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Building a research network to better understand climate governance in the Great Lakes ☆

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ABSTRACT

Climate-driven disturbances threaten the sustainability of coastal communities in the Great Lakes Basin. Because such disturbances are unpredictable, their magnitude, number and intensity are changing, and they occur at varying temporal and spatial scales. Consequently, communities struggle to respond in effective ways. The expected intensification of climate-driven disturbances will require that community capacity and governance structures match the spatial and temporal scales of these disturbances, as the most sustainable social and economic systems will be those that can respond at similar frequencies to key natural system drivers. The Climate Governance Variability in the Great Lakes Research Coordination Network (CGVG-RCN) was recently established to address questions about the relationship between climate-driven disturbances and community response. The objective of this short communication is to introduce the ideas behind the CGVG-RCN, outline its goals, and facilitate engagements and collaboration with social and natural scientists interested in social-ecological systems in the Great Lakes Basin.

Introduction

Climate-driven disturbances, including variable water levels, warming water temperatures, reduced lake ice extent, and intensified storms are increasingly threatening the sustainability of coastal communities across the Great Lakes Basin (Wuebbles et al., 2019, Bartolai et al., 2015). These physical disturbances are often closely followed by secondary disturbances such as cyanobacteria blooms (Ho et al., 2019) and aquatic invasive species (Rahel and Olden, 2008). Great Lakes coastal communities struggle to respond to climate-driven disturbances in part because their variability occurs over time scales from hours to centuries, and different social responses are necessary over such a wide range of scales. For example, short-term variability originates from sources such as storm events that can affect nutrient and pathogen delivery and threaten coastal infrastructure. Other rapid changes include microbial population changes that affect beach closures, or cyanobacterial harmful algal blooms (cHABs) that degrade fisheries, recreation, and threaten drinking water sources. At this short time scale social responses are behavioral and reactionary (Smith et al., 2000). Medium-term variability includes multi-annual lake level changes, waxing and waning of fisheries stocks, and introduction and impact of invasive species. At this medium time scale, more structural demographic or engineering-based human responses take place. Over the longest time scales, but still relevant to humans, are changing climate and even geologic forces such as isostatic rebound that affect water levels at decadal to century-long scales. Simultaneously, major shifts in human settlement over decadal and longer scales have the potential to increase the susceptibility of coastal communities to the impacts of climate-driven disturbances.

☆ *Given their roles as Guest Editors, Ryan Bergstrom and Alan Steinman had no involvement in the peer-review of this article and had no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Chris McLaughlin.*

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The Climate Governance Variability in the Great Lakes Research Collaboration Network (CGVG-RCN) was recently established to articulate and address pressing questions about the nature of climate-driven variability on Great Lakes shorelines, the synchronicity between natural variability and social change, and the feedbacks and couplings between one of Earth's largest surface fresh water sources and a large, intensive human social/economic system on its shores. The objective of this short communication is to introduce the CGVG-RCN, articulate its goals and objectives, and encourage engagement and collaboration with social and natural scientists who are interested in better understanding the coupled and complex relationship between climate-driven disturbances and coastal community response in the Great Lakes.

The Climate Governance Variability in the Great Lakes Project

In the spring of 2019, the National Science Foundation solicited proposals for research opportunities related to Coastlines and People (CoPe) via a cross-directorate (Geosciences; Social, Behavioral and Economic Sciences; Biological Sciences; Engineering; Education and Human Resources; and the Office of Integrative Activates) Dear Colleague Letter. The primary objective of CoPe projects is to better understand the impacts natural hazards have on coastal communities across a range of spatial and temporal scales, while broadening participation of researchers, decision-makers, practitioners, and stakeholders (NSF 19-059).

To address the overarching question as to whether the current governance structures and capacities of coastal communities in the Great Lakes can adapt to and optimize responses to the changing variability in climate-driven stressors and drivers, the Climate-Governance Variability in the Great Lakes (CGVG) Research Coordination Network (RCN) was proposed and established in April of 2020. The goal of the National Science Foundation's Research Coordination Network Program is to promote collaboration among scientists from a broad range of backgrounds and geographies. RCNs do not support new data generation; instead the aim of an RCN is to bring a network of scientists together to advance a specific research area through new, structured interactions. An RCN was chosen for this project because they have proven to increase the relevance of communities of practice, increase activity within the networks themselves, and produce highly interdisciplinary and influential publications (Porter et al., 2012).

The CGVG-RCN has the potential to transform collaborative research between social and natural scientists across the Great Lakes region, and contribute to the developing theory of social-ecological systems by advancing basic knowledge, while benefiting local stakeholders and decision makers through the dissemination of knowledge. Disciplines and areas of interest span the social sciences (e.g., economics, ecosystem services, communication, tribal impacts, amenity migration, tourism and recreation, transportation, planning, etc.), and natural sciences (e.g., water level modeling, coastal food webs, isostatic rebound, climate impacts, wetland ecology, etc.). It is understood that numerous networks currently exist in the Great Lakes that have similar end goals, but that may have different temporal, spatial, or thematic foci. Examples are: the Great Lakes and St. Lawrence Cities Initiative, the Organizing Urban Transects for a Sustainable Transformation of Economic Partnerships across the Lower Great Lakes (OUTSTEP-LGL), the Superior Watershed Partnership, and the Great Lakes Ecological Observatory Network, among a multitude of others. It is also understood that communication across such a wide diversity of networks is difficult and does not happen without focused efforts. However, the diversity of scholarship inherent in these organizations will benefit the CGVG RCN and the region as a whole. Thus, one of the primary objectives of the RCN is to bring together participants from the various networks and working groups across the basin to foster collaboration, disseminate information, and synthesize interdisciplinary data for the mutual benefit of stakeholders, decision makers, and the scientific community at large (Fig. 1).

