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Grand challenges for research in the Laurentian Great Lakes

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Abstract

The Laurentian Great Lakes (LGL) constitute one of the largest freshwater systems in the world while providing social and economic value to two powerful nations. The spatial scale of these inland seas falls between two endpoints: small lakes and oceans. Lacustrine in many characteristics, the LGL often require a scientific approach with attributes similar to those of oceanography. There is a strong sense that within the LGL support for scientific research has not kept pace with the need for process-oriented research and that we lack basic information needed to forecast change, mitigate impacts and restore and preserve the LGL. Consequently, 58 researchers met in September 2014 and identified five "Grand Challenges for Research in the LGL": (1) How has this vast inland freshwater system responded to shifting climate in the past, and how will it respond in the future? (2) What is the current status of the most important ecosystem processes, including their variability in space and time? (3) What processes are characteristic only of large lakes, and how do the distinct habitats integrate into a whole? (4) What are the ecosystem responses to major anthropogenic forces such as nutrients and invasive species, and are these reversible? and (5) What are the small to large-scale linkages and feedbacks among societal decisions, biological systems, and physicochemical dynamics? An urgent need exists for a unified scientific voice that articulates the Grand Challenges for research in the LGL and the need for associated funding. This treatise describing the Grand Challenges develops that voice.

The Laurentian Great Lakes (LGL) system in North America (LGL, Fig. 1) has the largest connected surface area (and second largest volume) of any unfrozen fresh surface water in the world (Gronewold et al. 2013). The catchment covers approximately 1 million km^2. It encompasses diverse climate and soil types and varied habitats including forests, wetlands, lakes, and urban areas (Wang et al. 2015). The lakes themselves contain 84% of North America's surface fresh water and 21% of the world's surface fresh water supply (Waples et al. 2008). The scale of the five lakes is so vast that they are often considered to be "inland seas." The LGL boast 16,000 km of shoreline, the U.S. portion of which exceeds the U.S. coasts of the Pacific and Atlantic oceans combined. The LGL holds 22,000 km^3 of water beneath a total lake surface area of 244,000 km^2; all of the five lakes number among the planet's 10 largest by area and 15 largest by volume. Biologically, the LGL support a globally important concentration of aquatic biodiversity (Vadeboncoeur et al. 2011) and support a multi-billion dollar recreational and commercial fishery (Waples et al. 2008; Southwick Associates 2012). The LGL anchor a region that was historically, and continues to be today, an economic engine of global significance (Austin and Affolter-Caine 2006; Austin et al. 2007), and which provide an array of critical ecosystem services (Steinman et al. 2017). Moreover, nearly 10% of the U.S. population and 32% of Canada's resides in the Great Lakes basin, approximately 40 million people (Méthot et al. 2015). To put this in perspective, the population of the Great Lakes basin would rank as the world's 12th largest country, while its binational (Canadian and U.S.) economic output would constitute the world's fourth highest GDP

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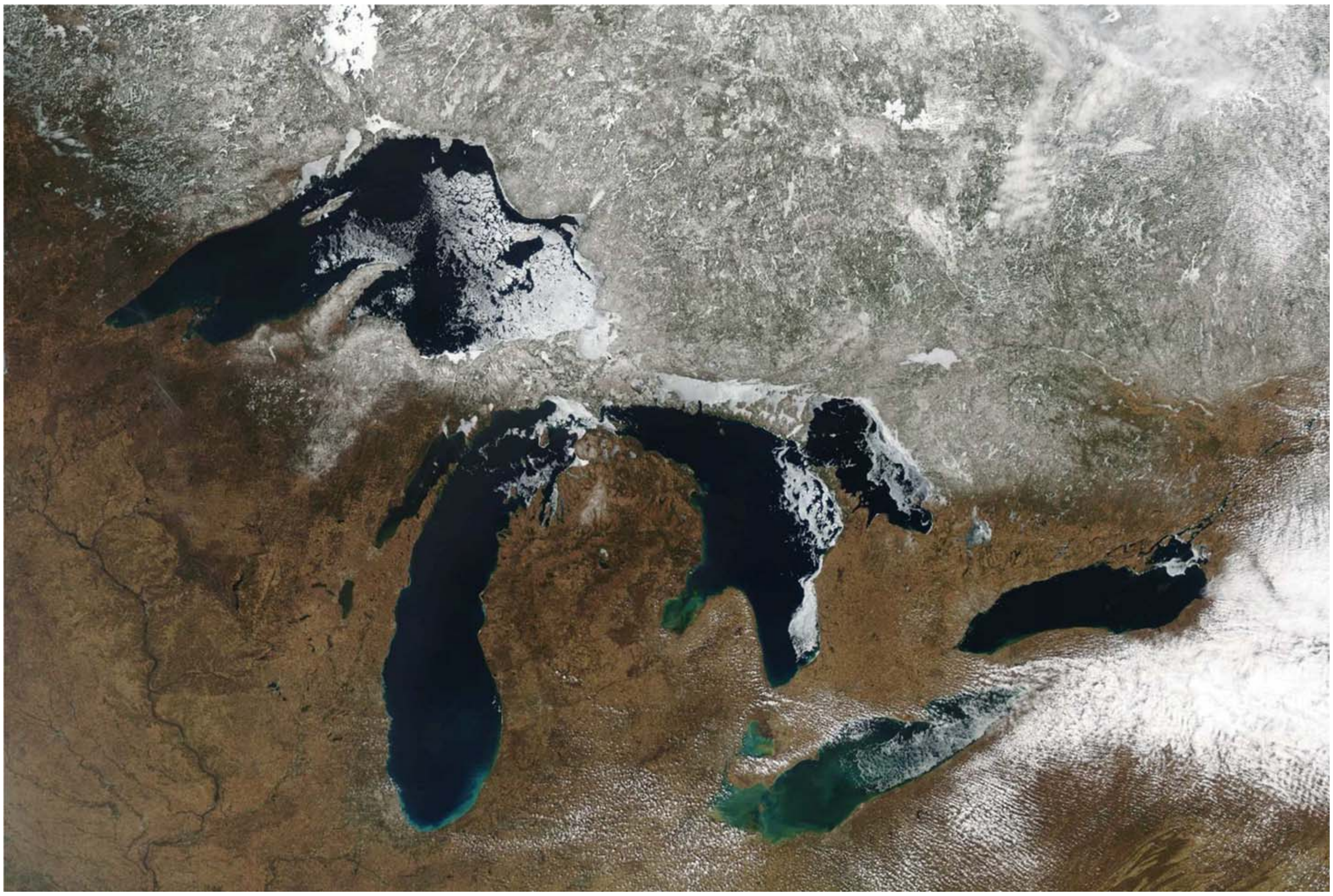

Fig. 1. Satellite (MODIS) image of the LGL from 13 April 2015 showing high spatial variability. At this time, portions of the LGL were still ice-covered while others were experiencing algal blooms and a sediment resuspension event was occurring in at least one location. Downloaded from http://coastwatch.glerl.noaa.gov/.

($5.2 trillion in 2012), supporting 56 million jobs in North America (ECCC 2016).

When considered in the context of their age, the LGL are a young ecosystem relative to the oceans and other comparable lakes such as the African Rift Valley lakes and Lake Baikal. They formed approximately 11,000 yr ago at the end of the last ice age and are continuing to respond to isostatic rebound resulting from retreat of that glaciation. Although the Great Lakes form a single hydrological unit, biophysical characteristics vary greatly among and within lakes. The lakes differ markedly in hydraulic residence time (just less than 200 yr for Superior to ~3 yr for Erie; Quinn 1992), annual lake surface temperatures (Trumpickas et al. 2009) and ice cover and extent (Assel et al. 2003). The lakes also differ markedly in primary production from the ultra-oligotrophic Lake Superior to hypereutrophic embayments and waters of western Lake Erie (Millie et al. 2009; Dove and Chapra 2015). Despite their size the LGL are among the fastest warming lakes on Earth with Lake Superior warming at twice the rate of the overlying atmosphere (Austin and Colman 2007). Consequently, the Great Lakes are highly susceptible and responsive to anthropogenically induced changes and serve as examples of the vulnerability of large ecological systems to rapid, system level change. They provide a uniquely scaled, model system to study the response of numerous variables to climate change including: the timing and duration of ice cover, changes in the timing of the annual spring bloom, response of energy and water fluxes to variations in ice cover, the influence of hypoxic zones and the response of zooplankton and fish communities.

