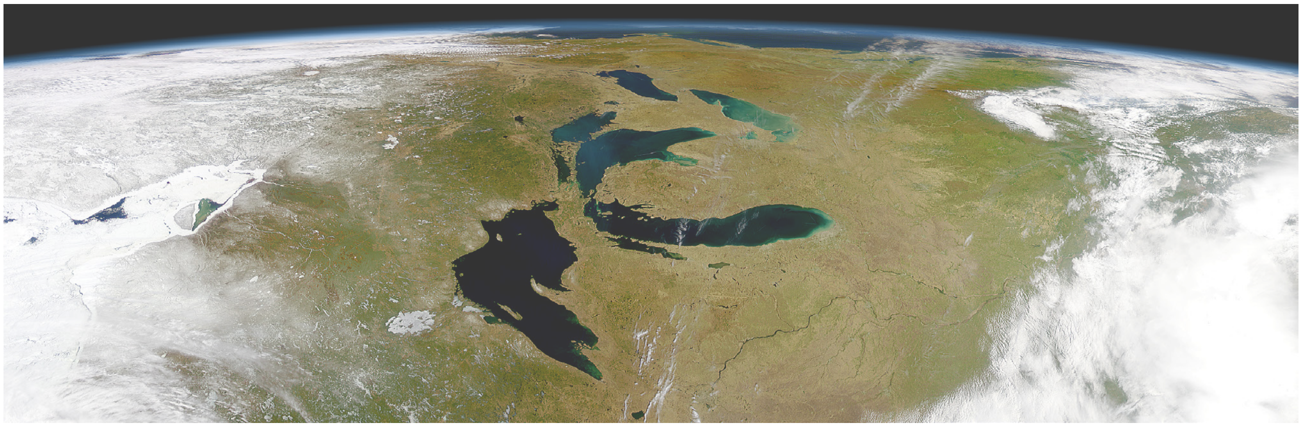

11. Great Lakes Region Acidification Research

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Abstract

The Great Lakes Region includes Lake Superior, Michigan, Huron, Erie, and Ontario representing a combined lake surface area of 244,000 km^2. Acidification in the Great Lakes Region is predicted to occur at a rate similar to the oceans as a result of anthropogenic carbon emissions. In the Great Lakes, pH is also influenced seasonally and spatially by local primary productivity and historical impacts from acid deposition associated with poor air quality. This region supports culturally and economically significant fisheries and recreational tourism that create significant income for the regional and U.S. economy. NOAA's Great Lakes research goals include:

- Establish a monitoring network that is designed to detect trends in pH and carbonate saturation states, taking into account the considerable spatial and temporal variability;
- Conduct research to understand the sensitivity of dreissenid mussels, plankton, fish, and other biota to changes in pH and carbonate saturation states, including early life stages;
- Develop physical/biogeochemical and food-web models that can project the impacts of changing pH and carbonate saturation states on important ecological endpoints, including plankton community composition and productivity, nuisance and harmful algae, dreissenid mussels, and fish; and
- Engage stakeholders in the process of evaluating impacts in order to identify research topics, communicate research findings, and develop mitigation and adaptation strategies.

Acidification in the Great Lakes Region

The Great Lakes are the largest freshwater system on Earth, holding 95% of the U.S.' and 20% of the world's surface freshwater (**Figure 11.1**). The Great Lakes basin is home to approximately 43 million people, 8% of the U.S. population, and 32% of Canada's population. The lakes provide culturally and economically important assets, including drinking water, commercial shipping, hydroelectric power, recreation, and a world-class fishery producing $7 billion in annual economic value (American Sportfishing Association, 2013). The positive regional economic impact generated by the Great Lakes is