CGVG RCN aims and outcomes

We have identified a set of aims (what do we want to accomplish), a set of topics (what aspects of the coastal system do we want to focus on), and a set of questions (what theoretical insights do we want to develop) (Fig. 2).

The primary aims of this RCN are to: 1) develop and deepen cross-disciplinary dialogue between social and natural scientists regarding climate-driven disturbances in the Great Lakes; 2) synthesize existing datasets and research to quantify important couplings between social and natural Great Lakes systems at a variety of scales, thus better informing decision making regarding solutions to existing and future challenges faced by coastal communities; 3) identify knowledge gaps for predicting impacts of climate-driven changes that impact coastal communities and relate these to potential community responses; 4) compare existing knowledge of climate-driven disturbances with community governance structures and community capacity building; and 5) provide mentoring and training to the next generation of social and natural scientists who focus on socio-ecological systems in the Great Lakes.

The benefit of this multi-faceted approach is that it will allow us to better understand the patterns of variability among natural processes, and, if and how such, processes align with local governance structures, decision making, and community resilience to change. Ultimately, the outcome of this project will be to better inform decision making as it relates to existing and future challenges faced by coastal communities across the Great Lakes, and move toward solutions that make these communities more resilient and sustainable.

GVGC RCN topics under examination

Thematically, the CGVG RCN will focus on hydrological, biological, and human (or societal) drivers of climate-driven disturbances. Hydrological drivers will emphasize storms and lake levels and their effects on lake ecosystems and the communities around them. Climate-driven perturbations have been well documented for the Great Lakes region, affecting both communities and the physical behavior of the lakes themselves (Melillo and Yohe, 2014). Most of these have some connection to the hydrologic cycle. Temperature extremes (for example, increasingly low temperatures in winter, and increasingly high temperatures in summer) (Wuebbles et al., 2019; Zobel et al., 2017) and heavy precipitation events (Suriano and Leathers, 2017; Wuebbles et al., 2019) are changing in the Great Lakes Basin, and their rates of change are outpacing other regions in the United States. As the atmosphere warms, it is able to retain additional moisture available for precipitation. Precipitation amounts vary across the Great Lakes Basin, with higher amounts in the east than in the west, and they are changing at different rates than the rest of the United States, with the basin-wide precipitation increasing nearly 10 percent since 1901, while the remainder of the country only witnessed a 4 percent increase. Simultaneously, there has been a seasonal shift in the timing of precipitation which has influenced flooding, erosion, and nutrient loading, and caused extensive damage to personal property and infrastructure (Wuebbles et al., 2019).

Climate change is also altering evaporation rates, and the Great Lakes' continued decline in winter ice cover and warming of summer water temperatures are of particular concern (Van Cleave et al., 2014). Such effects are known to cause an earlier start to