In addition to their response to climate, the LGL exhibit short and long-term changes associated with human alteration (Beeton 2002). Despite their large size, the LGL are, in many ways, surprisingly fragile ecosystems, highly susceptible to the perturbation, disruption, and stress imposed by the dependence of humans on the LGL (Allan et al. 2013). Throughout nearly their entire history humans have relied on the LGL as a source of food, a transportation conduit, and, more recently, a region of recreational activities and a source of hydroelectric power. Five million people alone depend on Lake Erie for these attributes (Millie et al. 2009) and the shutdown of drinking water from Lake Erie to 400,000 residences of Toledo, Ohio, in 2014 is a dramatic example of the importance of the LGL to humans (Michalak et al. 2013). The Great Lakes are also a classic example of a mass biological invasion (Ricciardi and MacIsaac 2000). The Great Lakes support 180 non-native species, which collectively have exerted major economic and ecological effects, and now dominate the biomass and food webs of these systems (Ricciardi and MacIsaac 2000; Rothlisberger et al. 2012). Dreissenid mussels (zebra and quagga mussels) have transformed LGL ecosystems by shifting productivity from the open water to the nearshore benthic zone (Hecky et al. 2004). Over 90% of presettlement wetlands surrounding the Great Lakes have been lost and efforts are underway to restore at least a portion of the wetlands (Mittag et al. 2006; Uzarski et al. 2017). The human footprint on the ecological vitality of the Great Lakes has been substantial and as freshwaters across the globe continue to be threatened by human activities and climate change the time has come to study and preserve this vital asset shared by two countries.

The value and delicate nature of the LGL ecosystem has long been recognized by the United States and Canada. As early as 1909, The Boundary Waters Treaty formalized a process of binational cooperation with the creation of the International Joint Commission (IJC). The IJC oversees boundary or transboundary waters, with the objective of preventing and resolving disputes between the U.S. and Canada (IJC 2000; IJC 2015). Since its inception, the IJC had assisted in the passage of numerous major federal environmental legislation including the Great Lakes Water Quality Agreement, a commitment between the U.S. and Canada to provide a framework for identifying binational priorities to improve and protect water quality (IJC 1972; IJC 2015). Significant improvements resulted, but many of the legacy ills remain and these persistent conditions spurred the development of restoration and management efforts such as the Great Lakes Restoration Initiative (GLRI), an initiative that is discussed more below.

Restoration is complex, changing, and expensive, with the investment to restore the Great Lakes estimated to be in excess of tens of billions of U.S. dollars (Austin et al. 2007). Restoring an ecosystem with the immense scale of the Great Lakes requires a solid scientific understanding of complex ecosystem interactions so that the appropriate evaluation of restoration costs vs. benefits can be made. The complex attributes and demands of the LGL ecosystem present both opportunities and challenges for the research enterprise, challenges that ultimately affect the management of these systems.

A recent priority setting exercise for oceanographic research culminated in the National Academy of Sciences report, *Sea Change: A Decadal Survey of Ocean Sciences, 2015–2025* (NAS 2015). The LGL were named twice in this report, indicating recognition of the importance of these systems to future research. However, there was no elaboration in this report on priorities specific to the LGL or how the broad research questions fit into the LGL context, emphasizing a need to identify a research horizon specific to the LGL.

The impetus for our workshop, titled the "Grand Challenges for Water Research in the LGL," derived from a growing concern that the LGL have not received sufficient research attention, especially with regard to the types of coordinated efforts that are needed to study a highly variable system of vast spatial scale. Among other attributes such efforts require observational networks. Although an expanding network of nearshore temperature observations (http://glos.us/) and offshore measurements of surface physical conditions (e.g., wind speed, surface water temperature, wave height) are recorded by several U.S.- and Canada-supported buoys in the LGL, over the past several years only three moorings provided observations of thermal structure of deep offshore water columns. These three moorings were all in Lake Superior. Sustained observations of chlorophyll, nutrients, and other ions in the vast offshore regions are performed only 1–2 times per year by federal agencies (Dove and Chapra 2015). Primary productivity, arguably the most fundamental measure of ecosystem functioning, is not routinely measured in any of the lakes. Researchers often are faced with data sets that are piecemeal and limited in spatial and temporal extent, falling far short of the scales relevant for understanding the LGL. The need for quality scientific information to better address current and future problems facing the LGL is critical. Without adequate scientific grounding, we are mostly unprepared to predict ecosystem responses to climate change and other anthropogenic impacts, placing managers in a reactive rather than proactive state.

For a host of reasons that we articulate here the LGL have, essentially, fallen through the cracks scientifically. In contrast to the U.S. Ocean Observatories Initiative (OOI), which hosts 89 platforms via consistent funding of approximately $55,000,000 per year, there are no efforts of similar magnitude in the LGL (National Science Foundation Program Solicitation 17-524, oceanobservatories.org). Moreover, none of the eight research arrays funded by the OOI are located in the LGL leaving long term in situ observations of the LGL to a sparse buoy network that primarily collects only easily measured surface physical and chemical data (Great Lakes Observing System). There also are no individual research sites within the LGL such as those supported by the National Science Foundation Long-Term Ecological Research Program or National Ecological Observatory Network or time-series stations such as the Hawaiian Ocean Time Series or Bermuda Atlantic Time Series anywhere in the LGL.

Without such a backbone of sustained observations, the ability to understand key processes and predict and forecast ecosystem responses is severely hampered.

Despite the lack of substantive dedicated and observational research platforms to document change paralleling the OOI, national and local investments totaling billions of dollars have been targeted at ecological restoration. The most significant U.S. example is the Great Lakes Restoration Initiative (GLRI). The GLRI, begun in 2010, has so far directed $1.6 billion to over 3000 projects that have had extraordinary positive environmental benefit. The fate of $1.5 billion recently authorized by Congress for the next 5 yr remains uncertain. In Canada, the only significant federal funding for restoration of the Great Lakes has been the Areas of Concern (AOC) program. The Canadian AOC program led by Environment Canada and Climate Change (ECCC) was developed under the Great Lakes Water Quality Agreement 1987 amendments and is much smaller than the GLRI. Since 2010 this program provided $8 million CDN each year for the remediation of highly contaminated sediments (mainly harbors). The GLRI and AOC programs have made progress with eight sites that are delisted or anticipated to be de-listed by 2019 (Great Lakes Interagency Task Force 2015; ECCC 2016). But funding for research is not targeted. Consequently, we next explore the focus of the GLRI and AOC programs and identify the need for research funding in the LGL.

The major foci of the recent GLRI Action Plan II (FY15-19) include: (1) cleaning up Areas of Concern (AOC), (2) preventing and controlling invasive species, (3) reducing nutrient runoff that contributes to harmful/nuisance algal blooms and (4) restoring habitats to protect native species (GLRI.us/index.html). The future envisioned for the GLRI echoes these priorities (Northland College 2016) but also calls for enhanced attention to research along with restoration. While the Canadian AOC effort is very much focused on contaminated sediments, other efforts parallel the broader goals of the GLRI and the US Environmental Protection Agency's Great Lakes Legacy Act. However, these broader efforts are largely handled in a piecemeal manner by federal (ECCC and Department of Fisheries and Oceans) and provincial agencies (Ontario Ministry of Natural Resources and Forestry and Ontario Ministry of the Environment and Climate Change). Even though the majority of the Canadian government funding for the Great Lakes has been focused on monitoring, scientists within Canada have made significant and important contributions to the understanding of LGL ecosystems (e.g., Hutchinson awardee: Robert Hecky; International Association for Great Lakes Lifetime Achievement awardees: Murray Charlton and Mohiuddin Munawar).

We argue that the restoration programs such as the GLRI and AOC are critical for stewardship and protection of the LGL. However, there is a failure to recognize the complexity with which natural processes drive change and confound restoration within the LGL, something that is in the realm of research. Thus, there is an underappreciated need for a research agenda that can help inform management and restoration agendas. Via the generation of new knowledge, a research agenda will innovate solutions to large-scale problems and rapidly developing issues in the LGL. This new knowledge will help evaluate the effectiveness of restoration and management and ensure the long-term stewardship of the LGL ecosystem in the face of unanticipated and unwanted ecosystem change. With a close eye to research, acute problems that develop rapidly can be predicted based on assessments of large-scale drivers such as climate, population increase, and land use change. Thus, we advocate for an enhanced research agenda beginning with a program entitled "The International Decade of Great Lakes Exploration and Research."