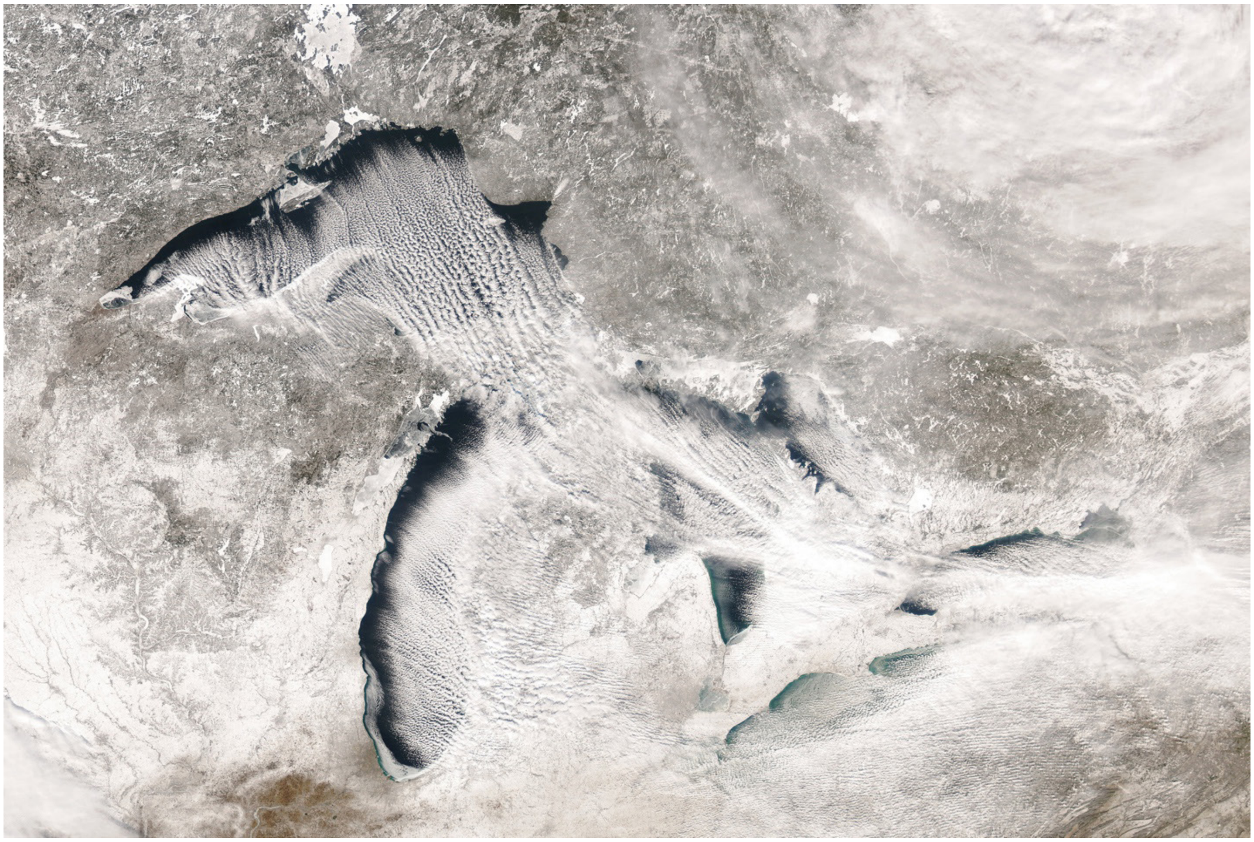


Figure 11.1. The Laurentian Great Lakes are a unique freshwater ecosystem shared between the United States and Canada. In early winter, cold air causes strong mixing in the lakes and atmospheric boundary layer, strong evaporation leading to lake-effect snow, and rapid equilibration with atmospheric gases (NOAA CoastWatch MODIS satellite image).

estimated at 1.5 million jobs directly connected to the lakes, resulting in $62 billion in wages (Michigan Sea Grant College Program, 2011). The services provided by this valuable ecosystem are vulnerable to multiple stressors, including eutrophication and oligotrophication, invasive species, contaminants, a changing climate, and acidification associated with increasing atmospheric carbon dioxide (CO_2).