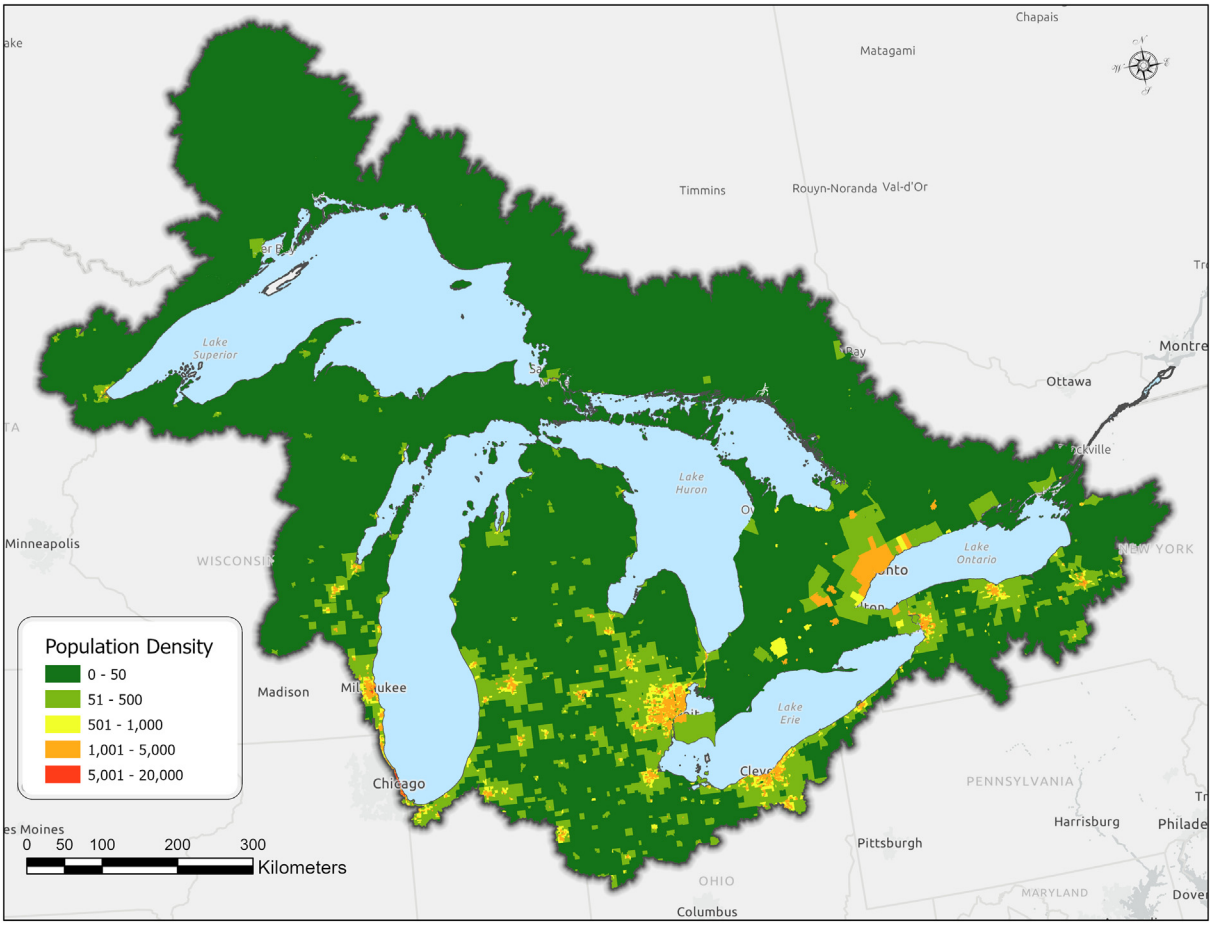

Fig. 1. The Laurentian Great Lakes – Great Lakes Basin.

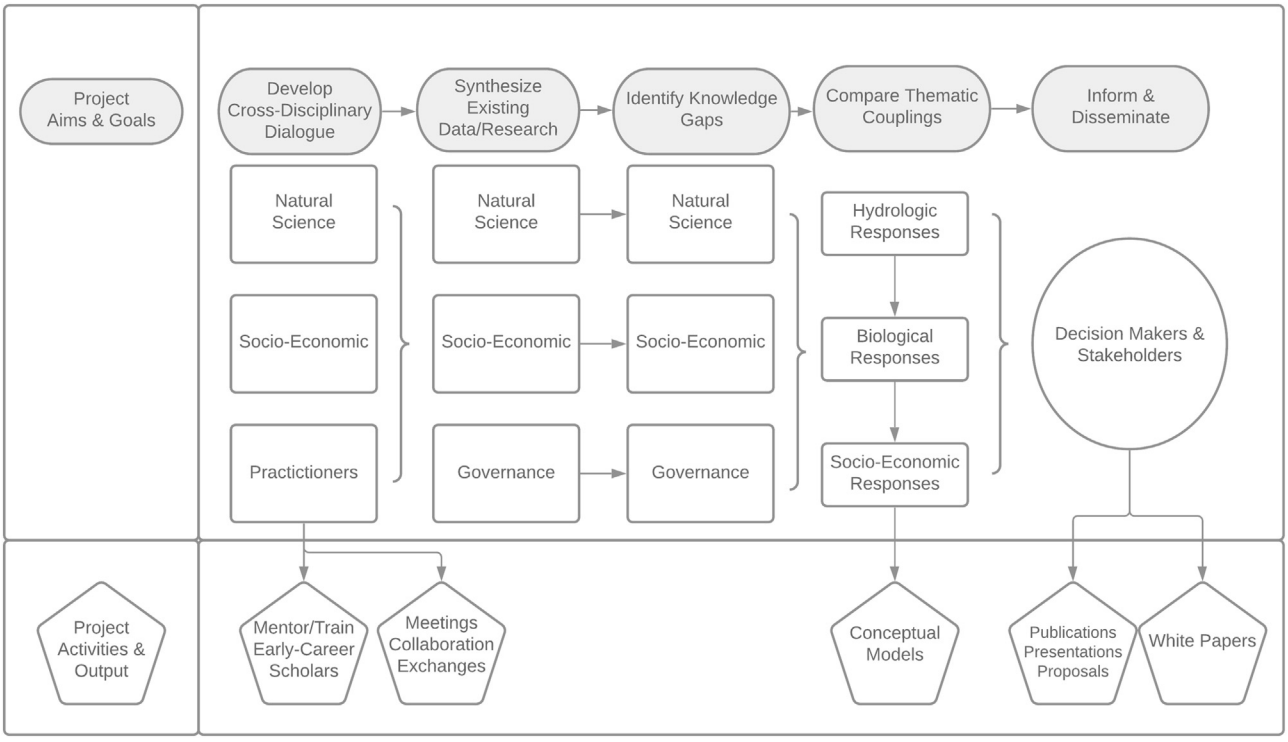

Fig. 2. The CGVG-RCN aims, goals, activities, and outcomes.

the evaporation season (Woolway et al., 2020) and higher cumulative water loss from the Great Lakes following warm, low-ice years (Spence et al., 2013). Large lakes such as the Great Lakes also have the added complexity of spatially variable ice cover (Wang et al., 2012), with the most extensive ice tending to form in shallow, nearshore waters, providing a protective, coastal barrier against winter storms.

Great Lakes water levels have undergone considerable variation over centuries, decades, and even within a single year or two (Gronewold et al., 2013; Lenters, 2001; Wilcox et al., 2007). Although the water levels of Lakes Superior and Ontario are weakly "regulated" at their outflow by dams (Clamen and Macfarlane, 2018; Clites and Quinn, 2003), the vast majority of Great Lakes water level variability is due to changes in weather and climate. These changes, in turn, alter the Great Lakes water balance through components such as precipitation, terrestrial evapotranspiration, snowmelt, streamflow into the lakes, interconnecting channel flow, and over-lake evaporation (Wilcox et al., 2007). The interplay of these components in driving lake level variability is especially evident on seasonal timescales (Lenters, 2004). Because each of the lakes typically rise in the spring when evaporation is low and runoff is high, but decline in the autumn when rates of evaporation increase. On longer timescales, interannual to decadal variability in precipitation can lead to changes in lake level on the order of 1.2–2 m (Wuebbles et al., 2019), dwarfing the (non-tidal) rates of sea level rise along the coastal oceans (Gronewold et al., 2013).