This paper lays out the consensus research agenda described by the community of scientists at the 2014 Grand Challenges for Water Research in the LGL workshop. Articulating this agenda is an important step in establishing research priorities for the LGL for which funding is not in keeping with either the economic importance of the LGL or the magnitude of the system. We believe that an imbalance in basic research funding developed for two reasons. First, the history of pollution in the LGL that required attention to health issues sidetracked the community away from basic research on fundamental ecosystem processes. Second, we envision that there is a positive feedback loop: low current and historic support has discouraged scientific interest and research productivity which, in turn, diminished funding success and scientific motivation to seek support. The depressed proposal pressure feeds back into continuing low support and, crucially, lack of strong fundamental data to justify new endeavors. Imbalanced funding is occurring on both sides of the LGL binational boarder. For example, $22.4 million in active US National Science Foundation awards were directed toward studying the LGL in comparison to a total of $660 million in active awards in the three primary oceanographic programs (Physical, Chemical, and Biological Oceanography: search conducted December 2016, key words names of the individual LGL, "Great Lakes" and "Laurentian"). In Canada, the National Science and Research Council of Canada supports academic research. National Science and Research Council of Canada funding for Great Lakes projects is $2.7 million CDN, less than one-seventh of that for oceans (a search of National Science and Research Council of Canada website funding for period 2015–2016, using keywords "Great Lake*" and "ocean*"). Importantly, Canada lacks research funding programs, like US Sea Grant, that provide opportunities for academics to study aquatic systems, ocean or freshwater, let alone the LGL. Canada also lags behind the U.S. in maintaining funding levels of binational programs that focus on the LGL, for example the Great Lakes Fishery Commission (GLFC). Compounding funding imbalances for LGL research is a 4% and 2% decline in US federal support for Earth Science and Oceanography, respectively, between 2014 and 2015 (Britt 2016). In Canada, the Department of Fisheries and Oceans 2016 budget increased significantly (~$40 million CDN per yr) but only 4% was used for staff positions or new base funding for freshwater ecosystems, with only half of that dedicated to the LGL.

To begin to rectify funding shortfalls and to attempt to catalyze a new era in LGL science, the research community is faced with the challenge of developing and articulating the need for a comprehensive research agenda to engage the federal governments of U.S. and Canada, funding agencies, the scientific and management community and the general public. The result would expand scientific frontiers and enrich our scientific understanding of this system. In turn, this understanding would provide the necessary foundation for efforts to manage, protect, and restore the largest fresh water life support systems on the planet.

To meet the challenge of identifying a research agenda for the LGL, 58 Great Lakes researchers from the U.S. and Canada met on 05–06 September 2014 at Michigan State University to outline the Grand Challenges for Research in the LGL (Table 1). Participants were predominantly from U.S. academic institutions and their geographic representation spanned seven states and one province. In addition to academia, government, and industry were represented and participants had diverse expertise ranging from engineering to biology and oceanography. Taking into consideration and expanding on past related efforts, e.g., the Workshop on the Science of Freshwater Inland Seas (Johnson 2003) and a report on the Biogeochemistry of the Great Lakes System (Baskaran and Bratton 2013), participants engaged in a structured series of discussions to (1) identify the Grand Challenges for Research in the LGL; (2) articulate mechanisms for facilitating research in the LGL; and (3) explore the development of regional research consortia to coordinate research and be the voice of Great Lakes' science to the public, the media and funding agencies. Near the outset, participants were asked to write down one or more individual words that they thought should be included in the Grand Challenges. The words so chosen were used to generate a word cloud (Fig. 2), which offers an indication of the nature of the conversations by giving prominence to words that appeared more frequently. This exercise clearly indicated that participants viewed the LGL as a system responding to a range of anthropogenic drivers.

Despite the wide range of disciplinary backgrounds that were present, workshop participants were able to reach consensus on many issues. Following the workshop, the many dozens of ideas that were generated and shared were condensed into five topic areas to which a single Grand Challenge question and an individual Scientific Priority was assigned (Table 2). Strong emphasis was placed on the lakes themselves; though there are many important topics of research in the LGL watersheds it was determined that focusing on the lacustrine systems would be more relevant. Moreover, workshop discussions emphasized that the lakes act as integrators of responses from the broader watershed. The Grand Challenges are meant to be broadly framed but still

Table 1. Summary data on workshop participants.

Number of participants	58
Number of females	11
Number of States	7
Number of Provinces	1
Number giving academic addresses	56
Number of Universities	19

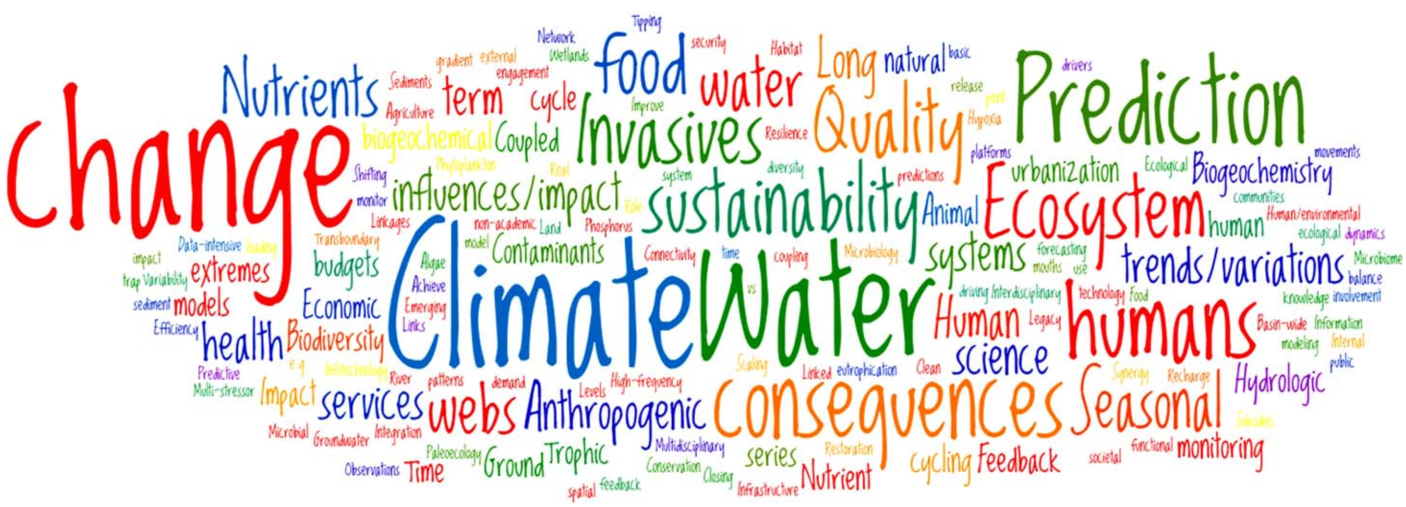

Fig. 2. Word cloud produced early in the workshop prioritization process. Words that appeared most frequently among a list gathered from participants appear more prominently. Color is used to differentiate word boundaries but is otherwise insignificant.

Table 2. Topic areas, grand challenges, and scientific priorities for research in the Great Lakes.

Topic area	Grand challenge	Scientific priority
1. Climate	How has this vast inland freshwater system responded to shifting climate in the past, and how will it respond in the future?	Strengthen and synthesize existing data to develop climate-sensitive models for all five lakes
2. Ecosystem processes	What is the current state of the most important ecosystem processes, including their variability in space and time?	Combine new technologies for observations with enhanced ship-based measurements leading to establishment of one time-series station in the offshore of each lake, coupled with time-series measurements from nearshore sites
3. Biophysical scale	What processes are characteristic only of such large systems and how do the smaller environmental units integrate into a whole?	Develop an understanding of the interaction of coastal and pelagic environments particularly in their role as critical habitats for Great Lakes food webs
4. Stressors	What are the expected responses to major anthropogenic forces such as nutrients and invasive species, and how many of these are reversible?	Improve our understanding of interacting stressors in the Great Lakes, and more specifically what imparts resilience to the Great Lakes ecosystems
5. Value to humans	What are the small to large-scale linkages and feedbacks among societal decisions, biological systems, and physicochemical dynamics?	Quantify the ecosystem services provided by the Great Lakes and develop an understanding of human-natural couplings operating at the scale of thousands of kilometers and involving millions of people

have enough specificity to establish genuine science goals, achievable with expanded but not wildly unrealistic levels of investment. The Scientific Priorities that go along with these questions are more specific than the Challenges. Addressing these individual priorities alone will not be enough to provide fully satisfying answers to the Grand Challenges, but meeting the challenges they represent would catalyze major progress. Combined, these topics, questions and priorities emphasize the need to develop a deeper understanding of the LGL that would contribute to enhanced ability to predict responses to drivers. The five topic areas and associated Grand Challenges and Scientific Priorities are listed in Table 2 and described more fully below.