Great Lakes pH is projected to decline at a rate similar to that of the oceans, in response to increasing atmospheric CO_2. Phillips et al. (2015) estimated a pH decline of 0.29-0.49 pH units by 2100, assuming current projections of anthropogenic carbon dioxide CO_2 emissions (IPCC IS92a business as usual scenario) and constant alkalinity (**Figure 11.2**). Present-day mean pH and alkalinity vary according to the geology of each lake basin, with Superior having the lowest values (pH 8.12, 838 meq m^{-3}) and Michigan the highest (pH 8.55, 2181 meq m^{-3}, Phillips et al., 2015). In addition, considerable short-term spatial and temporal variability in pH occurs, driven largely by varying rates of photosynthesis and respiration across trophic gradients. For example, episodes of high productivity can result in pH > 9.0, while net community respiration in hypolimnetic waters can lead to hypoxic conditions and pH < 7.5 (**Figure 11.3**). The predicted decline in pH would occur superimposed on this variability, making observation of long-term trends in the Great Lakes region particularly challenging (Phillips et al., 2015).

Effects of increasing atmospheric CO_2 on Great Lakes water chemistry may be confounded by regional recovery from acid deposition. The Midwestern and Northeastern United States experienced an increase in deposition of sulfuric and nitric acids from the early 20th century until air-quality regulations mitigated this trend. The pH of precipitation in the Midwest increased from ~4.2 in the 1980s to

~5.4 in 2018, with much of the increase occurring after 1995 (National Atmospheric Deposition Program, https://nadp.slh.wisc.edu/). The concentrations of major ions and alkalinity of the lakes were modified by the acid deposition period, and continue to change as a result of recovery from acid deposition, and the long residence time and connectivity of the lakes (Chapra et al., 2012).

In spite of the publication of the 2010 Great Lakes Acidification Research Plan little effort has been invested in monitoring or understanding potential effects of acidification in the Great Lakes on the part of NOAA or the broader Great Lakes research community. The review by Phillips et al. (2015) is a rare example of a publication devoted to the topic of Great Lakes acidification. Although not focused on acidification, there have been efforts to measure and estimate components of the lake-wide carbon budgets (Bennington et al., 2012).