Biological drivers will focus on harmful algal blooms and invasive species, and their associated impacts. Cyanobacterial harmful algal blooms (cHABs) are becoming more widespread globally due to factors that include climate change (both temperature and rainfall) and anthropogenic nutrient loadings (Ho et al., 2019). Bloom-forming cyanobacteria are known to produce a wide variety of toxic secondary metabolites that can kill fish, threaten wildlife and result in shutdown of water treatment facilities. A primary example of the threat posed by cHABs to municipalities is the 2014 toxic cyanobacterium outbreak near Toledo, Ohio that resulted in a suspension of drinking water supply for two days for nearly half a million residents (Bullerjahn et al., 2016; Steffen et al., 2014). Moreover, cHABs can form surface scums that result in losses in tourist revenue, property valuation and general quality of life in coastal communities. For example, Smith et al. (2019) found that cHABs in the Canadian portion of Lake Erie would have a $272 million annual impact on local economies, with the largest impact to the tourism and recreation industry ($110 million annually). In addition, although cHABs were once viewed a threat restricted to eutrophic embayments and western Lake Erie (Bullerjahn et al., 2016), they are now observed in oligotrophic systems such as coastal Lake Superior (Sterner et al., 2020b). Thus, mitigation and management of cHABs is a major priority going forward that must engage scientists, social scientists, coastal residents and policy makers.

Lastly, human drivers will focus on demographic shifts and shifting economies. Sixty-three percent of the human population in the basin resides in the United States, with the rest in Canada (Méthot et al., 2015). Seventy-three percent of the basin's population (~25 million) is located within the Lake Michigan and Lake Erie watersheds, followed by Ontario (17 percent), Huron (9 percent), and Lake Superior (2 percent) (Sterner et al., 2020a). Of the over 30 million residents who call the Great Lakes home, 28 million live within 100 km of a lake's shoreline, with the vast majority living in cities of over 100,000 inhabitants. Demographically, since 1960, the basin-wide population has not only increased (13 percent), it has also aged, from a median age of 30 years old in 1960 to 38 years old in 2010. The region has also become more racially, ethnically, and socially diverse, with immigration accounting for 26 percent of the population in 1960, rising to 34 percent in 2010 (Méthot et al., 2015).

Economically, the region supports the 3rd largest economy in the world (if counted as a country), and is thus an economic engine of global significance producing in excess of $4.7 trillion in economic output in 2011 alone (Austin and Affolter-Caine, 2006; Austin et al., 2007; Campbell et al., 2015; Laurent et al., 2015). Major industries in the region include agriculture ($15 billion annually), shipping ($35 billion annually), recreational fisheries ($7 billion annually), recreation ($4 billion annually), and tourism ($16 billion annually) (Wuebbles et al., 2019). Despite the historic success of the region's economy, there continues to be a shift from a manufacturing-based economy, to a service-based economy (Campbell et al., 2015).

CGVG RCN research questions

The ability of communities to manage disturbance is a function of their capacity, that is, their institutional, human, economic, and technical resources, their ability to implement effective policy, and the strength of their leadership (Kusumasari et al., 2010; Satterthwaite, 2011). Effective policy making must provide the ability to mobilize resources and engage appropriate public and private organizations when needed. In addition, communities must have appropriate levels of technical capabilities, including the logistical and technical information systems, as well as effective communication capabilities between relevant stakeholders. Most importantly, because of the time-sensitive nature before, during, and after disturbance events, communities must have leaders that are capable of making timely decisions, while simultaneously boosting the confidence of local stakeholders (Kusumasari et al., 2010).

The Great Lakes Futures Project (GFLP) was created as a result of the growing recognition of the impacts the region could face as a result of climate change (Creed and Laurent, 2015). The GLFP sought to bring together decision makers, stakeholders, and scholars from across the Great Lakes Basin to envision how the Laurentian Great Lakes (LGL) will change in coming decades. One of the primary findings of the GLFP was that because decision making had not been centralized in the past (Friedman et al., 2015), due to differences in governance capacity, experience, resources, knowledge and public support (Sandford, 2015), there was a corresponding failure in the implementation of policy recommendations (Friedman et al., 2015). Given these capacity and governance differences, the question is raised whether community responses to climate-driven disturbances can be aligned (synchronized) with the changing patterns of the natural systems. Synchronicity is defined here as the spontaneously ordered connections between natural and social processes (Bowen, 1985), or the idea that climate-driven disturbances align with social processes in ways that influence how people interact with coasts in the Great Lakes Basin. Thus, the goals and objectives of the CGVG RCN are predicated upon answering three fundamental questions:

What are the synchronicities (spatial and temporal) of natural disturbances and social processes across the Great Lakes Basin and how are they changing over time?

The scales of natural and social variability have been recognized as a fundamental problem in linking social and natural systems (Daniell and Barreteau, 2014; Peterson, 2000), but how do the couplings of humans and lakes differ across these scales? It has been argued that many of the problems in managing resources come about because of a mismatch between the scale of governance and the scale of environmental variability (Cumming et al., 2006), but that hypothesis has been little addressed. How institutions and agencies respond to environmental disturbances is also

a primary concern for researchers examining the adaptive capabilities of communities and governance structures in complex social-ecological systems (Abrams et al., 2018). While communities play a vital role before, during, and after natural disasters, our understanding of community capacities and capabilities is limited, especially as it relates to the demands and constraints placed on communities experiencing environmental disasters (Kusumasari et al., 2010). As Buma and Schultz (2020) suggest, climate-driven disturbances provide opportunities to fundamentally transform adaptation pathways such as governance, to address future challenges. What is needed most is an alignment between ecological and social systems; however, such activities are hindered by the magnitude, frequency, and intensity of disturbances, and economic and social system characteristics.

How do changes to the synchronicity of natural climate-driven disturbances influence a community's adaptation, mitigation, and resiliency pathways?