Challenge 1: Climate

The Great Lakes, though vast, are geologically young having reached their modern configuration near the end of the Wisconsin Glacial Episode ca. 11,000 yr ago. The region currently is warmer and wetter than it has been over most of the past 12,000 yr (Magnuson et al. 1997). Though uncertainty remains in establishing cause and effect, changes observed in the LGL during the past few decades have been tied to climate change (Kling et al. 2003; Zhong et al. 2016). Winter ice cover is reduced (Wang et al. 2011); stratification patterns are altered (Cline et al. 2013); summer temperatures have increased (Austin and Colman 2008; Van Cleave et al. 2014). Major storms are more frequent and more intense (Villarini et al. 2011). Climate-driven changes are thought to have exacerbated algal blooms in western Lake Erie in recent years and modified thermal conditions throughout the LGL making the Lakes susceptible to invasive species adapted to warmer climates (Hong et al. 2006; Gronewold et al. 2013; Michalak et al. 2013). The vast size of the LGL does not confer resistance to climate forcing (see, e.g., Gronewold et al. 2013). The Grand Challenge question identified in this topic area, "How has this vast inland freshwater system responded to shifting climate in the past, and how will it respond in the future?" seeks to quantify these climate-induced effects.

Work on understanding how climate affects the LGL began years ago (Mortsch and Quinn 1996; Van Cleave et al. 2014) and progress continues (Lofgren et al. 2002) but large gaps remain. Although physical data describing climate and hydrodynamics (Croley and Hunter 1994) in the LGL are starting to accumulate (Gronewold et al. 2013), we are still missing data crucial to advance climate modeling. For example, meteorological observations are geographically sparse, winter analyses are rare, and there are very few over-lake observations. Further, continuous measurements of the thermal structure are virtually non-existent. Expanded and enhanced data need to be collected and fed into improved models.

The Scientific Priority identified here is to strengthen and synthesize existing data to develop climate-forced regional earth system models for all five lakes, which would feed into models capable of predicting ecosystem responses to climate change. This will necessarily require expanding data collection efforts, in particular that are temporally and spatially relevant and developing a comprehensive data base that includes historic and current records. Because of their large size, regional feedbacks such as changing rain/snow shadows need to be incorporated into our understanding (Notaro et al. 2012; d'Orgeville et al. 2014).

Challenge 2: Ecosystem Processes

An ecosystem description, based on inputs, outputs, and transformations of materials, is the scaffold from which food web dynamics, fisheries production and many other important ecological aspects of any system can be examined and put into context (Chapin et al. 2011). The information needed for such a scaffold includes physical, chemical, and biological parameters, including pools and fluxes of carbon and nutrients among key biotic and abiotic components, as well as major riverine inputs and outputs (Odum 1969). But as stated earlier, significant spatial and temporal variability characterizes these pools and fluxes in the LGL. Aquatic invasive species have dramatically rearranged parts of these ecosystems, but the record of these dramatic changes often is spotty. A site-based, long-term approach to ecosystem dynamics has proven scientifically valuable in the LGL (Evans et al. 2011) and many other places (Hobbie et al. 2003; Carpenter et al. 2007). Because physical and biological processes vary seasonally, as well as within- and among-lakes, continuous measurements are especially important for understanding fast-changing variables. A rigorous time-series approach is especially valuable for the interaction of models and data (Lawson et al. 1996). In addition, evaluation of year-to-year or gradually changing parameters requires a good baseline and subsequent temporally continuous high-quality observations (Magnuson 1990). An approach leading to an accurate ecosystem description would be essential for detecting and forecasting changes in the environment that influence ecosystem services, including those with use values, such as clean water supply and fisheries (Van Dyne 2012), as well as those with non-use values, such as cultural and aesthetic aspects of the lakes (Steinman et al. 2017).

At present, data fall far short of what would be needed for a comprehensive ecosystem based understanding of the LGL, a particularly important issue during a time of rapid ecosystem change (Ricciardi 2006; Cuhel and Aguilar 2013; Michalak et al. 2013). Data gaps are much too wide, especially for the offshore zones. Regular monitoring of some of the necessary parameters is performed by Federal agencies on both sides of the international border (U.S. EPA, http://www.epa.gov/grtlakes/monitoring/guard/ship.html and Environment Canada, http://www.ec.gc.ca/scitech/default.asp?lang = en&n = 3F61CB56-1), which includes a set of standard physical, chemical, and biological parameters. Spatial coverage of these two efforts is substantial, with tens of sampling locations per lake, but temporal resolution is coarse (EPA, 2x/yr and EC each lake every ~2 yr). Generally, observational data are concentrated within the navigation season and nearly all observation systems "go dark" during winter. Importantly, little to no process (rate) data are collected in the LGL on a sustained basis. Even in Lake Erie, a system that has undergone marked changes in primary production in response to phosphorus loading and subsequent mitigation activities, we do not have a long-term record to know how primary production has responded to management (Ostrom et al. 2005). Given these limitations, basic information such as the seasonal waxing and waning of plankton populations, rates of primary production, or nearly any microbially mediated process is highly incomplete in the LGL. Given the limitations of available information, the Grand Challenge question identified in this topic area was, "What is the current state of the most important ecosystem processes, including their variability in space and time?" We considered primary production, respiration, nitrification, denitrification, mineralization, and sedimentation among those that are the most important. A backbone of physical data that meshes seamlessly with these process measurements is also essential.

A high-level Scientific Priority identified at the workshop was to "Combine new technologies for observations with enhanced ship-based measurements leading to establishment of one time-series station in the offshore of each lake, coupled with time-series measurements from nearshore sites." Addressing this priority requires long-term research sites for shipboard measurements supplemented with permanent observing networks using sensor technology. Shipboard measurements, though demanding from an infrastructure standpoint, allow for determinations of rates and certain parameters for which we still lack robust sensors, for example net primary productivity (NPP) and some of the important nutrients. Observing networks, instrumented with sensors, offshore profilers, remotely operated autonomous vehicles and regional cabled observatories for linking coastal to pelagic processes would provide the foundation for addressing this Grand Challenge question (National Research Council 2003). Just as with the ocean observatories initiative (http://oceanobservatories.org/), such a network would provide needed real-time observing data to a broad community of scientists in the United States and Canada. Including rapidly advancing DNA-sequencing technologies would provide new opportunities to track biological communities, their roles in ecosystem processes and their dynamics in the context of changing climate and environment (Kelly et al. 2014). Integrated observations and research efforts will reveal links between human, biological, chemical, and physical systems and improve our understanding and ability to predict ecosystem processes and feedbacks. It is through the implementation of complementary observation network and shipboard programs that we will begin to understand and predict ecosystem processes in the LGL.

Challenge 3: Biophysical Scale

That the LGL make up the largest freshwater ecosystem on Earth, itself, has a strong bearing on this scientific prioritization. Because of its extraordinary scale, the LGL contain all the biophysical processes characteristics of small lakes,