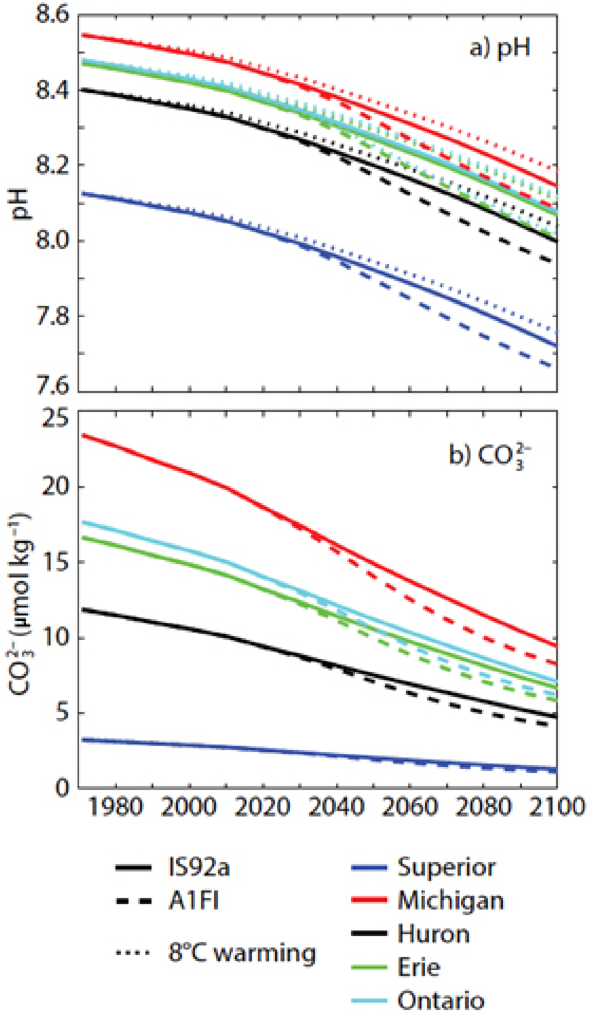


Figure 11.2. Projected mean annual (a) pH and (b) carbonate ion concentration for the five Laurentian Great Lakes under IPCC atmospheric CO_2 forcing: IPCC IS92a (the business as usual scenario) or A1FI (the fossil fuel intensive scenario). Also shown on (a) is an 8°C warming by 2100 scenario. Figure modified from Phillips et al., 2015; Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

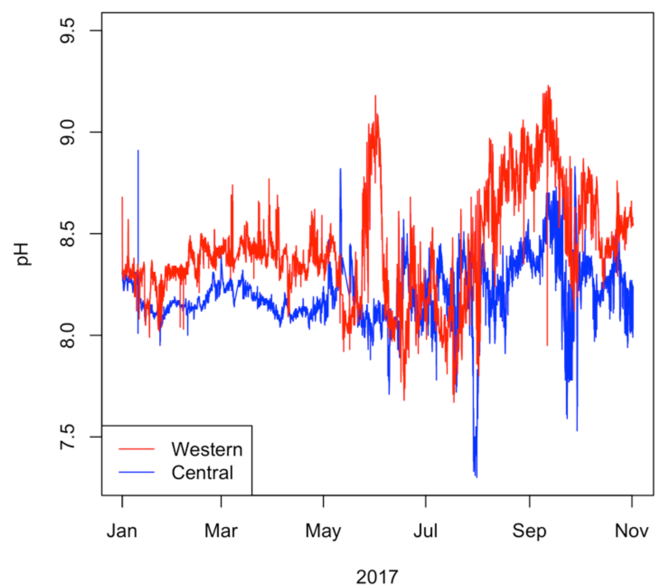
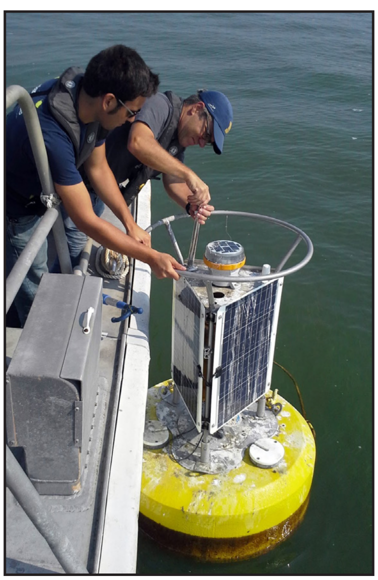


Figure 11.3. Time series of pH at drinking water intakes in the western and central basins of Lake Erie illustrating short-term variability of pH, which complicates detection of long-term trends. Episodes of high productivity cause pH > 9.0 in the eutrophic western basin, while coastal upwellings of hypoxic water in the central basin cause pH to drop below 7.5. Data source: Great Lakes Observing System, http://habs.glos.us.

Environmental Change in the Great Lakes Region

There are presently no long-term monitoring programs in the Great Lakes that are designed to detect long-term trends in pH and inorganic carbonate system variables. This lack of observations represents a major knowledge gap in understanding the past progression of acidification in the Great Lakes region. The U.S. EPA conducts a long-term water quality monitoring program; however, the sampling methodology and frequency are not well-suited to detect trends in pH (Phillips et al., 2015). At least two carbonate system components must be measured to fully characterize the system, for example pCO_2 and pH, and measurements must be made with methods that have sufficient precision in freshwater to detect the predicted trends. Recent developments in Great Lakes carbonate system observing include a long-term monitoring program for pCO_2 in Lake Michigan, using the Lake Express ferry (Milwaukee to Muskegon) and fixed moorings (University of Wisconsin Milwaukee). However, this program only monitors a single carbonate variable and would ideally be supplemented by pH (Harvey Bootsma, personal communication).