Although the concept of resiliency was originally described by Holling, (1973) in relation to natural systems, in recent decades it has shifted to include a focus on social systems. This shift has allowed for a greater understanding of community capacity building in various contexts, in particular, how differing capitals, most notably economic, social and environmental, are influenced by internal and external actors (Robinson and Carson, 2016). As Magis (2010) suggested, resilient communities are those that are able to sustain themselves through not only adaptation, but also transformation of their capital stocks (economic, social, and environmental). That is, communities must have the ability to thrive in environments that are continually changing. Because of the highly uncertain nature of climate-driven changes, a primary challenge for coastal communities in the LGL is in crafting regulation and planning policies that accommodate an uncertain future (Maghrebi et al., 2015). As Gregg et al. (2012) suggest, robust planning and resource management strategies are critical in the face of a changing climate in the region and its long-term impacts on ecological integrity and economic vitality. In particular, adaptation strategies include those related to capacity building, policy decisions, resource management, and infrastructure, planning and development. Central to capacity building for sustainable communities is institutional support as well as buy-in from local stakeholders (Gregg et al., 2012). Lastly, because climate-driven disturbances are transboundary in nature, they also require coordinated planning and policy considerations (Gregg et al., 2012); something the region has historically lacked (Friedman et al., 2015).

What are the essential governance structures and what are the capacities needed for coastal communities to respond effectively to changes in climate-driven disturbances over short vs. long scales?

Governance and decision making in the region is highly complex and multi-layered, with two federal governments, eight states, one province, over 164 First Nations, and 23 cities with populations over 100,000 (Botts and Muldoon, 2005). The LGL and their communities have become increasingly complex to manage comprehensively while stresses and threats accumulate (Allan et al., 2013). While each of the LGL has undergone ecological transformations in the past, it remains unclear how communities in the LGL will respond, especially as the number and intensity of climate-driven disturbances increase (Wuebbles et al., 2019). For example, compounded by record high water levels across all of the Great Lakes (US Army Corps of Engineers, 2019), storms have posed large recent threats to coastal infrastructure and property. Since 2012, the south shore of Lake Superior has experienced three storms classified as 500-year or greater (National Weather Service, pers. comm). As such, communities must necessarily adapt to these disturbances; the City of Duluth, MN, for example, has had to rebuild its iconic Lakewalk along Lake Superior twice since 2012. The city is investing $30 million to restructure the shoreline and harden the infrastructure after it was destroyed again in 2017 (Busche, 2019). Such investments are shared by city, state and federal governments, but the capacity of communities and governments to pay for such investments is not without limits; the intensification of these and other climate-driven disturbances (for example, unusual algal blooms on Lake Superior, June 2012 and August 2018; Sterner et al., 2020b) is presenting new challenges on top of the already stretched-to-capacity governance systems and economies.

CGVG RCN activities and products

The primary activity of the RCN will be a series of three summits (2021–2023), each with a defined set of goals and expected resulting publications. We anticipate that by the completion of this RCN, numerous participants will be collaborating on related funding proposals, developing manuscripts based on the analysis of existing datasets, that early career researchers will have developed a substantial network of collaborators from the spectrum of career phases ensuring long-term success, and that significant progress will have been made regarding understanding climate-driven coastal processes and their impact on governance structures and community capacity building. In addition, we envision the development of a series of conceptual models that are organized by interest sectors (e.g., environmental, recreation and tourism, navigation and shipping, real estate), that can be used to help inform local and regional planning and decision making.

Each three-day summit will include a series of presentations highlighting how climate-driven disturbances are impacting local communities. Because a primary goal of the RCN is to facilitate new and novel research collaborations, an emphasis will be placed on ensuring participation by scholars from both within and outside the Great Lakes research community, as well as a mixture of career stages. Further, international participants, especially those from the Canadian portion of the Great Lakes Basin, are particularly important to the success of this RCN. Summit participants will include a steering committee, 18 scholars from both the social and natural sciences, at least five early-career scholars, and local practitioners based on summit locale.

The global pandemic of 2020 and 2021 has prohibited face-to-face interaction among CGVG participants up to this point. However, the steering committee agreed that a virtual meeting would be the best possible route to maintain the initial momentum of the RCN. On March 25 and 26 of 2021, thirty-one participants gathered to discuss the project, and began addressing the relationship between climate-driven disturbances and community responses, as well as gaining a better understanding of current and projected data needs and knowledge gaps. Day one consisted of four case studies. The goal of these case studies was to provide contextual background for the importance of climate-driven disturbances in the Great Lakes, and serve as a catalyst for the more important component of the summit, world café-style breakout sessions during day two. Day two was divided into four separate breakout sessions, with all participants taking part in each session. Session one focused on climate-driven disturbances and their associated impacts, with an emphasis on the hydrological and socio-economic impacts of disturbances. Session two was focused on how coastal communities in the Great Lakes respond to climate-driven disturbances, with an emphasis on how disturbances influence community adaptation, mitigation, and resiliency pathways. Session three focused on the governance structures and community capacities needed to effectively respond to climate-driven changes. The final session was dedicated to identifying the current

data needs and gaps in knowledge that exist, and how such gaps influenced our understanding of this complex system.