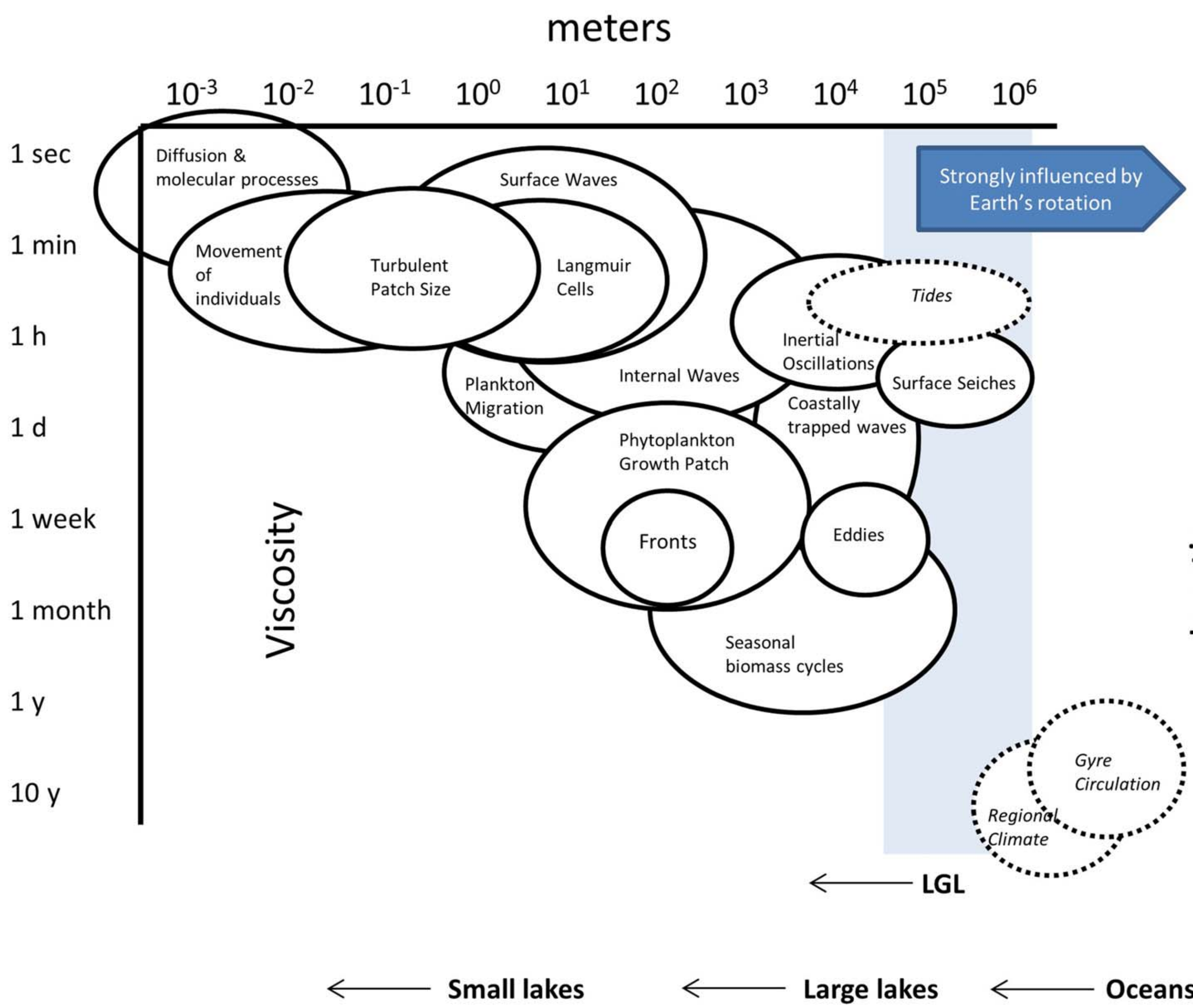

Fig. 3. Temporal and spatial scales associated with different biophysical phenomena. The Laurentian Great Lakes (gray shaded area) occupy intermediate positions between small lakes and oceans and as such they encompass phenomena such as seiches and coastally trapped waves that are not characteristic of smaller lakes but extend into the oceanic scale. Dotted ellipses are either oceanic or atmospheric.

plus those that are found only in the largest lakes on the planet. Thus, the lakes serve as a bridge in our understanding between smaller lakes and the oceans (Fig. 3). Because of their depth and surface area, large lakes are governed by physical processes that do not occur in small shallow lakes. Large lakes respond more slowly to atmospheric conditions, can maintain strong air-sea temperature gradients, and can develop persistent summer thermoclines that deepen, but do not erode, during strong wind forcing. Further, large lakes influence regional climates by buffering temperature extremes and producing "lake-effect" precipitation and maritime-like climatic conditions. Friction also plays a less dominant role in removing momentum from deep lakes, allowing currents in the mid- and upper-water column to persist for days or weeks.

Physical processes in large lakes are also different from those in small lakes because currents that extend over large distances (e.g., greater than 100 km) are strongly influenced by the Earth's rotation, i.e., dynamics of large lakes are strongly affected by the Coriolis force, such as inertial oscillations, coastally trapped waves, rotationally influenced nonlinear eddies, and geostrophic currents (Fig. 3). In addition, flows with large length scales are more strongly influenced by inertia than viscosity, which leads to motion at a wide range of temporal and spatial scales as energy cascades from large-scale features toward turbulence. In large lakes where motions occur at a broad range of scales, currents and temperatures can change rapidly over short distances, creating spatially complex but coupled mosaics of habitats. The transition zones themselves can function as hotspots of biogeochemical rates or biological activity (Biddanda and Cotner 2002; Klump et al. 2009; Chaffin et al. 2011). These physical properties mean one cannot simply "scale up" from small to large water bodies. On the other hand, the fact that these water bodies are much smaller than the world's oceans means that defining system bounds is much more straightforward for large-lake limnologists than for oceanographers. This intermediate scale, between most lakes and the oceans, makes the LGL a scientifically valuable test bed for understanding processes characteristic of 100s–1000s of km.

Physical processes and the resultant intermediate spatial gradients have biological significance that is still being determined. As an example, despite their small areal contribution to large lake surface area, littoral zones have the highest concentration of stressors (Allan et al. 2013) and are the dominant interface between the LGL systems and humans. Littoral zones also harbor an overwhelmingly large fraction of animal biodiversity in the LGL (Vadeboncoeur et al. 2011). Coupling of littoral and pelagic habitats appears to play a key role in determining ecosystem function of LGL system (Hecky et al. 2004; Larson et al. 2013; Althouse et al. 2014). In the horizontal dimension, shallow water habitats are vital for fish recruitment in offshore habitats with currents playing a key role in linking these habitats. Good examples of the importance of considering these processes have recently appeared in the study of fish recruitment (Janssen et al. 2014; Ludsin et al. 2014; Pritt et al. 2014). Coupling extends over the comparatively long vertical scale as well as the horizontal one; for example, filter feeding by dreissenid mussels has dramatically reduced seston and increased light penetration, leading to a cascade of changes that has been described as "the nearshore phosphorus shunt" (Hecky et al. 2004). It is only by understanding how diverse habitats are connected via broader-scale physical processes and integrated into a whole that we can successfully predict and manage environmental change and the implications for ecosystem services.

The Grand Challenge question identified in the topic area of Biophysical Scale was, "What processes are characteristic only of such large lentic systems and how do the smaller environmental units integrate into a whole?" Combining data from multiple sources is often a pre-requisite for progress in topics like this and tools that integrate information at the necessary scale are appearing and improving (Wang et al. 2015). The Scientific Priority identified within this topic area is to develop an integrated understanding of the coupling between coastal and pelagic, particularly in their respective role as critical habitats for Great Lakes food webs. To address this priority, research platforms associated with these large-scale gradients spanning estuarine, coastal, offshore, and deep-water environments are needed.

Challenge 4: Stressors

Humans are a powerful agent of change in the LGL in ways that affect, often negatively, the benefits that we receive. The Great Lakes are subject to a wide variety of anthropogenic influences that have degraded their recreational, economic, and spiritual value (Smith et al. 2015). These stressors include toxins, agricultural runoff, invasive species, urbanization and habitat, and hydrologic modification. Attention is directed toward nutrients and toxic chemicals, but invasive species and climate change are also taking center stage (Cuhel and Aguilar 2013; Smith et al. 2015). No other freshwater system contains as many non-native species as the LGL. Climate change is likely to have dramatic and still poorly understood impacts on the LGL in the coming decades. Indeed, the interaction of these two categories of stressors may also be crucial in that the LGL may be more vulnerable to invasive species as the waters warm (Hong et al. 2006; Pagnucco et al. 2014). It is difficult to disentangle a single stressor from the milieu of many anthropogenic impacts. Using a combined index, there was large variation in the intensity and spatial coverage of stressors across the LGL (Fig. 4) (Allan et al. 2013). The number of stressors and their combined impact was highest nearshore, and most areas were subjected to multiple stressors (Allan et al. 2013; Smith et al. 2015). Given this pattern, it is clearly necessary to adopt a more comprehensive approach to understanding human-induced degradation rather than a case-by-case approach examining single stressors. Furthermore, there is an urgent need to understand whether the ecosystem response to multiple stressors is simply additive, or involves synergistic or antagonistic effects and to understand the resilience and resistance of the LGL to both stressors and climate variability.

But not all trends involve environmental degradation. As discussed above, major efforts toward ecological restoration are occurring via programs such as the GLRI and AOC. Restoration is a concerted attempt to reverse past damages. Success of restoration projects naturally varies; those systems that are most resilient recover quickest. The Grand Challenge question identified in this topic area therefore was, "What are the ecosystem responses to major anthropogenic forces such as nutrients and invasive species and are they reversible?" To this end, the priority for this topic area is to "Improve our understanding of interacting stressors in the Great Lakes, and more specifically what imparts resilience to the Great Lakes ecosystems."