A NOAA Realtime Coastal Observation Network (ReCON) buoy being serviced in Lake Erie. Credit: Dack Stuart/Cooperative Institute for Great Lakes Research

Recently developed instrumentation that has the ability to monitor pCO_2 and pH with sufficient precision to document trends in acidification, and are suitable for deployment on remote buoys or moorings, provide a potential means to improve the carbonate chemistry observing gap in the Great Lakes region (https://oceanacidification.noaa.gov/WhatWeDo/Monitoring.aspx). New observations of the carbonate system may build upon existing observing networks, such as the Real-Time Coastal Observation Network (ReCON), National Data Buoy Center (NDBC), or Great Lakes Evaporation Network (GLEN). NDBC buoys may be well-positioned for the purpose of monitoring long-term trends, as these are located in central deep basins of all five of the Great Lakes that would be minimally influenced by local and seasonal variance in pH associated with coastal plumes of enhanced primary production (Phillips et al., 2015). Ideally, buoys with carbonate chemistry sensor packages would be deployed in each of the upper lakes (Superior, Huron, and Michigan) to provide an opportunity to compare and contrast these lakes over a range of alkalinity, carbonate saturation, and watershed geology, and to verify any trends by comparison across sites. In contrast to the upper lakes, the more productive waters of Erie and Ontario have greater short-term variability in pH, which would cause greater difficulty in detection of trends.

While a moored system would be best-suited for detecting long-term trends, mobile platforms such as ships or autonomous instruments would have an advantage in terms of monitoring spatial patterns. Addition of carbonate system observations to a ship-based long-term ecological monitoring program would have the benefit of observing changes in pH and carbonate saturation in conjunction with ecological changes. Long-term trends may be detectable using routine observations made at stations in relatively-deep and low-productivity regions of Great Lakes basins on a near-monthly basis, however the problem of aliasing spatial, seasonal, and diel patterns onto long-term trends would still exist. Novel technologies such as profiling floats could provide insights on the influence of primary production and respiration, by providing vertical resolution and potentially including ecological sensor packages.

Research Objective 11.1: Expand NOAA's OA monitoring network to include sampling sites in the Great Lakes Region

There is currently no existing long-term carbonate chemistry monitoring program in the Great Lakes region, representing a major observing and knowledge gap on how acidification has evolved in the past and continues to progress into the future. Building out an observing network will be critical to understanding the drivers of acidification and predicting future trends in pH.

Action 11.1.1: Leverage existing observing networks in the region to build a carbonate chemistry observing network through addition of sensor packages suited to make high quality measurements.

Action 11.1.2: Strategically identify priority sampling regions in order to best detect trends (relatively-deep basin and low-productivity environments) that can be compared across lakes.

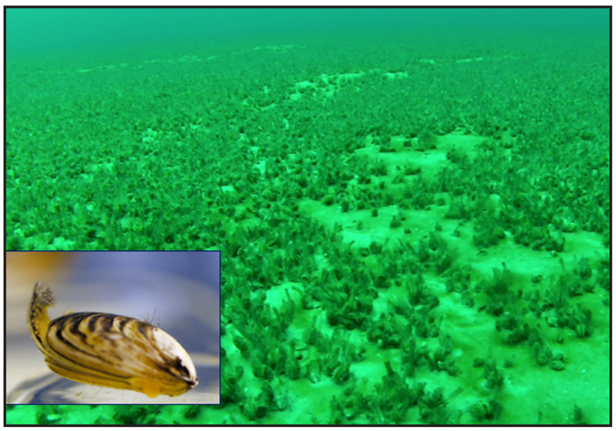
Biological Sensitivity in the Great Lakes Region

Effects of weak acidification of freshwater on biota at the organism, community, and ecosystem level are generally not well understood. With increasing pCO_2, primary producers tend to experience increased individual and community growth rates, while animals, including fish, amphibians, and macroinvertebrates, exhibit reduced growth rates; however, little is known regarding potential effects at the community or ecosystem level (Hasler et al., 2018). Little research has been devoted to the sensitivity of Great Lakes biota to weak acidification.

