish species in U.S. commercial and recreational fisheries: economic value as an incentive to protect and restore estuarine habitat. U.S. Department of Commerce, NOAA Technical Memo NMFS-F/SPO-90, 94 pp.

Lemmen, D.S., F.J. Warren, J. Lacroix, and E. Bush, editors. 2008. From impacts to adaptation: Canada in a changing climate 2007. Government of Canada, Ottawa, Ontario, 448 p.

Leung, L.R. and M.S. Wigmosta. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest. Journal of the American Water Resources Association 35:1463-1471.

Litchman, E., C.A. Klausmeier, and K. Yoshiyama. 2009. Contrasting size evolution in marine and freshwater diatoms. Proceedings of the National Academy of Science USA 106: 2665-2670.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. Ecological Applications 19:1003-1021.

Loeng, H. 1989. The influence of temperature on some fish population parameters in the Barents Sea. Journal of the Northwest Atlantic Fisheries Science 9:103-113.

MacKensie-Grieve, J.L. and J.R. Post. 2006. Thermal habitat use by lake trout in two contrasting Yukon territory lakes. Transactions of the American Fisheries Society 135:727-738.

Magnuson, J.J. 2002. A future of adapting to climate change and variability. Pages 273-282 *in* N. A. McGinn, editor. Fisheries in a Changing Climate. American Fisheries Society, Bethesda, MD.

Magnuson, J. J., J. D. Meisner, and D. K. Hill. 1990. Potential changes in thermal habitat of Great Lakes fish after global climate warming. Transactions of the American Fisheries Society 119:254-264.

Marcogliese, D.J. 2001. Implications of climate change for parasitism of animals in the aquatic environment. Canadian Journal of Zoology 79:1331-1352.

Matthews, W.J. and E.G. Zimmerman. 1990. Potential effects of global warming on native fishes of the southern Great Plains and the southwest. Fisheries 15:26-32.

Mawdsley, J. R., R.O. O'Malley, and D.S. Ojima. 2009. A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. Conservation Biology 23:1080-1089.

McCullough, D.A., J.M. Bartholow, H.I. Jager, R.L. Beschta, E.F. Cheslak, M.L. Deas, J.L. Ebersole, J.S. Foott, S.L. Johnson, K.R. Marine, M.G. Mesa, J.H. Petersen, Y. Souchon, K.F. Tiffan, and W.A. Wurtsbaugh. 2009. Research in thermal biology: burning questions for coldwater stream fishes. Reviews in Fisheries Science 171:90-115.

McFarlane, G.A., P.E. Smit, T.R. Baumgartner, and J.r. Hunter. 2002. Climate variability and Pacific sardine populations and fisheries. Pages 195-214 *In* N.A. McGinn, editor. Fisheries in a changing climate. American Fisheries Society, Symposium 32, Bethesda, Maryland.

McGrath, C.C. and W.M. Lewis Jr. 2007. Competition and predation as mechanisms for displacement of greenback cutthroat trout by brook trout. Transactions of the American Fisheries Society 136:1381-1392.

McHugh, P. and P. Budy. 2005. An experimental evaluation of competitive and thermal effects on brown trout (*Salmo trutta*) and Bonneville cutthroat trout (*Oncorhynchus clarkii utah*) performance along an altitudinal gradient. Canadian Journal of Fisheries and Aquatic Science 62:2784-2795.

Meisner, J.D. 1990. Potential loss of thermal habitat for brook trout, due to climatic warming, in two southern Ontario streams. Transactions of the American Fisheries Society 119:282-291.

Minns, C.K. 2009. The potential future impact of climate warming and other human activities on the productive capacity of Canada's lake fisheries: a meta-model. Aquatic Ecosystem Health and Management 12:152-167.

Morrill, J.C., R.C. Bales, and M.H. Conklin. 2005. Estimating stream temperature from air temperature: implications for future water quality. Journal of Environmental Engineering 131:139-146.

Muhlfeld, C.C., S.T. Kalinowski, T.E. McMahon, M.L. Taper, S. Painter, R.F. Leary, and F.W. Allendorf. 2009. Hybridization rapidly reduces fitness of a native trout in the wild. Biology Letters. In press.