In general, summit participants believed that current governance structures were inadequate to respond to climate-driven disturbances. This failure was due to a variety of factors such as the expense of adaptation plans, a lack of coordinated planning efforts, and the inability to mobilize community capital (human, social, and political), despite the fact that these were viewed as the most effective strategies to enhance resiliency. At the same time, issues of equity and access were cited as a fundamental challenge for coastal communities, with participants suggesting that an uneven distribution of community capacity existed and had the potential to lead toward greater vulnerability for some communities. Human capital, including strong leadership and institutional knowledge, was repeatedly cited as a concern by participants, especially for communities that were experiencing repeated disturbance events. These challenges were further compounded by the number and scale of managing organizations and agencies responsible for adaptation and mitigation strategies, and the lack of effective communication between organizations at all scales. Lastly, summit participants recognized the severe limitations present in the spatial and temporal coverage of data and resulting research that often drives policy and decision making in the region. Limitations in historical data, a lack of region-wide monitoring efforts, and the lack of research during winter months were all cited as major shortcomings to our current understanding of climate-driven disturbances and their impacts on coastal communities.

The summit breakout sessions also spurred two additional questions that while outside the original purview of the RCN, were recognized as fundamentally important to understanding and addressing how coastal communities respond to climate-driven disturbances. First, while the spatial understanding of social vulnerability was well understood for other coastal communities in the United States, it was lacking for the Great Lakes. Thus, a better understanding of how social vulnerability was distributed across the Great Lakes was needed. It was found that social vulnerability is highly variable across the region, with clusters of higher vulnerability in northern and central Michigan, and lower vulnerability in eastern Wisconsin. It was also found that a strong rural–urban divide exists in relation to social vulnerability, with rural communities more susceptible to change than their urban counterparts. This suggests the uneven distribution of community capacity that was discussed in the breakout sessions does in-fact lead to higher vulnerability for certain populations, and thus, place-based strategies that enhance resiliency are required (Fergen and Bergstrom, 2021). Secondly, when examining current data needs and knowledge gaps in the region it was found that the calculations used to determine the total population of the Great Lakes Basin were profoundly different, ranging from 27 to 52 million people. These differences led to questions as to whether practitioners, policy makers and researchers were counting the same people, which had the potential to have dramatic implications for public policy and the allocation of resources to reduce vulnerability and improve community resiliency. As a result, a social-ecological approach, using watershed boundaries, was utilized to calculate the estimated population of the basin (~38,327,681), and provided a spatial framework that can be utilized by decision makers and researchers going forward (Fergen et al., this issue).

Conclusions

We acknowledge that the sustainability of natural and social systems is predicated upon their ability to respond and adapt to uncertainty and disruptions (Fiksel, 2006), and that successful adaptation must be tailored to specific locales and situations (Olsson et al., 2004). We also recognize that communities that hope to remain resilient and decrease vulnerability must also continually develop and evolve their understanding of how complex systems cope with change and manage uncertainty (Carpenter and Gunderson, 2001). As such, communities, institutions, and agencies must be more flexible in their inclusion of diverse stakeholders and decision makers in order to become more resilient to the mismatch between governance responses and disturbances (Buma and Schultz, 2020).

The social response to ecological change in the Great Lakes is challenged by the mismatch between the time needed to address climate-driven disturbances and the political and management systems that are responsible for responding to them (Sandford, 2015). The Great Lakes are constantly challenged by multiple disturbances whose variability fluctuates over a wide range of temporal and spatial scales (Baustian et al., 2014). The challenges faced by coastal communities in the Great Lakes are shared by shared by numerous stakeholders, decision makers, and scholars at multiple levels from local to binational. However, our understanding of how best to address these challenges is often couched within disciplinary silos, including natural science, social science, policy, and law. Simultaneously, the cooperation needed among the various governing bodies of the region, from federal and tribal governments down to local jurisdictions, is fundamentally lacking and fragmented, further complicating the response to community challenges (Laurent et al., 2015).

The Climate Governance Variability in the Great Lakes Research Collaboration Network (CGVG-RCN) was established to address pressing questions about the nature of climate-driven variability and its synchronicity with community capacity in coastal communities around the Great Lakes. The objective of this short communication was to introduce the CGVG-RCN, articulate its goals and objectives, and encourage collaboration with practitioners, scholars and decisions makers across the region. It is our hope that the collaboration and engagement that is derived from the CGVG RCN will provide decision makers and stakeholders with information that can solve tangible community problems. It is also hoped that the relationships developed as a result of this research collaboration network will provide a framework that can benefit for the Great Lakes Basin long after this project concludes. As such, the CGVG-RCN is a significant step in helping to facilitate meaningful dialogue and relationships between natural and social scientists, practitioners from private and non-profit industry, and local, state, federal, and tribal governments, and agencies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abrams, J., Huber-Stearns, H., Palmerin, M.L., Bone, C., Nelson, M.F., Bixler, R.P., Moseley, C., 2018. Does policy respond to environmental change events? An analysis of Mountain Pine Beetle outbreaks in the Western United States. Environ. Sci. Policy 90, 102–109. https://doi.org/10.1016/j.envsci.2018.09.019.

Allan, J.D., McIntyre, P.B., Smith, S.D.P., Halpern, B.S., Boyer, G.L., Buchsbaum, A., Burton, G.A., Campbell, L.M., Chadderton, W.L., Ciborowski, J.J.H., Doran, P.J., Eder, T., Infante, D.M., Johnson, L.B., Joseph, C.A., Marino, A.L., Prusevich, A., Read, J.G., Rose, J.B., Rutherford, E.S., Sowa, S.P., Steinman, A.D., 2013. Joint analysis of stressors and ecosystem services to enhance restoration

