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Commentary

Great Lakes: Science can keep them great

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ABSTRACT

The Laurentian Great Lakes are an invaluable natural and economic resource for two North American countries, but really the entire world. They are threatened by anthropogenic, climate and biotic stresses; and it is increasingly difficult to manage them due to the complexity of interactions among these different stressors. At the same time, funding for Great Lakes scientific research is decreasing and there are threats from the current US administration to decrease funding significantly in the near future. Now is not the time to move our understanding of these incredible ecosystems back in time. We call for implementing a science plan that addresses critical Great Lakes issues, including upgrading infrastructure (e.g. field stations and observing networks) and resolving current and emerging issues (e.g. harmful algal blooms, recurring bottom water hypoxia, invasive species, changing water levels and nutrient cycles) by strengthening NSF, NOAA and EPA support of basic and applied science in the Great Lakes.

> "*A lake is the landscape's most beautiful and expressive feature. It is the earth's eye*"
>
> [- Henry David Thoreau (1854).]

Pressing science and management issues in the Great Lakes

The five contiguous Laurentian Great Lakes of North America cover ~250,000 km^2 and contain about one fifth of all the liquid freshwater water on the surface of our planet constituting a vitally important natural resource (Beeton, 1984; Fig. 1). This largest body of freshwater on Earth supports 179 different species of fish with commercial harvests valued at over 300 million US dollars. Furthermore, the Great Lakes basin is home to over 40 million residents – providing drinking water, and attracting millions of tourists each year. The economies of the Great Lakes states surrounding the lakes represent the world's fourth largest global economy. Clearly, this is a resource of incalculable ecological and economic value to humanity at large. However, today, the Great Lake's vast freshwater resources are facing a myriad of anthropogenic and climate-driven stresses (Allan et al., 2013) which is made even more troubling as support for their study, protection, and restoration is dwindling. It is critical at this time that the Great Lakes community of scientists, managers and policy makers implement a science plan that addresses critical issues by setting up programs specific to understanding, addressing and resolving Great Lakes science and management issues, and allocation of resources to reflect the size, value and vulnerability of the Great Lakes system.

There are three main categories of stressors in the Great Lakes, 1) climate and changing climate, 2) direct anthropogenic stressors, and 3) biotic stressors (Fig. 2). The climate-driven category is particularly problematic because it often accentuates many of the other stressors, potentially pushing the ecosystem non-linearly towards tipping points (Scheffer et al., 2012). Important climate stressors on the lakes are increased temperatures, decreased ice duration, changing water levels, altered precipitation patterns and runoff timing and quantities, and increased duration of summer stratification with implications for hypoxia and nutrient regeneration from the sediments. Today, ecologists are being challenged to predict dynamic tipping points of ecosystems and shifting thresholds under a confluence of conditions where interactive effects play a key role (Scheffer et al., 2012; Costanza, 2017). How to study the interactive effects of multiple stressors that are contemporaneously acting on an ecosystem is no small challenge – but one that must be addressed.

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Fig. 1. Image of North America's Laurentian Great Lakes from space showing visible coastal phytoplankton blooms in lakes Michigan, Huron, Erie and Ontario (Credit: NASA). The World's largest freshwater resource is under intense anthropogenic stress from forces such as climate change, invasive species, pollution, and eutrophication as well as oligotrophication – and there is urgent need for bold commitments to its understanding, protection and conservation.