Murawski, S.A. 1993. Climate change and marine fish distributions: forecasting from historical analogy. Transactions of the American Fisheries Society 122:647-658.

Najjar, R.G., H.A. Walker, P.J. Anderson, E.J. Barron, R.J. Bord, J.R. Gibson, V.S. Kennedy, C.G. Knight, J. P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele, and R.S. Swanson. 2000. T he potential impacts of climate change on the mid-Atlantic coastal region. Climate Research 14:219-233.

National Research Council (NRC). 2002. Abrupt Climate Change, Inevitable Surprises. National Academy Press, Washington, DC.

National Research Council (NRC). 2006. Surface Temperature Reconstructions for the Last 2,000 Years. National Academy Press, Washington, DC.

National Marine Fisheries Service (NMFS). 2009. Annual Report to Congress on the Status of U.S. Fisheries-2008. U.S. Department of Commerce, NOAA, National Marine Fisheries Service, Silver Spring, MD, 23 pp. Available at http://www.nmfs.noaa.gov/sfa/statusoffisheries/SOSmain.htm

Nunavut Wildlife Management Board (NWMB). 2004. The Nunavut Wildlife Harvest Study Report. Iqaluit:NWMB. 822 p.

Novinger, D.C. and F.J. Rahel. 2003. Isolation management with artificial barrier as a conservation strategy for cutthroat trout in headwater streams. Conservation Biology 17:772-781.

Nye, J.A., J.S. Link, J.A. Hare, and W.J. Overholtz. 2009. Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecological Progress Series 393:111-129.

Petersen, J.H. and J.F. Kitchell. 2001. Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. Canadian Journal of Fisheries and Aquatic Sciences 58:1831-1841.

Peterson, D.P., K.D. Fausch, and G.C. White. 2004. Population ecology of an invasion: effects of brook trout on native cutthroat trout. Ecological Applications 14:754-772.

Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegaard, B.D. Richter, R.E. Sparks, and J.C. Stromberg. 1997. The natural flow regime: a paradigm for river conservation and restoration. Bioscience 47:769-784.

Power, M., J.B. Dempson, G. Power, and J.D. Reist. 2000. Environmental influences in an exploited anadromous Arctic char stock in Labrador. Journal of Fish Biology 57:82-98.

Propst, D.L., K.B. Gido, and J.A. Stefferud. 2008. Natural flow regimes, nonnative fishes, and native fish persistence in arid-land river systems. Ecological Applications 18:1236-1252.

Propst, D.L., J.A. Stefferud, and P.R. Turner. 1992. Conservation and status of Gila trout (*Oncorhynchus gilae*). The Southwestern Naturalist 37:117-125.

Rahel, F.J., C.J., Keleherand, and J.L. Anderson. 1996. Potential habitat loss and population fragmentation for cold water fish in the North Platte River drainage of the Rocky Mountains: response to climate warming. Limnology and Oceanography 41:1116-1123.

Rahel, F.J. 2002. Using current biogeographic limits to predict fish distributions following climate change. Pages 99-110 In: N.A. McGinn editor. Fisheries in a changing climate. American Fisheries Society Symposium 32. Bethesda.

Rahel, F.J. and J.D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. Conservation Biology 22:521-533.

Reist, J.D., F.J. Wrona, T.D. Prowse, M. Power, J.B. Dempson, J. R. King, and R. J. Beamish. 2006. An overview of effects of climate change on selected arctic and freshwater and anadromous fishes. Ambio 35:381-387.

Rieman, B.E. and J. Clayton. 1997. Wildfire and native fish: issues of forest health and conservation of sensitive species. Fisheries 22:6-15.

Rieman, B., D. Lee, D. Burns, R. Gresswell, M. Young, R. Stowell, J. Rinne, and P. Howell. 2003. Status of native fishes in the western United States and issues for fire and fuels management. Forest Ecology and Management 178:197-211.

Rieman, B. E., D. Isaak, S. Adams, D. Horan, D. Nagel, C. Luce, and D. Myers. 2007. Anticipated climate warming effects on bull trout habitats and populations across the interior Columbia River Basin. Transactions of the American Fisheries Society 136:1552-1565.