Challenge 5: Value to Humans

It can be argued that the Great Lakes are the greatest freshwater life support systems on the planet—essential to the sustainability of North America as a whole, and providing billions of dollars in economic value to two powerful nations (Krantzberg and De Boer 2006; Campbell et al. 2015). Identifying the

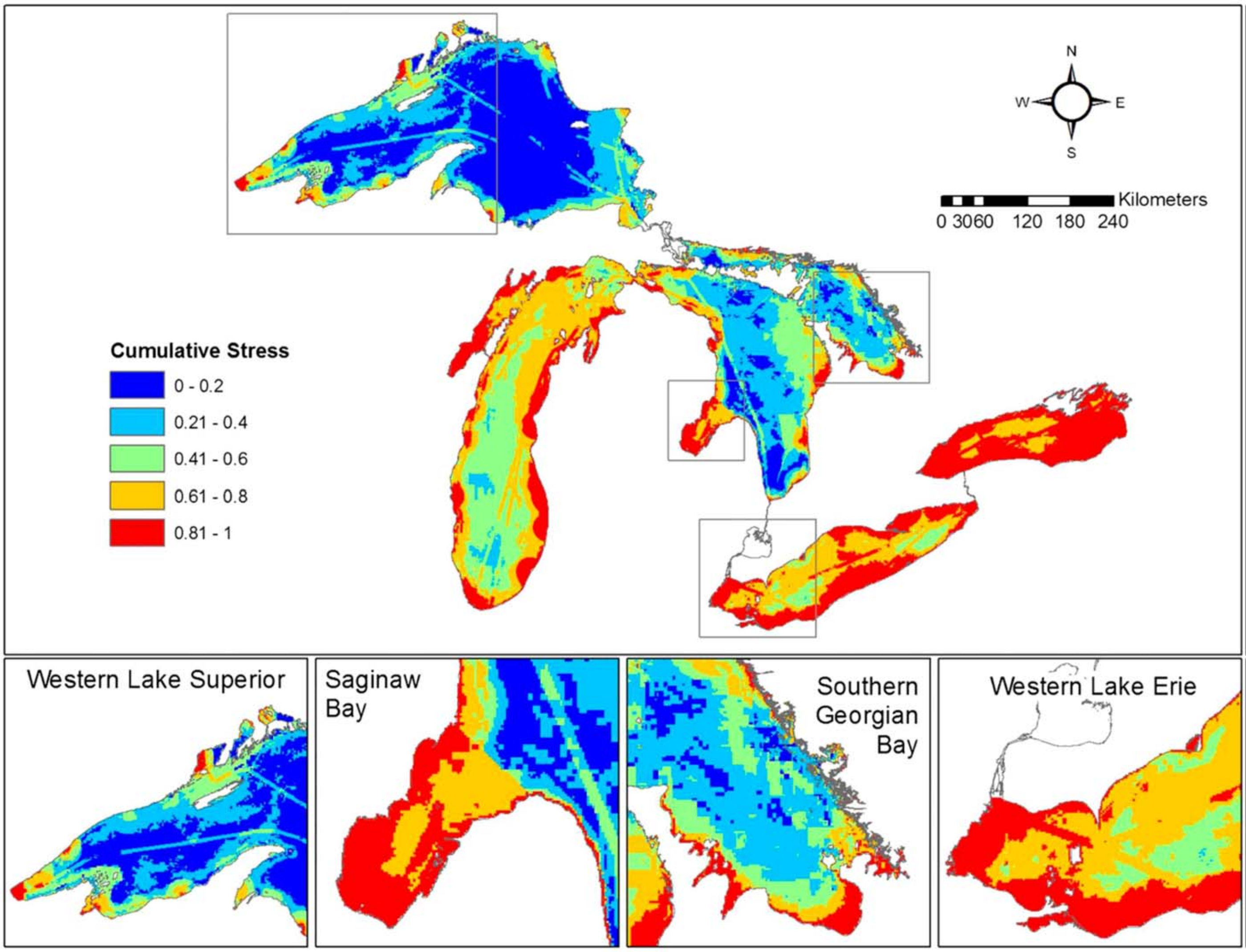

Fig. 4. Spatial pattern of a combined index of 34 stressors across the Great Lakes. Relative (percentile) scale. Most areas experience 10–15 stressors. From Allan et al. (2013).

impacts of human activities is particularly important. However, studies of the relationship between ecosystem responses and human activities, for example with the Millenium Ecosystem Assessment, have started only recently in the LGL (Stevenson 2011; Mavrommati et al. 2014). Thus, the services, benefits and vulnerability of the LGL to North America and the world are still imprecisely quantified and thus poorly recognized by decision makers and the public alike (Steinman et al. 2017). Only by describing and understanding the benefits that humans derive from the Great Lakes will we be able to factor the many benefits we receive into decision making.

Humans have exerted a powerful influence on many aspects of the Great Lakes system in a way that affects their value (Kalafatis et al. 2015). The future of this system is very much dependent on social forces (Laurent et al. 2015). This highlights the interactive feedbacks between humans and the Great Lakes system. These linkages and feedbacks directly determine both ecosystem and human well-being, but remain poorly understood. Similar to the biophysical processes described above, the social systems connected to the Great Lakes span a great range in scales with overlapping social and political boundaries. In response, the Grand Challenge question in this topic area was, "What are the small to large scale linkages and feedbacks among societal decisions, biological systems and physicochemical dynamics?" To address this question, a priority is to inventory and to value the ecosystem services provided by the Great Lakes and to develop an understanding of human-natural couplings operating up to the scale of thousands of kilometers and involving millions of people. To address this priority we seek to understand the reciprocal relationship between (1) biophysical components and ecosystem services and (2) humans and their environment using predictive modeling and social-ecological systems or coupled human and natural systems models (Liu et al. 2007; Ostrom 2009; Carpenter et al. 2011; Mavrommati et al. 2014). New models need to be informed by data from economic and social science research as well as information on ecosystem processes and climate change. In addition, adaptive risk management approaches offer an important strategy for decision making under highly variable conditions (Bidwell et al. 2013).

Conclusions

With the Michigan State University workshop and this white paper that emerged from it, the Great Lakes research community is beginning to come forth with a voice. The researchers who contributed to this effort are not an isolated interest group. Their goals coincide with other initiatives to support data gathering and increased attention on the LGL (e.g., Great Lakes Observing System) and indeed Earth's freshwaters in general (e.g., Shakhashiri et al. 2015). Greater scientific attention and increased binational research funding can only pay dividends in improving our ability to wisely manage the LGL, an immense and valuable system. Our efforts to identify a research agenda for the LGL coincide with a national and global water crisis that derives from climate and anthropogenic change coupled with increasing demands for water for drinking, industry, transportation, aqua- and agriculture, extraction of fossil fuels and recreation (Macdonald 2010; Carpenter et al. 2011; Wheeler and Von Braun 2013; Pekel et al. 2016).

We cannot take water for granted. In the summer of 2014, 450,000 residents of Toledo, Ohio, U.S.A. lacked drinking water for 2 d due to an outbreak of a toxic cyanobacterium, *Microcystis aeruginosa*, in Lake Erie. We know enough to predict the risk of occurrence of such blooms (Wynne et al. 2013) but without an in depth understanding of linkages among ecosystem processes and drivers we do not know what steps are needed to prevent toxic algal blooms. Our limited understanding of the biological, physiochemical and societal attributes of the LGL along with increasing frequency of anthropogenic perturbations places North America's freshwater life support system at risk. The dearth of societal support for science to underpin decision-making is a formula for exacerbating the current global freshwater crisis. Embracing the Grand Challenges outlined herein with an appropriate funding platform will produce an integrated understanding of the LGL ecosystem, advance technology, enable proactive management and secure the endurance of an irreplaceable freshwater resource.

References

Allan, J. D., and others. 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. Proc. Natl. Acad. Sci. USA **110**: 372–377. doi:10.1073/pnas.1213841110

Althouse, B. A., S. Higgins, and M. J. Vander Zanden. 2014. Benthic and planktonic primary production along a nutrient gradient in Green Bay, Lake Michigan, USA. Freshw. Sci. **33**: 487–498. doi:10.1086/676314

Assel, R., K. Cronk, and D. Norton. 2003. Recent trends in Laurentian Great Lakes ice cover. Clim. Chang. **57**: 185–204. doi:10.1023/A:1022140604052

Austin, J., and B. Affolter-Caine. 2006. The Vital Center: A Federal-State compact to renew the Great Lakes region, p. 50. The Brookings Institution Metropolitan Policy Program.

Austin, J. C., S. Anderson, P. N. Courant, and R. E. Litan. 2007. Healthy waters: The benefits of restoring the Great Lakes ecosystem, p. 16. The Brookings Institution - Great Lakes Economic Initiative.