Many of the anthropogenic stressors are well-known and well-studied in lakes around the world, such as excessive runoff of nutrients from land into aquatic ecosystems leading to eutrophication, emergence of harmful algal blooms and hypoxia (HABs; Paerl and Huisman 2008; Michalak et al., 2013; Zhou et al., 2015), but the manifestations in large lakes can be very different from what has been observed in smaller lakes (Downing, 2010; Finlay et al., 2013). Some of these differences are related to their long residence times, but also the increased role of atmospheric deposition across large surface areas implies management of a very different kind of input that is not a direct terrestrial point-source. It is also worth noting that differences in atmospheric deposition of nutrients can lead to large stoichiometric imbalances, which many have noted in Lake Superior but are also problematic in other large lakes (Finlay et al., 2013; Sterner, 2011). A related 'chemical' stressor that has passed under the radar for the most part is increased salinization of lakes in the northern USA and Canada, largely due to road salt use (Dugan et al., 2017). Although concentrations in the Great Lakes are not yet problematic, the trends are of uniformly increasing concentrations of chloride (Chapra et al., 2012). Other important stressors in this category include: toxic contaminants, plastic pollution, watershed diversions, habitat loss (particularly wetlands), and shoreline development that degrade the ecosystem services provided by the Great Lakes system (Niemi et al., 2007; Eriksen et al., 2013; Cornwell et al., 2015).

Biotic stressors include changing food webs, invasive species, bottom water hypoxia, and HABs. In Lake Erie, HABs have been particularly disruptive and costly recently, most visibly during the 2014 shutdown of the Toledo water supply (Michalak et al., 2013). The increased HABs are also coincident with record-setting bottom water hypoxia (Zhou et al., 2015). An important aspect of all of these stressors is that many of them interact with each other and, particularly in large lakes, these interactions develop over longer time scales that make it difficult to decipher the causes, effects and most importantly, the outcomes of such interactions. For instance, zebra mussels and quagga mussels have had an extremely disruptive effect on ecological and biogeochemical processes, particularly in lakes Michigan, Huron and Erie (Bunnell et al.,

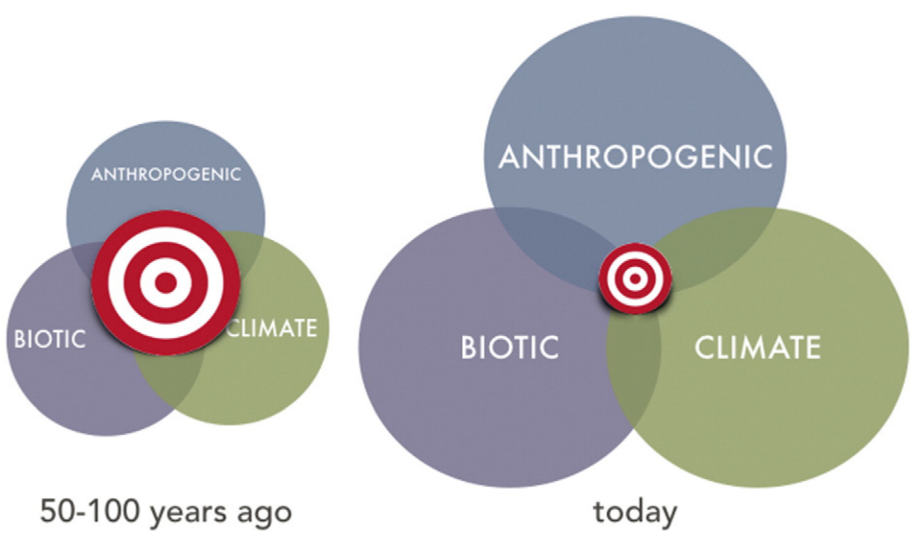

Fig. 2. Schematic diagram of the interactive role of climate and anthropogenic stressors on biotic integrity of the Great Lakes system that make their management ever more challenging (depicted here by the decreasing target size of the management "sweet spot" over time) as both the scale and intensity of stressor interactions are escalating due to the combination of rapidly changing climate and increasing human activity.

2013). While many effects on biogeochemistry were rapid, food web effects are still reverberating through the food webs (Hecky et al., 2004; Bunnell et al., 2013).