Phytoplankton community composition is influenced by weak acidification of freshwater. Diatoms are sensitive to pH to the extent that they are used to reconstruct the geologic history of lake pH. For example, statistical diatom models have been developed that can predict lake pH within 0.19–0.46 pH units over commonly-occurring pH range of lakes (6.0–8.5; Finkelstein et al., 2014); thus, we may expect changes in the diatom community to occur over the range of pH change predicted for the Great Lakes. Of particular concern with respect to phytoplankton communities in the Great Lakes is the increased presence of harmful algal species that produce neurotoxins and hepatoxins. In 2014, a Lake Erie harmful algal bloom (HAB) event associated with the freshwater cyanobacteria species *Microcystis aeruginosa* contaminated the public water system and caused a no-consumption advisory that left a half million people in Toledo, Ohio without access to drinking water for 2.5 days (Steffen et al., 2017). It has been suggested that elevated pCO_2 can contribute to the dominance of cyanobacteria within freshwater phytoplankton assemblages (Mooij et al., 2005; Trolle et al., 2011). Warming associated with the increase in atmospheric CO_2 is expected to lengthen and strengthen lake stratification (De Stasio et al., 1996; Peeters et al., 2002), leading to increased lake stability and conditions that favor phytoplankton species that can take advantage of vertical migration in the water column, such as cyanobacteria (Paerl & Huisman, 2008). Community shifts in the toxic species present may also be impacted, as acidified conditions promote non-toxigenic strains of *M. aeruginosa* (Van de Waal et al., 2011) while toxic strains of *Anabaena circinalis* and *A. eucompacta* are favored within a high pCO_2 environment (Shi et al., 2017).

Cyanobacterial harmful algal bloom in Lake Erie near Toledo, Ohio, August 2019. Acidification may alter phytoplankton community composition. Credit: NOAA

Calcifying organisms are sensitive to carbonate saturation states, and have gained an important influence on primary production and trophic connections in the Great Lakes with the colonization of the lakes by the invasive bivalves *Dreissena polymorpha* (zebra mussel) and *Dreissena rostriformis bugensis* (quagga mussel). Dreissenid mussels are an undesirable invasive species that heavily colonized each of the Great Lakes during the 1990s and 2000s, except Lake Superior, which has lower carbonate saturation than the other lakes. The mean aragonite saturation state (Ω_{arag}) varies across the Great Lakes, with Ontario, Erie, and Michigan having values > 2.0, Huron at 0.96 ±0.62 (mean ±std. error) and Superior at 0.15 ±0.08 (NOAA OA Steering Committee, 2010). It is not known whether Ω_{arag} in the main basin of Lake Huron is low enough to stress and limit dreissenid biomass in that lake. Dreissenids may be most vulnerable during their larval veliger stage, as calcium levels below 8 mg L^{-1} lead to significant decreases in larval growth (Mackie & Claudi, 2009) and larval settlement may be prevented below pH of 7.1 (Claudi et al., 2012).