effectiveness. Proc. Natl. Acad. Sci. 110, 372–377. https://doi.org/10.1073/pnas.1213841110.
Austin, J., Affolter-Caine, B., 2006. The Vital Center: A Federal-State Compact to Renew the Great Lakes Region. The Brookings Institution Metropolitan Policy Program. Retrieved from https://www.brookings.edu/research/the-vital-center-a-federal-state-compact-to-renew-the-great-lakes-region/.
Austin, J.C., Anderson, S., Courant, P.N., Litan, R.E., 2007. Healthy Waters, Strong Economy: The Benefits of Restoring the Great Lakes Ecosystem. The Brookings Institution - Great Lakes Economic Initiative. Retrieved from https://healthylakes.org/healthy-waters-strong-economy/.
Bartolai, A.M., He, L., Hurst, A.E., Mortsch, L., Paehlke, R., Scavia, D., 2015. Climate change as a driver of change in the Great Lakes St. Lawrence River Basin. J. Gt. Lakes Res. 41, 45–58. https://doi.org/10.1016/j.jglr.2014.11.012.
Baustian, M.M., Mavrommati, G., Dreelin, E.A., Esselman, P., Schultze, S.R., Qian, L., Aw, T.G., Luo, L., Rose, J.B., 2014. A one hundred year review of the socioeconomic and ecological systems of Lake St. Clair, North America. J. Gt. Lakes Res. 40, 15–26. https://doi.org/10.1016/j.jglr.2013.11.006.
Botts, L., Muldoon, P., 2005. Evolution of the Great Lakes Water Quailty Agreement. In: Evolution of the Great Lakes Water Quality Agreement. Michigan State University Press, p. 377.
Bowen, M., 1985. The ecology of knowledge: Linking the natural and social sciences. Geoforum 16, 213–225. https://doi.org/10.1016/0016-7185(85)90030-2.
Bullerjahn, G.S., McKay, R.M., Davis, T.W., Baker, D.B., Boyer, G.L., D'Anglada, L.V., Doucette, G.J., Ho, J.C., Irwin, E.G., Kling, C.L., Kudela, R.M., Kurmayer, R., Michalak, A.M., Ortiz, J.D., Otten, T.G., Paerl, H.W., Qin, B., Sohngen, B.L., Stumpf, R.P., Visser, P.M., Wilhelm, S.W., 2016. Global solutions to regional problems: Collecting global expertise to address the problem of harmful cyanobacterial blooms. A Lake Erie case study. Harmful Algae, Global Expansion of Harmful Cyanobacterial Blooms: Diversity, Ecology, Causes, and Controls 54, 223–238. https://doi.org/10.1016/j.hal.2016.01.003.
Buma, B., Schultz, C., 2020. Disturbances as opportunities: Learning from disturbance-response parallels in social and ecological systems to better adapt to climate change. J. Appl. Ecol. 57, 1113–1123. https://doi.org/10.1111/1365-2664.13606.
Busche, A., 2019. Extreme weather impacts tourism, city budgets [WWW Document] accessed 6.24.19 BusinessNorth http://www.businessnorth.com/businessnorth_exclusives/extreme-weather-impacts-tourism-city-budgets/article_f3503384-9119-11e9-b86e-535e0b180402.html.
Campbell, M., Cooper, M.J., Friedman, K., Anderson, W.P., 2015. The economy as a driver of change in the Great Lakes–St. Lawrence River basin. J. Gt. Lakes Res. 41, 69–83. https://doi.org/10.1016/j.jglr.2014.11.016.
Carpenter, S.R., Gunderson, L.H., 2001. Coping with collapse: Ecological and Social dynamics in ecosystem management. BioScience 51, 451. https://doi.org/10.1641/0006-3568(2001)051[0451:CWCEAS]2.0.CO;2.
Clamen, M., Macfarlane, D., 2018. Plan 2014: The historical evolution of Lake Ontario–St. Lawrence River regulation. Can. Water Resour. J. Rev. Can. Ressour. Hydr. 43, 416–431. https://doi.org/10.1080/07011784.2018.1475263.
Clites, A.H., Quinn, F.H., 2003. The history of Lake Superior Regulation: implications for the future. J. Gt. Lakes Res. 29, 157–171. https://doi.org/10.1016/S0380-1330(03)70424-9.
Creed, I.F., Laurent, K.L., 2015. The Great Lakes Futures Project. J. Gt. Lakes Res. 41, 1–7. https://doi.org/10.1016/j.jglr.2014.12.017.
Cumming, G., Cumming, D.H.M., Redman, C., 2006. Scale mismatches in social-ecological systems: causes, consequences, and solutions. Ecol. Soc. 11. https://doi.org/10.5751/ES-01569-110114.
Daniell, K.A., Barreteau, O., 2014. Water governance across competing scales: Coupling land and water management. J. Hydrol. 519, 2367–2380. https://doi.org/10.1016/j.jhydrol.2014.10.055.
Fergen, J.T., Bergstrom, R.D., 2021. Social vulnerability across the Great Lakes Basin: A county-level comparative and spatial analysis. Sustainability 13, 7274/. https://doi.org/10.3390/su13137274.
Fergen, Joshua, Bergstrom, Ryan, Twiss, Michael, Johnson, Lucinda, Steinman, Alan, Gagnon, Valoree, 2022. Updated census in the Laurentian Great Lakes watershed: A framework for evaluating the population of the region. Journal of Great Lakes Research. In this issue.
Fiksel, J., 2006. Sustainability and resilience: toward a systems approach. Sustain. Sci. Pract. Policy 2, 14–21. https://doi.org/10.1080/15487733.2006.11907980.
Friedman, K.B., Laurent, K.L., Krantzberg, G., Scavia, D., Creed, I.F., 2015. The Great Lakes Futures Project: Principles and policy recommendations for making the lakes great. J. Gt. Lakes Res. 41, 171–179. https://doi.org/10.1016/j.jglr.2014.11.026.
