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Climate Change Effects on North American Fish and Fisheries to Inform Adaptation Strategies

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Abstract

Climate change is a global persistent threat to fish and fish habitats throughout North America. Climate-induced modification of environmental regimes, including changes in streamflow, water temperature, salinity, storm surges, and habitat connectivity can change fish physiology, disrupt spawning cues, cause fish extinctions and invasions, and alter fish community structure. Reducing greenhouse emissions remains the primary mechanism to slow the pace of climate change, but local and regional management agencies and stakeholders have developed an arsenal of adaptation strategies to help partially mitigate the effects of climate change on fish. We summarize common stressors posed by climate change in North America, including (1) increased water temperature, (2) changes in precipitation, (3) sea level rise, and (4) ocean acidification, and present potential adaptation strategies that fishery professionals may apply to help vulnerable fish and fisheries cope with a changing climate. Although our adaptation strategies are primarily from North America, they have broader geographic applicability to fish and aquatic biota in other jurisdictions. These strategies provide opportunities for managers to mitigate the effects of climate change on fish and fish habitat while needed global policies to reduce greenhouse gas emissions emerge, which may offer more lasting solutions.

INTRODUCTION

Observed air temperature and other climatic trends provide widespread evidence that global climate is changing and that the changes are caused by humans. Thorough assessments from Canada (Cohen et al. 2019; Poesch et al. 2016); the United States Fourth National Climate Assessment (Reidmiller et al. 2018; Wuebbles et al. 2017), and Mexico (Cavazos et al. 2020; Colorado-Ruiz et al. 2018) summarize key climate observations to date and projected changes within North America (Figure 1, S1, S2). In Canada, annual precipitation has increased since the 1970s, and average annual air temperature rose from 1.7 °C to 2.3 °C (Cohen et al. 2019). In the United States, regional responses to global climate change vary from milder winters in the Northeast to intensifying droughts in the Southwest and increasing storms in the Caribbean and Pacific Islands. In Mexico, annual projections are for increased temperature, with warming particularly during the summer). Overall, precipitation is expected to decrease in Mexico (Cavazos et al. 2020; Colorado-Ruiz et al. 2018), but regional trends are more variable with significant declines expected in northwestern Mexico and increases possible in eastern Mexico (Cavazos et al. 2020).

North American fish and fisheries (which also includes commercially important aquatic invertebrates) are ecologically, culturally, and economically valuable resources. However, to manage fisheries sustainably and conserve fish diversity, managers now need a better understanding of how climate change affects freshwater, estuarine, and marine fish, and the habitats on which they depend is needed to sustainably manage fisheries and conserve fish diversity. This information is vital for managers and policymakers to craft adaptation strategies given a changing climate. Although adaptation strategies remain critical at local scales, it is noteworthy that the trajectory of climate change will persist unless broad-scale policy is enacted to reduce greenhouse gas emissions (Reidmiller et al. 2018; Wuebbles et al. 2017).

Building upon recent syntheses (e.g., the Fourth National Climate Assessment) as well as a July 2016 special issue of *Fisheries* magazine on climate change, we provide a summary of four of the most important climate effects on fish and fisheries through (1) warming water temperatures, (2) changes in precipitation patterns, (3) sea level rise, and (4) ocean acidification, and provide adaptation strategies for common challenges facing lakes and reservoirs, streams and rivers, wetlands, coastal and offshore marine ecosystems, and coral reefs. Our goal is to provide fishery managers and decision makers with a summary of the state of the science on fish and climate change and the “tools” that may be considered to better manage fish and fisheries as these systems change. Our scope is primarily North America, but the climate effects and adaptation strategies likely have applicability globally. We aim to inform climate policy considerations engaged by the public, decision makers, and other groups interested in fisheries and aquatic conservation and management.

WARMING WATER TEMPERATURES

Climate change affects the physiology, life history, phenology, survival, and distribution of fishes and commercially important invertebrates, while also imparting indirect effects through complex interactions with numerous other ecological processes (Table 1). Warming temperatures in combination with other climate stressors can create conditions suitable for biological invasions that may be unsuitable for native biota, and change vital rates such as growth and reproduction, and shift species distributions. For example, the Laurentian Great Lakes are experiencing shorter winters and less ice cover (Assel et al. 2003), leading to warmer surface temperatures (Dobiesz and Lester 2009) and changes in the reproductive phenology (Lyons et al. 2015) and recruitment of Yellow Perch *Perca flavescens* (Farmer et al. 2015). In Southeast Alaska where individual salmonid stocks have adapted life history strategies to the environmental conditions, Pink *Oncorhynchus gorbuscha* and Chum Salmon *O. keta* may migrate to the ocean earlier when food resources are limited (Bryant 2009). In subtropical lakes in south Florida, the distribution of invasive tropical fish has expanded, prompting eradication efforts (Schofield and Loftus 2015) due to their continued spread and exacerbating effects on native fishes, whereas Smallmouth Bass *Micropterus dolomieu* have invaded arctic, alpine, and temperate lakes (e.g., Alofs et al. 2014; Box 1), as well as the Columbia River basin (Rubenson and Olden 2020).

Climate warming can also magnify the effects of nonnative predators on native species with increasing metabolic rates and prey consumption. A global study of climate change effects on marine biota predicts an average 5% future loss of total animal biomass for every 1°C of warming (Lotze et al. 2019). Freshwater ecosystems have similar projections. For example, in the Columbia River Basin, bioenergetics models indicate that a 1°C increase in annual river temperatures may result in about a 5% increase in per capita consumption of salmonids by nonnative Smallmouth Bass and Walleye *Sander vitreus* (Petersen and Kitchell 2001), whereas in the Midwest streams Smallmouth Bass consumption would increase by 27%, but only gain an additional 6% in weight (Pease and Paukert 2014).

Warming water temperature has also increased the prevalence of disease. Warmer temperatures allow disease organisms to complete their life cycle more rapidly and thus attain higher population densities (Marcogliese 2008). *Myxobolus cerebralis*, which causes whirling disease in fish, is an example of a nonnative pathogen introduced from Europe to North America whose impact is likely to increase with climate warming (Rahel and Olden 2008).

Conditions may also become less suitable for native fishes through changes in reproduction, growth, or mortality, in response to climate change. Warmer summer temperatures have been associated with high mortality of adult salmon during upriver migrations and on spawning grounds (Krabbenhoft et al. 2020; Lynch et al. 2016). In lotic systems, end-of-century forecasts for headwater species with cold thermal niches such as Brook Trout *Salvelinus fontinalis* in the eastern USA (Flebbe et al. 2006) and Bull Trout *S. confluentus* in the western USA (Rieman et al. 2007; Ruesch et al. 2012) predict significant declines in habitats with suitable thermal conditions. Marine biota may also experience changes in vital rates due to climate warming. The time to hatching, the larval–juvenile transition, and likely even maturation will occur sooner coupled with smaller ova, smaller hatchlings, and smaller individuals at settlement (Pankhurst and Munday 2011; Whitney et al. 2016). However, not all species, life-stages, and behaviors may respond to temperature in the same way (Angilletta, Jr. and Angilletta 2009). Small increases in water temperature (e.g., 2^{o} C) may alter metabolic rates, population density, and food availability; and reduce maximum size and longevity of some coral reef fish species (Munday et al. 2008).