Invasive quagga mussels (Inset photo; also referred to as dreissenid mussels) carpet the bottom of Lake Michigan. Credit: NOAA

Fish are a primary means by which people interact with the Great Lakes, both culturally and economically. Acidification of poorly buffered fresh waters is known to cause mortality, reproductive failure, reduced growth rate, skeletal deformation, and increased uptake of heavy metals in fish. Generally, pH values below 5.5 result in reduced reproductive success of fish, but some deleterious effects on salmonids have been recorded at pH values of 6.5–6.7. Salmonids in the Great Lakes include the native top predator, lake trout, along with important native forage fish, coregonids, and introduced Pacific salmon that are the basis of an economically-important sport fishery. While the pH of Great Lakes waters is not predicted to reach such low levels (Phillips et al., 2015), important spawning and nursery habitats in tributaries and wetlands may be vulnerable. Acid precipitation can also leach Al^{3+} from soils, which has been shown to be highly toxic to certain fish larvae (Haines, 1981). Intense rainfall events, which lead to a sudden decrease in pH (< 5.5), or increase in toxic metal ions (namely Al^{3+}), in poorly buffered rivers may cause mortality of fish early life stages (Buckler et al., 1987; Hall, 1987), and has more severe effects compared to chronic low pH conditions. Indirect effects on fish may result from changes in species composition of lower trophic levels that support fish growth and production (Haines, 1981).

Great Lakes biophysical models have been used to elucidate lake-wide circulation patterns (Beletsky & Schwab, 2008; Bennington et al., 2010), oxygen cycling (Matsumoto et al., 2015), and the effects of invasive dreissenid mussels and changing lake nutrient concentrations on lakewide productivity (Pilcher et al., 2017; Rowe et al., 2017). Such models may be used to determine separate and combined effects of concurrent ecological stressors. Two Great Lakes biophysical models have included carbonate chemistry (Bennington et al., 2012 for Lake Superior; Pilcher et al., 2017 for Lake Michigan). Continued development of biophysical and food web models should be conducted in coordination with observational and monitoring work.

Research Objective 11.2: Conduct research on harmful algal bloom species and the influence of elevated pCO₂, and temperature on bloom toxicity, concentration and frequency

Cyanobacterial harmful algal blooms are a recurring issue in eutrophic areas of the Great Lakes that has had significant economic impacts, and is a human health concern.

Action 11.2.1: Conduct monitoring and experiments to understand the influence of elevated pCO_2 and temperature on bloom toxicity, concentration and frequency.

Action 11.2.2: Incorporate the influence of elevated pCO_2 and temperature into models that can predict HAB occurrence in short-term forecasts and in longer-term scenarios to inform nutrient management decisions.

Research Objective 11.3: Conduct research to understand the sensitivity of dreissenid mussels, plankton, fish, and other biota to changes in pH and carbonate saturation states, including early life stages

The influence of elevated pCO_2 on Great Lakes biota is relatively unknown at the organism, population, and ecosystem level, causing an unknown level of risk to an ecosystem that supports a multi-billion dollar tourism and sportfishing economy.

Action 11.3.1: Given its marginal Ω_{arag} values, and gradients in Ω_{arag}, Lake Huron dreissenid distributions may be most sensitive to acidification, and could serve as an early indicator of changing trends in pH and Ω_{arag}. Compare and contrast dreissenid distribution over time and with other lakes as a function of Ω_{arag}.

Action 11.3.2: Conduct monitoring and experiments to understand the influence of elevated pCO_2 on Great Lakes plankton community composition.

Action 11.3.3: Conduct monitoring and experiments to evaluate the influence of elevated pCO_2 on early life stages of fish and dreissenid mussels.

***Action 11.3.4*:** Focus research on nursery habitats for fish early life stages, such as poorly buffered tributaries and wetland habitats that currently experience fluctuating pH levels, and will be most at risk to anticipated pH declines.

Research Objective 11.4: Incorporate carbonate chemistry into biophysical and food web models to project the impacts of changing pH and carbonate saturation states on important ecological endpoints

Current biophysical models for the Great Lakes region often do not include effects of the carbonate system and pH on ecological endpoints.

Action 11.4.1: Develop biophysical models capable of simulating the carbonate system, pH, and Ω_{arag} in the Great Lakes.