Austin, J. A., and S. M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophys. Res. Lett. **34**. doi:10.1029/2006GL029021

Austin, J. A., and S. M. Colman. 2008. A century of temperature variability in Lake Superior. Limnol. Oceanogr. **53**: 2724–2730. doi:10.4319/lo.2008.53.6.2724

Baskaran, M., and J. Bratton. 2013. Investigating human-induced changes of elemental cycles in the Great Lakes. Eos Trans. AGU **94**: 248. doi:10.1002/2013EO280005

Beeton, A. M. 2002. Large freshwater lakes: Present state, trends and future. Environ. Conserv. **29**: 21–38. doi:10.1017/S0376892902000036

Biddanda, B. A., and J. B. Cotner. 2002. Love handles in aquatic ecosystems: The role of dissolved organic carbon drawdown, resuspended sediments, and terrigenous inputs in the carbon balance of Lake Michigan. Ecosystems **5**: 431–445. doi:10.1007/s10021-002-0163-z

Bidwell, D., T. Dietz, and D. Scavia. 2013. Fostering knowledge networks for climate adaptation. Nat. Clim. Chang. **3**: 610–611. doi:10.1038/nclimate1931

Britt, R. 2016. Universities report fourth straight year of declining federal R&D funding in FY 2015. InfoBrief National Center for Science and Engineering Studies. 6 pp. Available from https://www.nsf.gov/statistics/2017/nsf17303/nsf17303.pdf

Campbell, M., M. J. Cooper, K. Friedman, and W. P. Anderson. 2015. The economy as a driver of change in the Great Lakes–St. Lawrence River basin. J. Great Lakes Res. **41**: 69–83. doi:10.1016/j.jglr.2014.11.016

Carpenter, S., and others. 2007. Understanding regional change: A comparison of two lake districts. BioScience **57**: 323–335. doi:10.1641/B570407

Carpenter, S. R., E. H. Stanley, and M. J. Vander Zanden. 2011. State of the world's freshwater ecosystems: Physical, chemical, and biological changes. Annu. Rev. Environ. Resour. **36**: 75–99. doi:10.1146/annurev-environ-021810-094524

Chaffin, J. D., B. Bridgeman, S. A. Heckathorn, and S. Mishra. 2011. Assessment of Microcystis growth rate potential and nutrient status across a trophic gradient in western Lake Erie. J. Great Lakes Res. **37**: 92–100. doi:10.1016/j.jglr.2010.11.016

Chapin, F. S., II, P. A. Matson, and P. M. Vitousek. 2011. Principles of terrestrial ecosystem ecology, 2nd ed. Springer.

Cline, T. J., V. Bennington, and J. F. Kitchell. 2013. Climate change expands the spatial extent and duration of preferred thermal habitat for Lake Superior fishes. PLoS One **8**: e62279. doi:10.1371/journal.pone.0062279

Croley, T. E. I., and T. S. Hunter. 1994. Great Lakes monthly hydrologic data, NOAA Technical Memorandum ERL GLERL-83, p. 83. Great Lakes Environmental Research Laboratory.

Cuhel, R. L., and C. Aguilar. 2013. Ecosystem transformations of the Laurentian Great Lake Michigan by nonindigenous biological invaders. Mar. Sci. **5**: 289–320. doi:10.1146/annurev-marine-120710-100952

d'Orgeville, M., W. R. Peltier, A. R. Erler, and J. Gula. 2014. Climate change impacts on Great Lakes Basin precipitation extremes. J. Geophys. Res. **119**: 799–10812. doi:10.1002/2014JD021855

Dove, A., and S. C. Chapra. 2015. Long-term trends of nutrients and trophic response variables for the Great Lakes. Limnol. Oceanogr. **60**: 696–721. doi:10.1002/lno.10055

ECCC. 2016. Environment Canada and Climate Change Great Lakes Quickfacts. Available from www.ec.gc.ca/grandslacs-greatlakes/default.asp?lang=En&n=B4E65F6F-1

Evans, M. A., G. Fahnenstiel, and D. Scavia. 2011. Incidental oligotrophication of North American Great Lakes. Environ. Sci. Technol. **45**: 3297–3303. doi:10.1021/es103892w

Great Lakes Interagency Task Force. 2015. Great Lakes Restoration Initiative report to congress and the President, Fiscal Years 2010-2014. Available from https://www.glri.us//pdfs/21050720-report_to_congress.pdf

Gronewold, A., V. Fortin, B. Lofgren, A. Clites, C. Stow, and F. Quinn. 2013. Coasts, water levels, and climate change: A Great Lakes perspective. Clim. Chang. **120**: 697–711. doi:10.1007/s10584-013-0840-2

Hecky, R. E., R. E. H. Smith, D. R. Barton, S. J. Guildford, W. D. Taylor, M. N. Charlton, and T. Howell. 2004. The nearshore phosphorus shunt: A consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. Can. J. Fish. Aquat. Sci. **61**: 1285–1293. doi:10.1139/f04-065

Hobbie, J. E., R. Carpenter, N. B. Grimm, J. R. Gosz, and T. R. Seastedt. 2003. The US long term ecological research program. BioScience **53**: 21–32. doi:10.1641/0006-3568(2003)053[0021:TULTER]2.0.CO;2]

Hong, Y., A. Steinman, B. Biddanda, R. Rediske, and G. Fahnenstiel. 2006. Occurrence of the toxin-producing cyanobacterium Cylindrospermopsis raciborskii in Mona and Muskegon Lakes, Michigan. J. Great Lakes Res. **32**: 645–652. doi:10.3394/0380-1330(2006)32[645:OOTTCC]2.0.CO;2]

International Joint Commission (IJC). 1972. Report on Great Lakes Water Quality for 1972. Available from http://www.ijc.org/files/publications/ID610.pdf

International Joint Commission (IJC). 2000. Protection of the Waters of the Great Lakes Final Report to the Governments of Canada and the United States, February 22, 2000. Available from http://www.ijc.org/files/publications/C129.pdf

International Joint Commission (IJC). 2015. Protection of the Waters of the Great Lakes: 2015 Review of the recommendations from the February 2000 report. Available from http://ijc.org/files/tinymce/uploaded/Publications/IJC_2015_Review_of_the_Recommendations_of_the_PWGL_January_2016.pdf

Janssen, J., J. E. Marsden, T. R. Hrabik, and J. D. Stockwell. 2014. Are the Laurentian Great Lakes great enough for Hjort? ICES Journal of Marine Science **8**: 2224–22251. doi:10.1093/icesjms/fst220

Johnson, T. C. 2003. Science of freshwater inland seas (SOFIS) contributions from the SOFIS working group. Large Lakes Observatory Technical Report, 1.

Kalafatis, S. E., M. Campbell, F. Fathers, K. L. Laurent, K. B. Friedman, G. Krantzberg, D. Scavia, and I. F. Creed. 2015. Out of control: How we failed to adapt and suffered the consequences. J. Great Lakes Res. **41**: 20–29. doi:10.1016/j.jglr.2014.12.002

Kelly, R. P., and others. 2014. Harnessing DNA to improve environmental management. Science **344**: 1455–1456. doi:10.1126/science.1251156

Kling, G. W., and others. 2003. Confronting climate change in the Great Lakes region: Impacts on our communities and ecosystems. Union of Concerned Scientists, Cambridge, Massachusetts and Ecological Society of America Washington, DC, 92.

Klump, J. V., A. Fitzgerald, and J. T. Waples. 2009. Benthic biogeochemical cycling, nutrient stoichiometry, and carbon and nitrogen mass balances in a eutrophic freshwater bay. Limnol. Oceanogr. **54**: 792–812. doi:10.4319/lo.2009.54.3.0692

Krantzberg, G., and C. De Boer. 2006. A valuation of the ecological services in the Great Lakes Basin Ecosystem to sustain healthy communities and a dynamic economy. Prepared for the Ontario Ministry of Natural Resources by Dofasco Centre for Engineering and Public, Policy McMaster University. Retrieved March 8, 2007.

Larson, J. H., S. Trebitz, A. D. Steinman, M. J. Wiley, M. C. Mazur, V. Pebbles, H. A. Braun, and P. W. Seelbach. 2013. Great Lakes rivermouth ecosystems: Scientific synthesis and management implications. J. Great Lakes Res. **39**: 513–524. doi:10.1016/j.jglr.2013.06.002

Laurent, K. L., D. Scavia, K. B. Friedman, G. K. Krantzberg, and I. F. Creed. 2015. Critical forces defining alternative futures for the Great Lakes–St. Lawrence River basin. J. Great Lakes Res. **41**: 131–138. doi:10.1016/j.jglr.2014.11.006

Lawson, L. M., E. Hofmann, and Y. H. Spitz. 1996. Time series sampling and data assimilation in a simple marine ecosystem model. Deep-Sea Res. Part II **43**: 625–651. doi:10.1016/0967-0645(95)00096-8

Liu, J., and others. 2007. Coupled human and natural systems. Ambio **36**: 639–649. doi:10.1579/0044-7447(2007)36[639:CHANS]2.0.CO;2

Lofgren, B. M., H. Quinn, A. H. Clites, R. A. Assel, A. J. Eberhardt, and C. L. Luukkonen. 2002. Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. J. Great Lakes Res. **28**: 537–554. doi:10.1016/S0380-1330(02)70604-7

Ludsin, S. A., M. Devanna, and R. E. H. Smith. 2014. Physical–biological coupling and the challenge of understanding fish recruitment in freshwater lakes. Can. J. Fish. Aquat. Sci. **71**: 775–794. doi:10.1139/cjfas-2013-0512

Macdonald, G. M. 2010. Water, climate change, and sustainability in the southwest. Proc. Natl. Acad. Sci. USA **107**: 21256–21262. doi:10.1073/pnas.0909651107