Climate driven temperature changes can alter population productivity, which may affect the amount of biomass of important fish stocks that can be sustainably harvested. A meta-analysis of marine stock assessment models aggregated for multiple stocks and species worldwide reveals climate change “winners” and “losers” and a net overall loss of sustainable yield of 4.1% from 1930 to 2010 (Free et al. 2019). This net loss may be higher still as Free et al. (2019) included few species from tropical and subtropical waters, where stock assessments are rare but deleterious effects are expected to be more common (Comte and Olden 2017). Even within the United States, only 14% of marine fish and invertebrate stock assessment models explicitly include environmental or oceanographic conditions (Marshall et al. 2019). In the Gulf of Maine, which is warming faster than 99% of the world's oceans (Pershing et al. 2015), climate change may be at least partially responsible for frequent inaccuracies in fishing mortality rates predicted by stock assessments (Wiedenmann and Jensen 2018).

Warming water temperatures have also been linked to coral reef bleaching, which in turn affects coral reef fishes. Ocean temperatures near coral reefs in Hawaii have increased over 1^{o} C in the past 58 years and are expected to increase several degrees C over the next century (Guinotte et al. 2003), which could trigger more mass bleaching events (Strong et al. 2011) and result in ecosystem transformation (Thompson et al. 2021). In Hawaii, warming temperature have already resulted in coral bleaching and mortality rates as high as 50% in some areas. Coral reef assemblages in the Florida Keys recently shifted after 8,000 years of relatively stable composition (Toth et al. 2019). Since the 1980s, mass coral bleaching and mortality have resulted from rising sea temperatures in warm water coral reef systems (Hoegh-Guldberg et al. 2017). In Florida, reef building corals have declined substantially, largely due to rising ocean temperatures, sedimentation, and overfishing.

Climate change has also altered the availability and distribution of thermally suitable habitats and caused shifts in fish species ranges, population productivity, and communities (Comte and Olden 2017; Meisner et al. 1988; Box 2). In the Northeast, northward shifts in the distribution of multiple species has been shown (Kleisner et al. 2017; Nye et al. 2009), with further shifts predicted as ocean warming continues (Morley et al. 2018). In the Bering Sea, warming temperatures and declines in the extent of sea ice have transformed an arctic into a subarctic ecosystem, with evidence that fish populations such as Pacific Cod *Gadus macrocephalus* are moving north (Spies et al. 2019). Kelp forests are critical habitats for nearshore marine fish and fisheries, but kelp community composition along the Pacific coast from Mexico to Alaska has changed with warming temperatures (Beas-Luna et al. 2020), although local stressors and regional variation may be equally important (Krumhansl et al. 2016). Marine fish and invertebrate stocks throughout the USA are shifting in synchrony with climate velocities (Pinsky et al. 2013). Species like Black Sea Bass *Centropristis striata* in Massachusetts (Box 3) or Cobia *Rachycentron canadum* in Chesapeake Bay, once rare in these locations, are now supporting recreational fisheries. By contrast, coral reef communities are becoming less resilient as the climate changes; coral is less likely to recover from major storms, which are expected to increase (Reidmiller et al. 2018), or disease (Hoegh-Guldberg et al. 2017). There is documented evidence that fish species reliant on corals for food and shelter have decreased within 3 years of bleaching events (Hoegh-Guldberg et al. 2017). Consequently, bleached corals may not recover quickly and different species may repopulate, leading to a new associated fish community, novel food webs, and changing energy transfer (Berumen and Pratchett 2006).

Adaptation Strategies

Non-climate related stressors such as harvest, land use, and pollution can all interact with climate to create complex responses to ecosystems and may need to be considered when developing adaptation strategies (Lynch et al. 2016; Staudt et al. 2013). Regulating harvest (Aronson and Precht 2006; Campbell et al. 2020) and designating protected areas (Chung et al. 2019) can benefit freshwater and marine biota (Chu et al. 2017), but they are not a climate change panacea (Graham et al. 2020). Harvesting practices that focus on a diversity of species that demonstrate varying levels of vulnerabilities and sensitivities to climate change may allow systems to be more resilient in the future (Hansen et al. 2015). In some systems such as coral reefs or systems with substantial recreational use understanding how tourism may affect systems (e.g., pollution) provides information on additional stressors beyond climate change. Tourism itself could be an opportunity to educate the public on climate effects to these systems and encourage citizen science as a useful adaptation strategy (Hafezi et al. 2020; McKinley et al. 2017). Therefore, implementing adaptation strategies related to harvest, protected lands, and pollution may be tangible strategies to support climate change adaptation.

One adaptation strategy considered primarily for marine commercial fisheries is the re-tooling of fishing vessels to exploit "new" stocks caused by distributional shifts. However, many smaller vessels have been driven out of business or forced to diversify their target species (Young et al. 2019). As fish distributions continue to shift, more fishing communities in the Northeast and Mid-Atlantic regions of the United States are expected to face this choice between long travel times in search of historically abundant stocks or re-gearing to target new species (Rogers et al. 2019). Management strategies that are responsive to shifting fish distributions, such as changing harvest allocations to better match shifting ranges of transboundary stocks (Pinsky et al. 2018), enhance the flexibility and adaptive capacity of fishermen (Stoll et al. 2017), prioritize ecosystem-based management over single species management (Howell et al. 2021), or capitalize on newly established invasive species, such as Lionfish *Pterois* sp. (Malpica-Cruz et al. 2021), are important components of any climate change adaptation strategy for marine fisheries. Therefore, managing marine fisheries may likely improve through continued development of stock assessment models that better capture the dynamic environment, shifting fish stocks, and its effects on life history and population parameters of fisheries resources.

Prevention and control of harmful invasive species that continue to spread in response to climate change represents an important adaptation strategy (Rahel and Olden 2008). Early detection and rapid response strategies remain critical to prevent or quickly eradicate newly arriving invasive species (Table 1). This include options such as establishing check stations to screen watercraft for invasive species (Fischer et al. 2021), or creating barriers to upstream movement by invasive species that are responding to more favorable thermal conditions (Rahel and Olden 2008). Removal or suppression of invasive species could also increase the resiliency of aquatic systems. For example, the removal of *Phragmites australis* and hydrologic restrictions may benefit impacted salt marshes, provide critical sediment delivery, and improve fish habitat (Dibble et al. 2013; Woodroffe et al. 2016), whereas the removal of sea urchins may allow for native red abalone *Haliotis rufescens* recovery (Rogers-Bennett et al. 2010; Box 4). Liberalized harvest regulations for invasive species expanding due to increasing temperatures is also an option, but the success of these programs has been mixed (Paukert et al. 2021).

