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

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INTRODUCTION

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

WATER TEMPERATURE INCREASE IN SURFACE WATERS

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

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

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

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

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

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

HYDROLOGY-RELATED WATER QUALITY CHANGES

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

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

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

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

**DISSOLVED ORGANIC CARBON AND METAL PROBLEMS AS AIR EMISSIONS CHANGE**

Air emission of CO$_2$, SO$_2$, and NO$_x$ can affect water quality through the change in precipitation chemistry. For instance, when the emission of SO$_2$ is increased, more SO$_4^{2-}$ will be available in receiving water bodies, reducing pH in the water. One chemical within water bodies that appears to be increasing as a result of a combination of declines in acidification, as well as increasing temperatures, is dissolved organic carbon (DOC; Evans et al. 2005). Increasing pH and decreasing aluminum in water bodies recovering from acidification also have been accompanied by increasing DOC (Lawrence et al. 2013), which partially offsets pH increases and complicates assessment of recovery from acidification. DOC change affects drinking water quality, metal and organic contaminant transport and toxicity, nutrient availability, and attenuation of solar radiation (Erlandsson et al. 2011).

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

**CONCLUSIONS**

In summary, global climate change is predicted to change air temperature; precipitation; emissions of CO$_2$, SO$_2$, and NO$_x$; and other aspects. These changes are expected to lead to increased water temperatures (in most cases), decreasing dissolved oxygen concentration, altered water chemistry and chemical loads, and, in certain regions, create new water quality challenges including increased dissolved organic carbon and toxic metal loads. As fishery professionals, we suggest the need to be proactive and anticipate these changes to allow for adaptation in fisheries management and conservation.

**REFERENCES**


Figure 2. A typical small, shallow fish pond in the Lower Mississippi River Basin. Photo credit: Yushun Chen.