Rinne, J.N. 1996. Short-term effects of wildfire on fishes and aquatic macroinvertebrates in the southwestern United States. North American Journal of Fisheries Management 16:653-658.

Rodtka, M.C. and J.P. Volpe. 2007. Effects of water temperature on interspecific competition between juvenile bull trout and brook trout in an artificial stream. Transactions of the American Fisheries Society 136:1714-1727.

Rosentrater, L. and A.E. Ogden. 2003. Building Resilience in Arctic Ecosystems in Buying time: A Users Manual for Building Resistance and Resilience to Climate Change in Natural Systems. Edited by L.J. Hansen, J.L. Biringer, and J.R. Hoffman. www.panda.org/climate/pa_manual

Running, S.W. 2006. Is global warming causing more, larger wildfires? Science 313:927-928.

Salathé E.P., P. W. Mote, and M. W. Wiley. 2007. Review of scenario selection and downscaling methods for the assessment of climate change impacts on hydrology in the United States Pacific Northwest. International Journal of Climatology 27: 1611-1621.

Scheffer, M., and S. R. Carpenter. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology and Evolution 18:648-656.

Scheuerell, M.D. and J.G. Williams. 2005. Forecasting climate-induced changes in the survival of Snake River spring/summer Chinook salmon (*Oncorhynchus tshawytscha*). Fisheries Oceanography 14:448-457.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Canadian Journal of Fisheries and Aquatic Sciences 58:18-29.

Schweigert, J.F. 1993. Environmental effects on long-term population dynamics and recruitment to Pacific herring (*Clupea pallasi*) populations in southern British Columbia, p. 569-583, *In* R.J. Beamish, editor. Climate change and northern fish populations. Canadian Journal of Fisheries and Aquatic Sciences Special Publication 121.

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 13:2052-2064.

Seager, R., M.F. Ting, I.M. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, N. Naik, 2007. Model projections of an imminent transition to a more arid climate in Southwestern North America. Science 316:1181-1184.

Seiler, S.M. and E.R. Keeley. 2009. Competition between native and introduced salmonid fishes: cutthroat trout have lower growth rate in the presence of cutthroat-rainbow trout hybrids. Canadian Journal of Fisheries and Aquatic Science 66:133-141.

Selong, J. H., T. E. McMahon, A. V. Zale, and F. T. Barrows. 2001. Effect of temperature on growth and survival of bull trout, with application of an improved method for determining thermal tolerance in fishes. Transactions of the American Fisheries Society 130:1026-1037.

Shepard, B.B. 2004. Factors that may be influencing nonnative brook trout invasion and their displacement of native Westslope cutthroat trout in three adjacent southwestern Montana streams. North American Journal of Fisheries Management 24:1088-1100.

Smith, L.C., Y. Sheng, G.M. Mac Donald, and L.D. Hinzman. 2005. Disappearing arctic lakes. Science 308:1429.

Smol J.P., A.P. Wolfe, H.J.B. Birks, M.S.V. Douglas, V.J. Jones, A. Korhola, R. Pienitz, K. Ruhland, S. Sorvari, D. Antoniades, S.J. Brooks, M.-A., Fallu, M. Hughes, B.E. Keatley, T.E. Laing, N. Michelutti, , L. Nazarova, M. Nyman, A.M. Paterson, B. Perren, R. Quinlan, M. Rautio, E. Saulnier-Talbot, S. Siitoneni, N. Solovieva, and J. Weckstrom. 2005. Climate-driven regime shifts in the biological communities of arctic lakes. Proceedings of the National Academy of Sciences 102:4397–4402.

Spencer, C. N. and F. R. Hauer. 1991. Phosphorus and nitrogen dynamics in streams during a wildfire. Journal of the North American Benthological Society 10:24-30.

Snieszko, S.F. 1974. The effects of environmental stress on outbreaks of infectious disease of fishes. Journal of Fish Biology 6:197-208.

Stapanian, M.A., V.L. Paragamian, C.P. Madenjian, J.R. Jackson, J. Lappalainen, M.J. Evenson and M.D. Neufeld. 2009. Worldwide status of burbot and conservation measures. Fish and Fisheries DOI:10.1111/j.1467-2979.2009.00340.x 1-23.