One challenge across multiple ecosystems is to moderate increased water temperatures resulting from climate change. Although strategies may vary by system, in streams and rivers thermal regimes downstream of dams may be improved by variable depth (and hence temperature) water releases that mimic seasonal patterns (i.e., natural thermal regimes; Olden and Naiman 2010), and can be cooled by protecting and increasing riparian vegetation that provides shade from direct solar radiation (Lawrence et al. 2014). Water policy decisions that allocate water among reservoirs can alter downstream thermal regimes and may be used as a tool to discourage non-native fish invasion into critically important habitats (Dibble et al. 2021). Improving the physical diversity of river and stream habitats by re-establishing linkages with floodplains and enhancing in-channel complexity with large woody debris may provide greater exchange with cooler hyporheic waters and microrefugia for fish use during periods of extreme heat. In addition, options for moderating extreme thermal regimes and concurrent environmental co-stressors in marine systems include minimizing the addition of excess nutrients such as nitrogen, which increased the severity of coral bleaching (Donovan et al. 2020), or reduction in thermal effluent to estuaries, reducing activities that lead to eutrophication and hypoxia, and lessening releases and spills of toxicants (Baumann 2019; Rogers-Bennett and Catton 2019).

Augmenting populations that face risks from climate change may also be feasible for some taxa through stock enhancement and assisted migrations (Molony et al. 2005; Ronald and Mia 2000). Creating diverse habitats or creating biologically robust populations through stocking, particularly when natural recruitment may be limited, could be a viable alternative to create diverse stocks that may be more resilient to climate change (Hansen et al. 2015), although an understanding of the ability of new habitat to support the translocated fish needs to be considered (Berger-Tal et al. 2020). However, long-term husbandry of freshwater fish populations may play an increasingly important conservation role in the future, and managed relocations of wild populations to locations projected to be suitable in the future but are currently unoccupied may need to be considered (Olden et al. 2011).

CHANGES IN PRECIPITATION

Changes in precipitation timing and intensity may have substantial effects on fish and aquatic biota in lakes, wetlands, and streams through loss of connectivity, changes in lake size and depth, habitat diversity, and disruption of spawning cues (Table 2). Increased evaporation, coupled with decreasing runoff from lessening snowpack in higher elevations, may reduce the size and depths of high elevation lakes (Adrian et al. 2009), whereas changes in precipitation may lead to increased salinity and decreased water levels in Great Plains lakes. Fish communities in this region are structured along a gradient of salinity, and endemic fish species already close to their thermal and saline limits are at risk (Covich et al. 1997). In addition, endemic fishes are found in many lakes in the western USA and the desert Southwest (Dickerson and Vinyard 1999), and future water levels may depend on the balance between evaporation, snowmelt/precipitation runoff, and water withdrawals from the system. In lotic systems and wetlands, instream flows are considered a master variable that dictated many life history triggers including reproduction (Poff et al. 1997).

Disruption of flows due to changes in precipitation is one of the primary concerns of how climate change may affect stream and river fish. Hydrologic connectivity is key to determining whether and how species will be able to sufficiently track changing climate. For example, more frequent and severe droughts associated with climate change may alter patterns in zero flow days and hydrologic connectivity in dryland streams of the American Southwest, leading to reduced opportunities for native fish to access spawning habitats and seasonally available refuges (Jaeger et al. 2014). Climate tracking of many warm-water Midwest fish was limited by unsuitably steep channels and changes in habitat conditions across a mountain–plains transition zone (Gibson-Reinemer et al. 2017). Similar limitations to fish dispersal in response to climate change are created by anthropogenic impediments in rivers and streams such as dams and water diversions that often lack adequate fish passage facilities (LeMoine et al. 2020).

In addition, linkages among climate change, salinity, and osmoregulation can also influence fish species distributions and local abundances. For example, the abundance of stenohaline fish in the Rio Grande River decreased from the 1970s to the 2010s, a result partially explained by a decreasing trend in heavy precipitation events that previously diluted salinity concentrations (Miyazono et al. 2015). Climate-induced changes to river flows and temperature have also resulted in changes to both upstream and downstream migration dates of warm-water species such as freshwater eels *Anguilla* spp. (Drouineau et al. 2018) and Striped Bass *Morone saxatillis* (Peer and Miller 2014).

Changes in precipitation patterns from climate change coupled with other stressors can manifest through changes in water quality. Shallow temperate lakes may transition from clear to turbid states as nutrient loading increases from intense precipitation (Scheffer and van Nes 2007), resulting in a loss of macrophyte habitats which can decrease sport fish production (Johnson et al. 2014). In wetlands along the Laurentian Great Lakes, terrestrial organic carbon loading rates have increased due to higher precipitation (Solomon et al. 2015). Similar increases have been shown to decrease secondary production in many lakes of the United States (Leech et al. 2018). In temperate lakes of Minnesota, for example, fish abundances have declined where longer durations of stratification have negatively affected oxythermal habitat (Jacobson et al. 2012). Conversely, increased colonization beaver *Castor canadensis* and thawing of permafrost from climate change have modified tundra stream dynamics and increased lake and wetland area under recent warm, wet conditions (Tape et al. 2018). Ultimately, these changes in fish communities from climate change may lead to loss of native fishes and reduced the diversity of fish communities.

Adaptation Strategies

Protecting least disturbed habitats and restoring habitat connectivity and diversity is an essential climate adaptation strategy for aquatic systems (Table 2; Erwin 2009; Tingley et al. 2019). Although reducing water withdrawals may be appropriate when declining lake levels is a concern (Magee et al. 2019), many measures extend beyond the waterbody by also focusing on enhancing and protecting watershed processes (Schindler 2009). Therefore, identifying areas for barrier removal (e.g., obsolete dams) to allow for connectivity, while also identifying where best management practices to control excessive nutrients may be useful (Johnson et al. 2014; Solomon et al. 2015); such management has led to more resilient lakes for cold-water fish that require high quality oxythermal habitat (Jacobson et al. 2013). However, increased connectivity may not be universally positive as this may facilitate invasive species (Jones et al. 2021). Decision support tools that identify these stressors to determine when and where conservation efforts are best invested will continue to be important, because needs will undoubtedly outstrip limited resources (Peterson et al. 2013; Tingley et al. 2019)

The translocation of fishes may also be considered an adaption strategy, but careful consideration of the effects of the donor population on the receiving ecosystem may need to be considered before implementation. In systems where translocation may be feasible, employing hatchery practices to provide sufficient genetic diversity that mimic wild populations, or have phenotypes that exhibit different life history strategies, will be critical to create more resilient fish populations (Olden et al. 2011). Therefore, decision support tools that consider the risk and benefits to the donor and receiving ecosystem (Galloway et al. 2016), while also being prepared with emergency action plans to rescue fish during droughts (Beebe et al. 2021) can be useful to help managers decisions if managed relocation may be feasible option.