Action 11.4.2: As understanding develops regarding the influence of elevated pCO_2 on Great Lakes biota, incorporate these mechanisms into biophysical and food web models.

Human Dimensions in the Great Lakes Region

Potential impacts of Great Lakes acidification are largely unknown at this time. If ecological impacts of acidification are documented in the Great Lakes, then it will be important to engage with stakeholders in the region and evaluate economic impacts. Human dimensions of environmental stressors can be described as three points of interaction between human and environmental systems, 1) including human actions as causes for environmental changes, 2) impacts on society, and 3) effective responses (NRC, 1992). NOAA in the Great Lakes Region engages with a wide range of stakeholder groups including drinking water system managers, hydroelectric power managers, commercial shipping industry, coast guard, recreational and charter anglers, and environment protection agencies. These relationships can serve as a foundation for human dimensions work related to Great Lakes acidification.

Researchers at NOAA's Great Lakes Environmenatal Research Laboratory, Lake Michigan Field Station use seine nets to monitor larval white fish abundance for use in recruitment models for the lake whitefish fishery. Credit: NOAA

NOAA and its academic and government partners use social science methods such as needs assessments, focus groups, and surveys to learn about the human dimensions of issues facing the Great Lakes. In 2018, the International Joint Commission (IJC) conducted a binational poll of residents of the Great Lakes basin, and identified over fifteen top of mind problems faced by the Great Lakes, which included pollution in general, invasive species, nuisance algae, and water levels (IJC, 2018), but acidification did not appear as a top of mind issue for the public. Recent studies have evaluated the economic impact of the Great Lakes through fishery, shipping, and beach visits (NOAA, 2019; Wolf et al., 2017; Martin Associates, 2018). Environmental pressures on Great Lakes such as HABs in Lake Erie can cause $2.25 million to $5.58 million in lost fishing expenditures (Wolf et al., 2017). In addition to economic studies, there is a need to measure impacts of environmental changes on quality of life, sense of place, and community wellbeing. Studying how stakeholders address uncertainty and long-term changes and take precautionary actions fit NOAA's vision of building healthy ecosystems, communities and economies that are resilient in the face of change. For example, a focus group study documented the influence of Lake Erie HABs on decision making by recreational and charter anglers and the potential utility of a HAB forecast to these stakeholders (Gill et al., 2018). While acidification is not currently a focus among Great Lakes stakeholders or the research community, policy makers and resource managers should be informed about ongoing research directions. The sooner stakeholders and the public are engaged in research, the more likely they will be to trust the scientific information and to accept new management goals (Bauer et al., 2010).

Research Objective 11.5: Engage stakeholders and public in the knowledge production process

The scientific research on Great Lakes acidification can have greater impact with better understanding of stakeholders' and public needs and strengthened public trust and awareness of NOAA's efforts.

Action 11.5.1: As research activities are undertaken, develop engagement, communication, and training programs to increase stakeholder and public awareness of NOAA's acidification research as a scientific frontier. Test hypotheses about best ways to engage stakeholders and public.

Research Objective 11.6: Evaluate economic and social impacts of ecological outcomes or mitigation actions

Well-documented economic and social impacts help policy makers and the public to prioritize adaptation tasks and select mitigation actions.

Action 11.6.1: As the ecological impacts of Great Lakes acidification are identified, conduct vulnerability assessments to identify sectors of the economy that are vulnerable to Great Lakes acidification, and measure economic and social impacts of acidification.

References

[INTRO] = Introduction;

[NAT] = National Ocean & Great Lakes;

[OO] = Open Ocean Region;

[AK] = Alaska Region;

[ARC] = Arctic Region;

[WC] = West Coast Region;

[PAC] = U.S. Pacific Islands Region;

[SAG] = Southeast Atlantic & Gulf of Mexico Region;

[FLC] = Florida Keys and Caribbean Region;

[MAB] = Mid-Atlantic Bight Region;

[NE] = New England Region;

[GL] = Great Lakes Region

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