Research, education, protection and restoration funding shortfall

Most scientists agree that these systems are terribly understudied and underfunded relative to their value in providing ecosystem services. Scientific and management funding for the Great Lakes is mandated by the National Science Foundation, (NSF), Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration (NOAA) – but very little is actually being spent to address the science issues that are facing this ecosystem. For example, there are no NSF Long Term Research (LTER) sites in the Great Lakes despite their unique role, ecology and biogeochemical function relative to other water bodies from wetlands to oceans. Quite honestly, it is a national embarrassment that one of the most valuable ecosystems on the face of the Earth has not been prioritized in such a way that we will be able to say 30 years from now what the most important drivers of change have been and what will be most important in the future. Additionally, there is no particular emphasis being laid on Great Lakes science in the decadal Ocean Research Plan that is currently being developed (www.nsf.gov/geo/oce/orp/); and that, as in the past, Great Lakes science at NSF will continue to be subsumed within the much larger ocean-centric Oceanography program. At NSF, oceanographers do not want to see limited funds 'diverted' to scientists working on these unique, but non-oceanographic ecosystems. The situation is further exacerbated by the fact that most limnologists that work on the Great Lakes do not even see NSF as a funding option and therefore do not submit grant applications for Great Lakes work there.

And the situation has gone from bad to worse. Despite winning an election largely due to critical electoral votes from the Great Lakes states of Michigan, Wisconsin, Indiana, Ohio, and Pennsylvania, President Trump's proposed EPA budget slashes Great Lakes restoration funding by 97%, and NOAA's long-standing Sea Grant Program would be completely eliminated! Although no one anticipates that this regressive approach to the Great Lakes ecosystem and Great Lakes science will be completely adopted, it represents a huge threat to the region and harkens back to a time when these systems were a dumping ground for the industrial Midwest. In our view, funding for Great Lakes research, education and restoration was terribly inadequate even before President Trump proposed the cuts to NOAA and the EPA's Great Lakes Restoration Initiative (GLRI), which provides 300 million US dollars to the Great Lakes region in all of these areas. The loss of NOAA's Sea Grant would be a significant loss to all of the states where this program exists, but in the Great Lakes region, this would be a much bigger loss given the lack of funding from other sources. Only six of the 33 Sea Grant states have a Sea Grant Program due to only Great Lakes coastline (Minnesota, Wisconsin, Illinois, Indiana, Ohio and Michigan). In 2015, Minnesota Sea Grant calculated that 1.2 million US dollars in federal investment resulted in 10 million US dollars of economic impact. The federal government would be hard-pressed to find a better return on investment. Although important, Sea Grant budgets are not sufficient to support science in the Great Lakes and should likely be increased in Great Lakes states, not eliminated!

Former president of the Association for the Sciences of Limnology and Oceanography, Peter Jumars, lamented the sad state of limnological funding many years ago (Jumars, 1990). Little has changed since then, except that the ecological problems and the difficulty understanding them have increased greatly (Fig. 2). Harmful algal blooms (HABs) are more toxic, bottom water hypoxia is more extensive and invasive species more pervasive in the Great Lakes, small lakes and oceans than they were back then (Diaz and Rosenberg, 2008; Michalak et al., 2013; Zhou et al., 2015). Climate change is manifesting in multiple ways throughout the Great Lakes, with warmer temperatures, longer and stronger stratification and increased hypoxia. All of these changes are happening virtually in our backyards, but under cover of darkness, because we do not have the appropriate infrastructure (both physical and intellectual) to see what is going on. The people and economies of the Great Lakes are compromised by the inability to forecast HABs, to remediate them so they do not occur again, to implement best management practices, and to understand how fisheries and recreational use of the lakes are changing in the face of changing eutrophication and climate change.