Streamflow is considered a master variable in structuring lotic systems so efforts to restore natural flows provides a useful strategy that can have multiple benefits (Poff et al. 1997). Supporting natural hydrologic regimes through reducing agricultural tiling and water diversions, reducing the flashiness of flows in urban areas, modifying dam releases to mimic natural flows to trigger spawning, and restoring wetlands and riparian zones will help offset the effects of changing precipitation patterns. Nature-based solutions such as restoring beaver dams have also been used to restore streamflow and connectivity (Ronnquist and Westbrook 2021). Wetland restoration may help mitigate negative effects related to climate change, however, such actions are dwarfed in comparison to the already significant loss of natural wetland habitat across North America (Mitsch and Hernandez 2013). Nonetheless, lateral connectivity with floodplains and/or marshes, restoring native vegetation and woody debris (Beechie et al. 2013), and mimicking seasonal thermal and flow patterns can partially offset the deleterious effects of climate change.

SEA LEVEL RISE

Climate change is affecting coastal and estuarine fish and fish habitat in a variety of ways that can be somewhat unique to marine systems (Table 3). The combination of lengthy coastlines on the Atlantic (22.5 degrees of latitude, 3,300 km) and Pacific (38.3 degrees of latitude, 6,200 km) coasts of North America, and their largely north–south orientation supports a range of biomes from the subtropics to the Arctic.

Sea level rise will continue to intensify the effect of hurricanes and storms (Vitousek et al. 2017) and may result in lower water quality from increased turbidity and the disturbance and resuspension of coastal contaminants (Byrnes et al. 2011). Models predict a 46–59% loss of global coastal wetlands by 2100 due to climate-induced rising sea levels of 0.5 m (Spencer et al. 2016). Mangroves provide nursery habitat to reef-dwelling fish and are vulnerable to sea-level rise in areas with high coastal development and low sediment sources to support landward migration and vertical accretion (Woodroffe et al. 2016), which is the largest climate threat to mangroves (Gilman et al. 2008), and may eventually lead to large-scale marsh drowning, vegetation dieback, and coastal erosion (Osland et al. 2016; Thorne et al. 2018). Coastal lagoons, a prominent feature along the Pacific and North Atlantic coastlines, provide high-quality habitat for threatened and endangered species such as steelhead *Oncorhynchus mykiss*. These systems are influenced by sea-level rise, frequency and intensity of storms that breach the lagoons (leading to fish kills), and declining freshwater inflows (Anthony et al. 2009; Hayes et al. 2008). These studies show the importance of these ecosystems to fishes, and that adaptation strategies for these systems may be critical as the climate changes.

Adaptation Strategies

There are several adaptation strategies to combat climate change effects on nearshore marine habitats and aquatic biota (Table 3). Protecting mudflats and marshes can help protect infrastructure and people during low-category hurricanes and coastal flooding (Gittman et al. 2014; Narayan et al. 2017). The dense vegetation combined with nature-based structures like oyster reefs can act as a coastal defense by attenuating wave energy, accreting sediment (which is also a large carbon sink), and stabilizing shorelines (Gittman et al. 2014; Narayan et al. 2017; Roberts et al. 2017). In addition, connecting freshwater sources to downstream deltas may provide sediment sources for marshes and mangroves, and provide buffering capacity to extreme events such as hurricanes (Ellison 2015). Manual application of fine sediment to marshes and mangroves or facilitating marsh migration are other adaptation strategies (see case studies in

Lynch et al. 2016). Finally, working with local governments to modify zoning laws to minimize coastal development may be another option (Powell et al. 2019).

OCEAN ACIDIFICATION

By the end of the century, ocean pH may decrease by 0.4 to 0.5 units (Raven et al. 2005), which reduces the available carbonate needed to build coral reef structures (Hoegh-Guldberg et al. 2017). These changes in dissolved oxygen and CO_2 form the basis of ocean and coastal acidification, which can affect the survival, growth, reproduction, and calcification of marine organisms (Table 4; Kroeker et al. 2010) and even auditory behavior (Radford et al. 2021). These changes are further amplified by the diverse set of factors from human activities located along the nearshore environment or in rivers and streams that flow into estuaries (e.g., increases in eutrophication, impervious surfaces, and shoreline hardening; pollution, physiological disruptors, and agricultural run-off; and general habitat degradation and fragmentation). Increased acidification coupled with increased nitrogen can promote growth of boring sponges that erode coral reefs (Zhao et al. 2021). Acidification can increase the food availability for some fishes, but at the same time it also increases their reproductive investment (Nagelkerken et al. 2021). These responses show the complex interactions among climate change and other stressors. However, because corals are sensitive to the effects of climate change, they can be early warning indictors for climate related effects (Kayanne 2016).

Adaptation Strategies

Adaptation strategies to combat ocean acidification are challenging, particularly when they are combined with other stressors like eutrophication (Wilson et al. 2020). Recent reviews of climate effects on coral reefs indicate a rapid reduction in greenhouse gas emissions that stabilize global temperatures and CO_2 is the only viable long-term solution for ensuring survival of coral reefs (Hoegh-Guldberg et al. 2017; Munday et al. 2008). However, mitigating the effects of other stressors such as curtailing nitrogen (e.g., from coastal development in Mexico; Rioja-Nieto and Álvarez-Filip 2019) may be beneficial if bleaching has not severely damaged the coral (Zhao et al. 2021). Maintaining seagrass can also help protect coral reef habitats from ocean acidification (Table 4; Liu et al. 2020). For shellfish, aquaculture has been considered a possible adaption strategy because in facilities pH can controlled (Wilson et al. 2020). Similar to strategies for sea level rise, managers can cultivate a diversity of habitats that may establish unique populations and broaden the gene pool which may help the systems adapt to ocean acidification.

CONCLUSIONS

Adaptation strategies are recognized as stopgap actions and not the ultimate solution to mediate climate change effects on aquatic ecosystems. The overarching issues of increased greenhouse gas emissions from fossil fuels, deforestation, and land use change are the primary causes of climate change, thus necessitating policies that reduce greenhouse gas emissions both today and in the future (Reidmiller et al. 2018). However, the adaptation strategies summarized here provide more localized and actionable options to help fisheries professionals address effects from climate change on freshwater and marine fish and fisheries as policies to reduce greenhouse gas emissions evolve and continue to be considered (Thompson et al. 2021).