Magnuson, J. J. 1990. Long-term ecological research and the invisible present. BioScience **40**: 495–501. doi:10.2307/1311317

Magnuson, J. J., and others. 1997. Potential effects of climate changes on aquatic systems: Laurentian Great Lakes and Precambrian Shield region. Hydrol. Process. **11**: 825–871. doi:10.1002/(SICI)1099-1085(19970630)11:8 < 825::AID-HYP509 > 3.0.CO;2-G

Mavrommati, G., M. M. Baustian, and E. A. Dreelin. 2014. Coupling socioeconomic and lake systems for sustainability: A conceptual analysis using Lake St. Clair region as a case study. Ambio **43**: 275–287. doi:10.1007/s13280-013-0432-4

Méthot, J., X. Huang, and H. Grover. 2015. Demographics and societal values as drivers of change in the Great Lakes–St. Lawrence River basin. J. Great Lakes Res. **41**: 30–44. doi:10.1016/j.jglr.2014.11.001

Michalak, A. M., and others. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proc. Natl. Acad. Sci. USA **110**: 6448–6452. doi:10.1073/pnas.1216006110

Millie, D. F., L. Fahnenstiel, J. D. Bressie, R. J. Pigg, R. R. Rediske, D. M. Klarer, P. A. Tester, and R. W. Litaker. 2009. Late-summer phytoplankton in western Lake Erie (Laurentian Great Lakes): Bloom distributions, toxicity, and environmental influences. Aquat. Ecol. **434**: 915–934. doi:10.1007/s10452-009-9238-7

Mittag, M., J. Bails, B. Brown, M. J. Kealy, and D. Medina. 2006. A watershed process to quantify and facilitate ecosystem improvements through flow regime restoration, p. 109. *In* R. Graham [ed.], World Environmental and Water Resource Congress 2006: Examining the Confluence of Environmental and Water Concerns (p. 1–9).

Mortsch, L. D., and F. H. Quinn. 1996. Climate change scenarios for Great Lakes Basin ecosystem studies. Limnol. Oceanogr. **41**: 903–911. doi:10.4319/lo.1996.41.5.0903

National Academy of Sciences (NAS). 2015. Sea Change: 2015-2025 decadal survey of ocean sciences. The National Academy Press.

National Research Council. 2003. Enabling ocean research in the 21st century: Implementation of a network of ocean observatories. The National Academies Press.

Northland College. 2016. The future of the Great Lakes restoration initiative. Northland College.

Notaro, M., K. Holman, A. Zarrin, E. Fluck, S. Vavrus, and V. Bennington. 2012. Influence of the Laurentian Great Lakes on regional climate. J. Clim. **26**: 789–804. doi:10.1175/jcli-d-12-00140.1

Odum, E. P. 1969. The strategy of ecosystem development. Science **164**: 262–270. doi:10.1126/science.164.3877.262

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. Science **325**: 419–422. doi:10.1126/science.1172133

Ostrom, N. E., J. Carrick, M. R. Twiss, and L. Piwinski. 2005. Evaluation of primary production in Lake Erie by multiple proxies. Oecologia **144**: 115–124. doi:10.1007/s00442-005-0032-5

Pagnucco, K. S., A. Maynard, S. A. Fera, N. D. Yan, T. F. Nalepa, and A. Ricciardi. 2014. The future of species invasions in the Great Lakes-St. Lawrence River basin. J. Great Lakes Res. **41**: 96–107. doi:10.1016/j.jglr.2014.11.004

Pekel, J. F., A. Cottam, N. Gorelick, and A. S. Belward. 2016. High-resolution mapping of global surface water and its long-term changes. Nature **540**: 418–422. doi:10.1038/nature20584

Pritt, J. J., F. Roseman, and T. P. O'Brien. 2014. Mechanisms driving recruitment variability in fish: Comparisons between the Laurentian Great Lakes and marine systems. ICES J. Mar. Sci. **71**: 2252–2267. doi:10.1093/icesjms/fsu080

Quinn, F. H. 1992. Hydraulic residence times for the Laurentian Great Lakes. J. Great Lakes Res. **18**: 22–28. doi:10.1016/S0380-1330(92)71271-4

Ricciardi, A. 2006. Patterns of invasion in the Laurentian Great Lakes in relation to changes in vector activity. Divers. Distrib. **12**: 425–433. doi:10.1111/j.1366-9516.2006.00262.x

Ricciardi, A., and H. J. MacIsaac. 2000. Recent mass invasion of the North American Great Lakes by Ponto–Caspian species. Trends Ecol. Evol. **15**: 62–65. doi:10.1016/S0169-5347(99)01745-0

Rothlisberger, J. D., C. Finoff, R. M. Cooke, and D. M. Lodge. 2012. Ship-borne nonindigenous species diminish Great Lakes ecosystem services. Ecosystems **15**: 462–476. doi:10.1007/s10021-012-9522-6

Shakhashiri, B. Z., L. Sedlak, and J. L. Schnoor. 2015. ACS Global water initiative: The grand challenge of water. Chem. Eng. News **91**: 37.

Smith, S. D. P., and others. 2015. Rating impacts in a multi-stressor world: A quantitative assessment of 50 stressors affecting the Great Lakes. Ecol. Appl. **25**: 717–728. doi: 10.1890/14-0366.1

Southwick Associates. 2012. Sportfishing in America: An Economic Force for Conservation. A report for the American Sportfishing Association.

Steinman, A. D., and others. 2017. Ecosystem services in the Great Lakes. J. Great Lakes Res. **43**: 161–168.

Stevenson, R. J. 2011. A revised framework for coupled human and natural systems, propagating thresholds, and managing environmental problems. Phys. Chem. Earth Parts A/B/C. **36**: 342–351. doi:10.1016/j.pce.2010.05.001

Trumpickas, J., B. J. Shuter, and C. K. Minns. 2009. Forecasting impacts of climate change on Great Lakes surface water temperatures. J. Great Lakes Res. **35**: 454–463. doi: 10.1016/j.jglr.2009.04.005

Uzarski, D. G., and others. 2017. Standardized measures of coastal wetland condition: Implementation at a Laurentian Great Lakes basin-wide scale. Wetlands **37**: 15–32. doi:10.1007/s13157-016-0835-7

Vadeboncoeur, Y., P. B. Mcintyre, and M. J. Vander Zanden. 2011. Borders of biodiversity: Life at the edge of the world's large lakes. BioScience **61**: 526–537. doi:10.1525/bio.2011.61.7.7

Van Cleave, K., J. D. Lenters, J. Wang, and E. M. Verhamme. 2014. A regime shift in Lake Superior ice cover, evaporation, and water temperature following the warm El Niño winter of 1997–1998. Limnol. Oceanogr. **59**: 1889–1898. doi:10.4319/lo.2014.59.6.1889

Van Dyne, G. 2012. The ecosystem concept in natural resource management. Elsevier.

Villarini, G., A. Smith, M. L. Baeck, R. Vitolo, D. B. Stephenson, and W. F. Krajewski. 2011. On the frequency of heavy rainfall for the Midwest of the United States. J. Hydrol. **400**: 103–120. doi:10.1016/j.jhydrol.2011.01.027

Wang, J., X. Bai, H. Hu, A. Clites, M. Colton, and B. Lofgren. 2011. Temporal and spatial variability of Great Lakes ice cover, 1973–2010. J. Clim. **25**: 1318–1329. doi:10.1175/2011JCLI4066.1

Wang, L., and others. 2015. A spatial classificiation and database for management, research, and policy making: The Great Lakes aquatic habitat framework. J. Great Lakes Res. **41**: 584–596. doi:10.1016/j.jglr.2015.03.017

Waples, J. T., B. Eadie, J. V. Klump, M. Squires, J. Cotner, and G. Mckinley. 2008. The Laurentian Great Lakes. Continental Margins: A synthesis and planning workshop. North American Continental Margins Working Group for the U.S. Carbon Cycle Scientific Steering Group and Interagency Working Group. US Carbon Cycle Program.

Wheeler, T., and J. Von Braun. 2013. Climate change impacts on global food security. Science **341**: 508–513. doi:10.1126/science.1239402

Wynne, T. T., R. P. Stumpf, M. C. Tomlinson, G. L. Fahnenstiel, J. Dyble, D. J. Schwab, and S. Joseph Joshi. 2013. Evolution of a cyanobacterial bloom forecast system in western Lake Erie: Development and initial evaluation. J. Great Lakes Res. **39**: 90–99. doi:10.1016/j.jglr.2012.10.003

Zhong, Y., M. Notaro, S. J. Vavrus, and M. J. Foster. 2016. Recent accelerated warming of the Laurentian Great Lakes: Physical drivers. Limnol. Oceanogr. **61**: 1762–1786. doi:10.1002/lno.10331

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Conflict of Interest

None declared.

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