Emerging Great Lakes issues and possible solutions

There is an urgent need for Great Lakes-specific investment towards understanding the basic workings of this ecosystem for better forecasting of its changing dynamics and restoration of past ecosystem services. There is a gradient from the upper to the lower lakes of increased human stressors (Allan et al., 2013). In Lake Superior, climate is a strong stressor due to rapid warming of the lake (Austin and Coleman, 2008) while in the lower lakes eutrophication and contaminants are particularly important. At the same time, lakes Huron and Michigan seem to be undergoing increasing 'oligotrophication' perhaps due to a combination of effective nutrient management and the invasion of zebra and quagga mussels (Evans et al., 2011). As water demands increase in the most productive agricultural region of the USA, as well as other water poor regions, there will be increased pressure to divert more and more water from these basins, with profound long-term consequences. In addition, there are emerging issues in the Great Lakes that are starting to receive attention such as microplastic pollution, which could have complex impacts on the overall ecosystem that we are not yet aware of (Eriksen et al., 2013). Managing these lakes is incredibly difficult given the multiple stressors, uses, and needs of people both inside and outside the watershed. But managing them in the absence of understanding is impractical, and this situation needs to be rectified.

Therefore, we call for implementing a science plan for addressing critical Great Lakes issues of upgrading lacking infrastructure (e.g. field stations and observing networks) and resolving current and emerging issues (e.g. harmful algal blooms, recurring bottom water hypoxia, invasive species, changing water levels and nutrient cycles) by strengthening NSF, NOAA and EPA support of basic and applied science in the Great Lakes. A simple, practical start would be setting up programs specific to Great Lakes science issues, and allocation of resources that reflect the significance of the value of this system. Having freshwater research and Great Lakes research at NSF embedded in multiple directorates at NSF means that there is no coordinated and dedicated funding directed towards this important resource. Change can come through what every developed country already recognizes: the importance of freshwater to food security and human well-being is paramount.

Relevance to lakes great and small

Various national and global reports during the last decade point out that the gap between the availability of freshwater and the human need for it will widen greatly during the remainder of this century. Furthermore, multiple observations and models suggest that world's freshwater systems play an active role in regional as well as global biogeochemical cycles (Tranvik et al., 2009; Weinke et al., 2014; Biddanda, 2017). However, despite the critical importance of the world's lakes to society and climate, they are rapidly changing and fundamental aspects of how and why these ecosystems are transforming remain poorly understood (Alin and Johnson, 2007; Austin and Coleman, 2008; Allan et al., 2013).

Climate change is amplifying the hydrologic cycle in ways that will increase the pressure on managers to make correct decisions (Gorham, 1996). At the same time, human population growth, coupled with increased food demands and increased deleterious effects of both of these factors on aquatic systems have made the management 'sweet spot' much harder to hit than it was 50–100 years ago, when populations were much smaller, agricultural demands were less and climate change had not manifested itself as clearly as it is today (Fig. 2). Already, anthropogenic climate change is disproportionately warming lakes – both great and small – across the globe, and measurably impacting the productivity of the African Great Lakes – with potentially destabilizing effects on both water and food security (Borges et al., 2015; O'Reilly et al., 2015). With appropriate and timely investment, we have the opportunity to better understand and protect North America's Great Lakes, in effect, increasing the management sweet spot – serving as a model for saving threatened lakes everywhere. Current and future generations of scientists and policy makers have great need for great science for the sustainable management of Earth's freshwater resources. By all accounts, this is not the time to divest from much needed science in the Earth's largest freshwater ecosystem. Isn't it time for a strong and renewed commitment to the protection and conservation of the very basis of civilization – our troubled freshwaters?

The Great Lakes are an international treasure that, were it manmade, would today be protected as an UNESCO cultural world heritage site. Today, the Great Lakes ecosystem is experiencing marked changes driven by multiple stressors that are on the path to loss of the many essential ecosystem services it provides. It is our intent in this essay to rally support for them, rally support for developing our scientific understanding of them and to 'make the Great Lakes great again' despite enormous political and economic pressure to let them languish. Over 150 years ago, Thoreau captured the essence of lakes as "Earth's eyes" because they best reflect the deep and tangible links between the landscape and humanity (Thoreau, 1854; Biddanda and Cotner, 2002). Isn't it time to prioritize the protection of the "Earth's largest eye"?

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