Although some climate change stressors may be system-specific, many of the stressors and adaptation strategies are common across marine and freshwater environments. For example, changes in water temperature may provide more suitable conditions for the spread of invasive species in freshwater lakes and rivers (Rahel and Olden 2008), and in marine systems such as estuaries (Woodroffe et al. 2016). In addition, mechanisms to identify and prioritize water bodies that are vulnerable to climate change effects are valuable regardless of the system (Tingley et al. 2019). However, we also recognize that all adaptation strategies are not created equal, and some strategies may be difficult to implement (e.g., eliminate water withdrawals, remove large dams, create lateral connectivity to floodplains), or require multiple stakeholders (implement best management practices in watersheds, increase cooperation across multiple jurisdictions) or may affect livelihoods (re-gear commercial fishing vessels), or may face complex economic, political, or cultural issues of a region (Vázquez 2017). Though surely not fully comprehensive, our hope is that these adaptation strategies provide options for policymakers and fisheries managers to consider when addressing climate change within their mandates.

Substantial uncertainties persist with climate science, and communicating this uncertainty to the public and policymakers remains challenging (Juanchich et al. 2020). Many climate change and fisheries studies focus on modeled projections of how fish distributions (or other parameters) may change under various emissions scenarios. However, modeled projections may have more uncertainty and may need to be corroborated with observed effects (Lynch et al. 2016). Although modeled projections continue to emerge, we now have the ability to use long-term monitoring data to examine and document how climate change has already affected fisheries. These data can be used to validate additional models and provide more data-driven evidence of climate change. In a recent literature review, there were at least 87 peer-reviewed studies (71 since 2010) that documented how climate change affects inland fish alone (Krabbenhoft et al. 2020). These documented changes have less uncertainty than projected changes and are therefore easier to communicate to communities, stakeholders, and policymakers when conveying climate change effects on fish or seeking buy-in for adaptation (Lynch et al. 2016).

Resources to help scientists and other stakeholders communicate the implications of climate change for fish and fisheries are needed. Audiences are diverse, and so must be our messaging strategies. Communicating with stakeholders (e.g., angler groups) to temper expectations may be useful as managers cope with societal and economic shifts in angler behaviors due to other factors (e.g., higher transportation costs to fishing destinations, diversity of water demands of lake and rivers; Hunt et al. 2016). Communication tactics may include personal stories (Gustafson et al. 2020) and a variety of media types that include the arts (Bentz 2020) and film (Banchero et al. 2020). Working with communication professionals is a useful direction to consider. The American Fisheries Society has developed a website specifically about climate change that provides suggestions on communication (available: https://bit.ly/35TXe97). The AFS Climate Ambassadors Program is a training program for aquatic scientists to develop communication skills specifically for climate science (available: https://bit.ly/3xSA1yn). Resources like these programs may be a useful tool for scientists to better communicate about climate effects to non-scientists.

Evaluation of how climate adaptation strategies achieve desired outcomes is needed to better identify successful future approaches. The effects of climate change on fish and fisheries are often synergistic with other stressors (Lynch et al. 2016; Murdoch et al. 2020; Staudt et al. 2013). This issue, although challenging, is not uncommon in ecological studies, and similar strategies to control for variation or "noise" for ecological studies may also be considered for climate change adaptation strategies. However, long-term monitoring to evaluate climate change adaptation strategies (which may need to cross interjurisdictional boundaries; (Beas-Luna et al.

2020) and provide sufficient data to tease out other stressors will help provide more certainty in our management actions and can help identify more robust management actions moving forward.

Climate change is a global issue and there are global efforts to help inform policymakers on how best to respond. AFS, in conjunction with over 110 aquatic scientific societies representing over 80,000 scientists, announced a Statement on Climate Change that provides information that can help inform policymakers on actions that can help reduce climate change and its effects on aquatic biota (this issue; available: https://bit.ly/3mtQFAr). This effort also lends voice to that unifying chorus of aquatic scientific societies who recognize the dramatic ways that climate change is impacting and will continue to impact fish and fisheries across the globe. Partnerships among these and other organizations and agencies may be needed to maximize the effectiveness of adaptation strategies, particularly where fish and fisheries transcend interjurisdictional boundaries. Partnerships may also cultivate more creative and inclusive solutions when identifying potential funding sources for climate adaptation strategies (Paukert et al. 2016; Tingley et al. 2019). In addition, developing governance structures that are able to train staff and adapt management under climate change can support these current and future challenges.

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Table 1. Summary of climate change effects of marine and freshwater biota from warming water temperature with potential adaptation strategies for each effect.

CLIMATE EFFECTS & ADAPTATION STRATEGIES	FRESHWATER SYSTEMS			MARINE SYSTEMS		
Warming Water Temperatures	Lakes & reservoirs	Freshwater wetlands	Streams & rivers	Estuaries & coasts	Coral reefs	Offshore
Changes in native fish vital rates such as reproduction, growth, and mortality						
Leverage tourism to promote citizen science	●	●	●	●	●	●
Use Ecosystem Based Management instead of single stock management	●	●	●	●	●	●
Maintain or create large and diverse essential habitat that broadens the gene pool	●	●	●	●	●	●
Enhance buffering capacities of population through stocking species with limited recruitment	●	●	●	●	●	
Protect/increase riparian vegetation for shading	●		●			
Enhance instream water exchange with cool hyporheic flows to develop local microrefugia			●			
Deploy variable depth releases at deep storage reservoirs to approximate natural thermal conditions or reduce temperatures during thermally stressful periods			●			
Distribution shifts of fish species or guilds, often across political boundaries						
Implement protected areas to restore ecosystems and support the growth of important species	●	●	●	●	●	●
Use fishing regulations to increase harvest of warmwater winners and reduce harvest of coldwater losers	●	●	●	●	●	●
Identify resilient systems and protect critical undisturbed lands within watersheds	●	●	●	●		
Develop dynamic harvest allocation mechanisms that re-allocate quota to states, countries, or other jurisdictions on the receiving end of shifting fish stocks				●		●
-ntegrate dynamic environmental variables and range shifts in stock assessments				●		●
Re-gear fishing vessel to target new species at the leading edge of their shifting range				●		●
Conditions suitable for nonnative species						
Activate early detection and response or eradication processes to minimize introductions and establishment of nonnative species	●	●	●	●	●	
Use fishing regulations to increase harvest of nonnatives or restrict nonnative introductions through permitting	●		●	●	●	
Establish check stations at waterways and travel corridors to screen watercraft for invasive species	●		●			
Create barriers to upstream movement by nonnative species where feasible to decrease connectivity			●			
Remove nonnative vegetation to increase the resiliency of systems				●		

Table 2. Summary of climate change effects of marine and freshwater biota from changes in precipitation with potential adaptation strategies for each effect.