Stedman, S. and T.E. Dahl. 2008. Status and trends of wetland in the coastal watersheds of the Eastern United States 1998 to 2004. National Oceanic and Atmospheric Administration, National Marine Fisheries Service and U.S. Department of the Interior, Fish and Wildlife Service. 32 pp.

Stefan, H.G., M. Hondzo, X. Fang, J.G. Eaton, and J.H. McCormick. 1996. Simulated long-term temperature and dissolved oxygen characteristics of lakes in the north-central United States and associated fish habitat limits. Limnology and Oceanography 41: 1124-1135.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. Changes toward earlier streamflow timing across western North American. Journal of Climate 18:1136-1155.

Taniguchi, Y., F.J. Rahel, D.C. Novinger, and K.G. Gerow. 1998. Temperature mediation of competitive interactions among three fish species that replace each other along longitudinal stream gradients. Canadian Journal of Fisheries and Aquatic Science 55:1894-1901.

Todd, A.S., M.A. Coleman, A.M. Konowal, M.K. May, S. Johnson, N.K.M Vieira, and J.F Saunders. 2008. Development of new water temperature criteria to protect Colorado's fisheries. Fisheries 33:433-443.

U.S. Climate Action Report. 2006. Fourth National Communication of the United States of America Under the United Nations Framework Convention on Climate Change. http://www.state.gov/g/oes/rls/rpts/car/

U.S. Global Change Research Program (USGCRP). 2009. Global Climate Change Impacts in the United States. Cambridge University Press.

Walther, G. R., A. Roques, P.E. Hulme, M.T. Sykes, P. Pysek, I. Kuhn, M. Zobel, S. Bacher, Z. Botta-Dukat, H. Bugmann, B. Czucz, J. Dauber, T. Hickler, V. Jarosık, M. Kenis, S. Klotz, D. Minchin, M. Moora, W. Nentwig, J. Ott, V.E. Panov, B. Reineking, C. Robinet, V. Semenchenko , W. Solarz, W. Thuiller, M. Vila, K. Vohland and J. Settele. 2009. Alien species in a warmer world: risks and opportunities. Trends in Ecology and Evolution 24:686-693.

Ware, D.M. and G.A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. Pages 359-379 *in* Beamish, R.J., and G.A. McFarlane, editors. Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models. Canadian Special Publication of Fisheries and Aquatic Sciences 108, Ottawa, Ontario.

Wedemeyer, G.A., D.J. McLeay, and C.P. Goodyear. 1984. Assessing the tolerance of fish and fish populations to environmental stress: the problems and methods of monitoring. V.W. Cairns, P.V. Hodson, and J.O. Nriagu, editors. John Wiley & Sons.

Wehrly, K. E., L. Wang, and M. Mitro. 2007. Field-based estimates of thermal tolerance limits for trout: incorporating exposure time and temperature fluctuation. Transactions of the American Fisheries Society 136:365-374.

Weiss, J.L. and J.T. Overpeck. 2005. Is the Sonoran Desert losing its cool? Global Change Biology 11:2065-2077.

Welch, B.L., Y. Ishida, and K. Nagasawa. 1998. Thermal limits and ocean migration of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. Canadian Journal of Fisheries and Aquatic Sciences 55:937-948.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase: Western U.S. forest wildfire activity. Science 313:940-943.

Williams, J.E., A.L. Haak, H.M. Neville, and W.T. Colyer. 2009. Potential consequences of climate change to persistence of cutthroat trout populations. North American Journal of Fisheries Management 29:533-548.

Worm, B., E.B. Barbier, N. Beaumont, J.E. Duffy, C. Folke, B.S. Halpern, J.B.C. Jackson, H.K. Lotze, F. Micheli, S.R. Palumbi, E. Sala, K.A. Selkoe, J.J. Stachowicz, and R. Watson. 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314:787-790.

Zimmer, K.D., M.A. Hanson, and M.G. Butler. 2003. Relationships among nutrients, phytoplankton, macrophytes, and fish in prairie wetlands. Canadian Journal of Fisheries and Aquatic Sciences 60:721-730.