CLIMATE EFFECTS & ADAPTATION STRATEGIES	FRESHWATER SYSTEMS			MARINE SYSTEMS		
Changes in precipitation	Lakes & reservoirs	Freshwater wetlands	Streams & rivers	Estuaries & coasts	Coral reefs	Offshore
Loss of connectivity, habitat diversity, or variable water levels						
Identify locations with the capacity to support local populations (and identify donor populations) via managed relocation and serve as climate refugia	●	●	●	●	●	
Identify potential donor populations with surplus individuals to support managed relocation actions	●	●	●	●	●	
Implement watershed nutrient Best Management Practices and restore water retention capacity	●	●	●	●		
Eliminate water withdrawals that critically threaten water supplies	●	●	●			
Increase lateral connectivity between floodplains, rivers, and streams	●	●	●			
Restore watershed hydrology by restoring wetlands and reducing agricultural tiling and draining	●	●		●		
Screen water diversion intakes to prevent fish entry and mortality		●	●	●		
Remove obsolete dams and barriers so fish can access suitable habitats		●	●			
Protect shallow or isolated basins, and reduce anthropogenic connectivity among basins	●					
Protect and restore native vegetation to reduce sediment erosion and dampen hydrologic fluctuations	●					
Add large woody debris to streams or allow natural recruitment of woody debris to increase channel roughness			●			
Limit overgrazing by livestock to encourage healthy riparian conditions that provide cover for fish			●			
Develop emergency plans for use during heat waves to capture and transport fish to suitable habitats or temporary occupancy of hatcheries			●			
Restore beavers and establish sustainable colonies where feasible			●			
Remove impediments to tidal inundation of salt marshes, and downstream movement of freshwater and inorganic sediment, to increase the health of and sediment accumulation in salt marshes				●		
Saltwater intrusions into freshwater wetlands						
Few available beyond local engineering solutions	●					
Disruption of natural hydrological regime						
Encourage efficient irrigation and water storage facilities to minimize water diversions		●	●			
Develop/maintain instream flows so aquatic biota are not adversely affected by acute flow declines			●			
Minimize "flashiness" from urban runoff by use of best practices and permeable surfaces			●			
Changes in water quality from increased nutrient loading						
Implement meaningful agricultural and urban Best Management Practices and protect undisturbed lands in watershed	●	●	●	●		
Disruption of spawning cues						
Understand environmental cues for reproductive phenologies and adaptive behavior	●	●	●	●	●	●
Time the release of water from reservoirs to mimic seasonal flow patterns downstream			●			
Reduced biodiversity through loss of native species						
Encourage management actions that promote phenotypes which use a diversity of habitats and exhibit different life histories (e.g., resident populations and migratory populations)	●	●	●	●	●	●
Employ hatchery practices that maintain genetic diversity observed in wild populations	●	●	●	●		

Table 3. Summary of climate change effects of marine and freshwater biota from sea level rise with potential adaptation strategies for each effect.

CLIMATE EFFECTS & ADAPTATION STRATEGIES	FRESHWATER SYSTEMS			MARINE SYSTEMS		
Sea level rise	Lakes & reservoirs	Freshwater wetlands	Streams & rivers	Estuaries & coasts	Coral reefs	Offshore
Loss of salt marsh, sea grass and mangrove habitat						
Work with local governments to revise zoning laws (or land purchases or agreements) to decrease coastal development adjacent to habitats of importance to fisheries						
Reduction of sediment sources from shoreline development						
Reconnect freshwater sources to downstream deltas to provide sediment sources for marshes and mangroves to counteract sea level rise						
Manually apply fine sediment to marsh or mangrove surfaces to assist in vertical accretion						

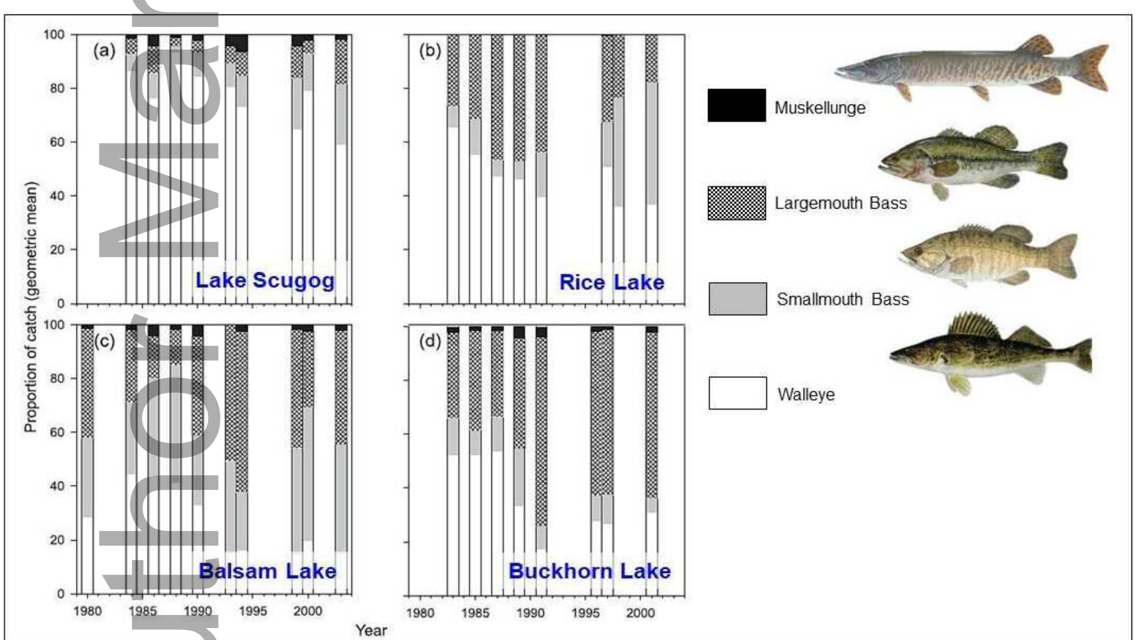
Table 4. Summary of climate change effects of marine and freshwater biota from ocean acidification with potential adaptation strategies for each effect.

CLIMATE EFFECTS & ADAPTATION STRATEGIES	FRESHWATER SYSTEMS			MARINE SYSTEMS		
Ocean acidification	Lakes & reservoirs	Freshwater wetlands	Streams & rivers	Estuaries & coasts	Coral reefs	Offshore
Reduced calcification of marine organisms						
Maintain intact seagrass to protect coral from disease and ocean acidification						

Box 1. Shifts in predatory fish catches in Ontario lakes.

Warming of lakes due to climate change has resulted in shifting species composition of fish communities. In Central Ontario, Canada, four predatory fish species have demonstrated shifts in abundance (based on mean of the proportion of each species in the catch) from cool-water (Walleye *Sander vitreus* and Muskellunge *Esox masquinongy*) to warmwater (Smallmouth Bass *Micropterus dolomeui* and Largemouth Bass *M. salmoides*) species from 1980 to 2003. These changes were associated with reductions in phosphorus concentration, increases in water clarity, and summer temperature (Robillard and Fox 2006).

Figure B1. Catch-per-unit-effort of predatory fish species in four lakes of central Ontario, Canada, showing the shifts in abundance from coolwater (Walleye and Muskellunge) to warmwater (Smallmouth Bass and Largemouth Bass) species from 1980 to 2003.

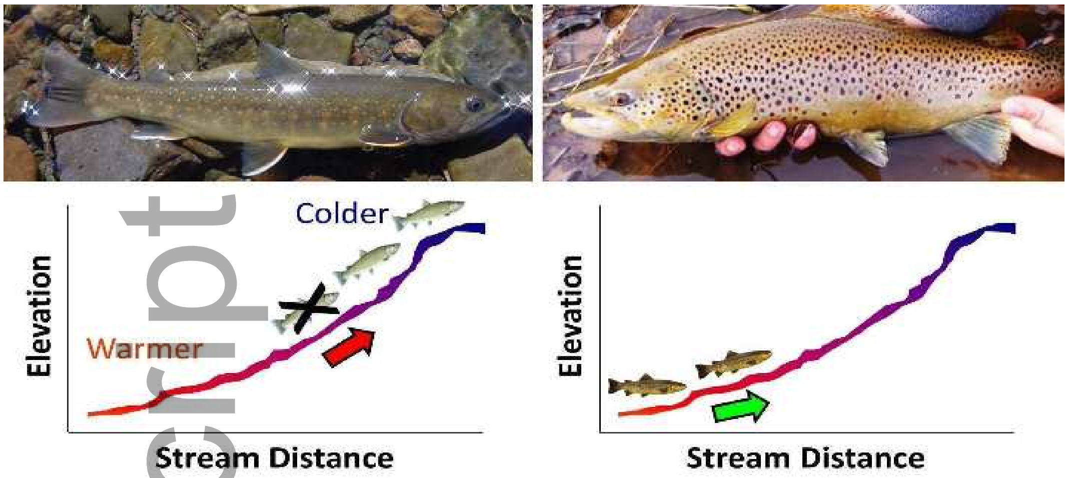


Box 2. Distribution shifts of trout populations in cold-water rivers

Numerous studies predict future shifts in spatial distributions of riverine fish species caused by climate warming, but few case histories exist to validate these predictions (Comte et al. 2013).

Long-term monitoring studies in western Montana confirm that distribution shifts of trout have already begun in association with historical river warming trends (Isaak et al. 2018). One study, which revisited stream survey sites 20 years after original surveys were conducted in the 1990s, documented the loss of Bull Trout *Salvelinus confluentus* from 17 of 74 sites that were originally occupied (Eby et al. 2014). Site extirpations were significantly related to local stream temperatures and were most common at sites with the warmest temperatures near the downstream range boundaries of Bull Trout. As Bull Trout contract into headwaters their population sizes also decrease, and fragmentation among populations increases, thereby increasing the risks of local population extinctions due to environmental stochasticity (e.g., wildfires, floods, droughts). Documented upstream distribution shifts in populations of Brown Trout *Salmo trutta* that were previously limited by unsuitably cold headwater temperatures have also been observed in Montana (Al-Chokhachy et al. 2016). Brown Trout are a popular sport fish, so expanding populations may provide additional angling opportunities, but they are also a nonnative invader and top-level predator that prey on native species and may alter the structure of aquatic communities. As this example illustrates, climate change can result in very different outcomes for closely related species that occupy the same stream networks, and this will stimulate complex human social responses that require nuanced conservation and management policies (Lamborn and Smith 2019).

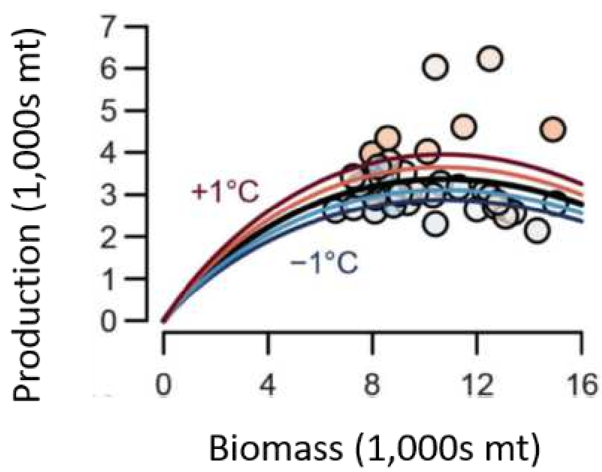
Figure B2. Bull Trout in western Montana have cold thermal niches and are confined to the coldest streams in the headwaters of mountain river networks. As streams have warmed in recent decades, population boundaries at the downstream extent of Bull Trout distributions have contracted further upstream (left panel). Distributions of Brown Trout, which has a warmer thermal niche, have simultaneously expanded upstream in many rivers (right panel; photo credits: bull trout, Bart Gamett; brown trout, Brett Roper).



Box 3 –Black Sea Bass shifting distributions and increased productivity demonstrate challenges even for climate change "winners."

The northern stock of Black Sea Bass *Centropristis striata* has emerged as one of the climate change "winners." Their productivity appears to have increased with ocean warming (Free et al. 2019) and their geographic distribution has expanded northward (Bell et al. 2015), where more of the bottom is made up of the hard, structured habitat the species prefer. Black Sea Bass abundance in 2015 (the most recent year in the stock assessment model) is estimated to have been near an all-time high and well above the spawning stock biomass associated with maximum sustainable yield (Northeast Fishery Science Center 2017). However, with the growth and expansion of the population have come conflicts and management challenges. The newfound abundance of Black Sea Bass in the northern portion of their range in Rhode Island and Massachusetts has created new recreational fishing opportunities. However, allocation of the allowable catch among states is based on historical landings. Thus, anglers in New England have limited access to this new resource. So far, no acceptable mechanism has been found to shift allocations as the stock distribution shifts. This disconnect between the geographic distribution of the stock and the allocation of catch has created discontent among anglers and pressure to reform the management system. Additionally, and perhaps more problematically, the Black Sea Bass stock increasingly overlaps with the distribution of American lobster *Homarus americanus*, which support some of the most valuable U.S. fisheries (Le Bris et al. 2018). As Black Sea Bass are omnivores, reports of juvenile lobster in their stomachs have raised concerns that their range expansion may come at a cost to a more valuable fishery.

Figure B3. The estimated effect of temperature on the U.S. northern stock of Black Sea Bass. Blue and red points represent cooler- and warmer-than-average years, respectively. Black lines show production at the populations' average temperature. Blue and red lines show production at temperatures progressively cooler and warmer than average, respectively (–1.0°, –0.5°, +0.5°, and +1.0°C). mt = metric tons. Reprinted from Free et al. 2019.




Sunflower Stars


Purple Sea Urchin


Red Abalone

Box 4. Northern California bull kelp forests turn to urchin barrens closing abalone fishery.

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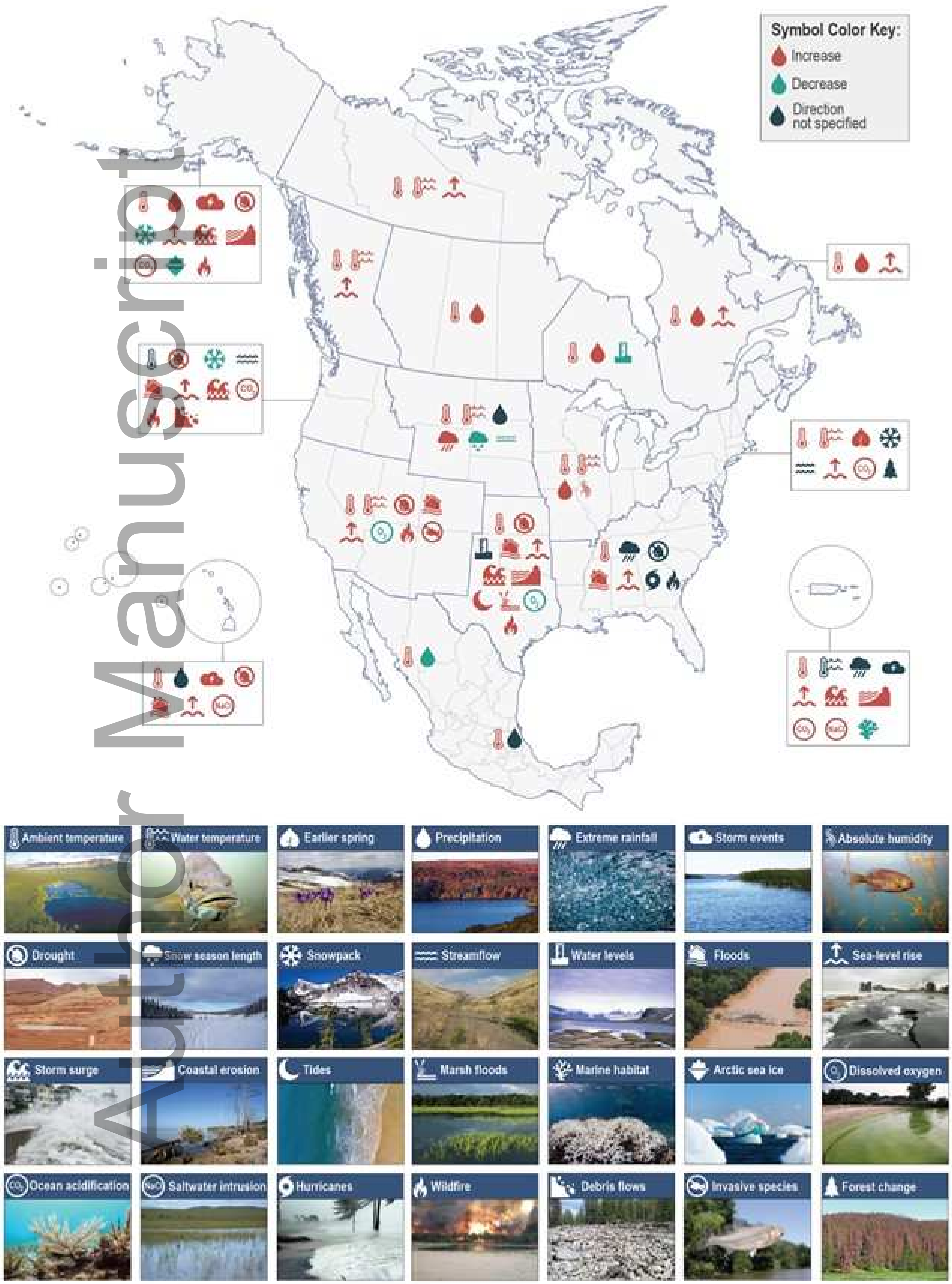
Kelp forests provide a wide range of ecosystems services including habitat and food resources for important fisheries (Carr and Syms 2006). Historically, bull kelp *Nereocystis luetkeana* supported strong fisheries including red abalone *Haliotis rufescens* and red sea urchins *Mesocentrotus franciscanus* (Reid et al. 2016). In 2013, a record-breaking marine heat wave (MHW) hit the northeastern Pacific Ocean, spreading from Alaska south to Baja California, leading to declines of offshore marine populations and ecosystems (Di Lorenzo and Mantua 2016). Harmful algal bloom associated with the warm MHW water further increased the number of mass mortalities in marine mammals and birds, as well as prolonged fishery closures (McCabe et al. 2016). In California, the low nutrient warm water (2.5^{o}C warmer than average) persisted for 226 days, the longest MHW ever recorded (Bond et al. 2015; Di Lorenzo and Mantua 2016).

Bull kelp forests in northern California (350 km range) were particularly vulnerable to the MHW and concurrent ecological stressors. The mass decline of bull kelp in 2014 coincided with the onset of MHW conditions. Kelp canopy in the region exceeded 50 km^2 in 2008, declined to less than <2 km^2 in 2014; there has been no appreciable recovery since (Rogers-Bennett and Catton 2019). In addition to the MHW and El Niño oscillation, a mass mortality of 20 sea star species decimated sea star populations along the entire northern California coast. Sunflower stars *Pycnopodia helianthoides*, an important sea urchin predator, were driven to probable extirpation, leading to a 60-fold increase in the historically low-density species of purple sea urchins *Strongylocentrotus purpuratus* (Rogers-Bennett and Catton 2019). When bull kelp communities did not recover in 2015, purple sea urchins exhibited a more aggressive feeding behavior associated with food limited environments (urchin barrens) grazing down stipes of kelps and fleshy algae, further exacerbating the urchin barren problem (Rogers-Bennett and Catton 2019).

As food limited conditions persisted, red abalone experienced prolonged starvation, which initiated a mass mortality event (Rogers-Bennett and Catton 2019) and closure of the fishery in northern California and Oregon in 2018. The starvation conditions are further exacerbated by warm water, leading to poor health and reproduction in red abalone (Rogers-Bennett et al. 2010). Even if kelp recovers from these multiple stressors, it could take decades to recover the complex biologic communities and their ecosystem services. Kelp forests are historically persistent, which makes the speed (1 year), scale (>300 km), and magnitude (>90%) of bull kelp loss incredible (Rogers-Bennett and Catton 2019). The severity demonstrates the need to understand how multiple stressors and climate effects change the vulnerability of marine ecosystems.



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