Gregg, R.M., Feifel, K.M., Kershner, J.M., Hitt, J.I., 2012. The State of Climate Change Adaptation in the Great Lakes Region. EcoAdapt, Bainbridge Island, WA.
Gronewold, A.D., Fortin, V., Lofgren, B., Clites, A., Stow, C.A., Quinn, F., 2013. Coasts, water levels, and climate change: A Great Lakes perspective. Clim. Change 120, 697–711. https://doi.org/10.1007/s10584-013-0840-2.
Ho, J.C., Michalak, A.M., Pahlevan, N., 2019. Widespread global increase in intense lake phytoplankton blooms since the 1980s. Nature 574, 667–670. https://doi.org/10.1038/s41586-019-1648-7.
Holling, C.S., 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst. 4 (1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245.
Kusumasari, B., Alam, Q., Siddiqui, K., 2010. Resource capability for local government in managing disaster. Disaster Prev. Manag. Int. J. 19, 438–451. https://doi.org/10.1108/09653561011070367.
Laurent, K.L., Scavia, D., Friedman, K.B., Krantzberg, G.K., Creed, I.F., 2015. Critical forces defining alternative futures for the Great Lakes–St. Lawrence River basin. J. Gt. Lakes Res. 41, 131–138. https://doi.org/10.1016/j.jglr.2014.11.006.
Lenters, J.D., 2004. Trends in the Lake Superior Water Budget Since 1948: A weakening seasonal cycle. J. Gt. Lakes Res. Exploring Superior 30, 20–40. https://doi.org/10.1016/S0380-1330(04)70375-5.
Lenters, J.D., 2001. Long-term trends in the seasonal cycle of Great Lakes water levels. J. Gt. Lakes Res. 27, 342–353. https://doi.org/10.1016/S0380-1330(01)70650-8.
Maghrebi, M., Nalley, D., Laurent, K.L., Atkinson, J.F., 2015. Water quantity as a driver of change in the Great Lakes–St. Lawrence River Basin. J. Gt. Lakes Res. 41, 84–95. https://doi.org/10.1016/j.jglr.2014.12.005.
Magis, K., 2010. Community resilience: an indicator of social sustainability. Soc. Nat. Resour. 23, 401–416. https://doi.org/10.1080/08941920903305674.
Melillo, J., Yohe, G.W., 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, Washington, D.C..
Méthot, J., Huang, X., Grover, H., 2015. Demographics and societal values as drivers of change in the Great Lakes–St. Lawrence River basin. J. Gt. Lakes Res. 41, 30–44. https://doi.org/10.1016/j.jglr.2014.11.001.
Olsson, P., Folke, C., Hahn, T., 2004. Social-ecological transformation for ecosystem management: the development of adaptive co-management of a wetland landscape in Southern Sweden. Ecol. Soc. 9. https://doi.org/10.5751/ES-00683-090402.
Peterson, G., 2000. Political ecology and ecological resilience. Ecol. Econ. 35, 323–336. https://doi.org/10.1016/S0921-8009(00)00217-2.
Porter, A.L., Garner, J., Crowl, T., 2012. Research coordination networks: evidence of the relationship between funded interdisciplinary networking and scholarly impact. BioScience 62, 282–288. https://doi.org/10.1525/bio.2012.62.3.9.
Rahel, F.J., Olden, J.D., 2008. Assessing the effects of climate change on aquatic invasive species. Conserv. Biol. 22, 521–533. https://doi.org/10.1111/j.1523-1739.2008.00950.x.
Robinson, G.M., Carson, D.A., 2016. Resilient communities: transitions, pathways and resourcefulness: Resilient communities. Geogr. J. 182, 114–122. https://doi.org/10.1111/geoj.12144.
Sandford, R.W., 2015. Lessons learned from the Great Lakes Futures Project: A commentary. J. Gt. Lakes Res. 41, 195–196. https://doi.org/10.1016/j.jglr.2014.11.010.
Satterthwaite, D., 2011. Editorial: Why is community action needed for disaster risk reduction and climate change adaptation? Environ. Urban. 23, 339–349. https://doi.org/10.1177/0956247811420009.
Smith, B., Burton, I., Klein, R.J.T., Wandel, J., 2000. An anatomy of adaptation to climate change and variability. In: Kane, S.M., Yohe, G.W. (Eds.), Societal Adaptation to Climate Variability and Change. Springer, Netherlands, Dordrecht, pp. 223–251. https://doi.org/10.1007/978-94-017-3010-5_12.
Smith, S.D.P., Bunnell, D.B., Burton, G.A., Ciborowski, J.J.H., Davidson, A.D., Dickinson, C.E., Eaton, L.A., Esselman, P.C., Evans, M.A., Kashian, D.R., Manning, N.F., McIntyre, P.B., Nalepa, T.F., Pérez-Fuentetaja, A., Steinman, A.D., Uzarski, D.G., Allan, J.D., 2019. Evidence for interactions among environmental stressors in the Laurentian Great Lakes. Ecol. Indic. 101, 203–211. https://doi.org/10.1016/j.ecolind.2019.01.010.
Spence, C., Blanken, P.D., Lenters, J.D., Hedstrom, N., 2013. The importance of spring and autumn atmospheric conditions for the evaporation regime of Lake Superior. J. Hydrometeorol. 14, 1647–1658. https://doi.org/10.1175/JHM-D-12-0170.1.
Steffen, M.M., Belisle, B.S., Watson, S.B., Boyer, G.L., Wilhelm, S.W., 2014. Status, causes and controls of cyanobacterial blooms in Lake Erie. J. Gt. Lakes Res. 40, 215–225. https://doi.org/10.1016/j.jglr.2013.12.012.
Sterner, R.W., Keeler, B., Polasky, S., Poudel, R., Rhude, K., Rogers, M., 2020a. Ecosystem services of Earth's largest freshwater lakes. Ecosyst. Serv. 41, 101046. https://doi.org/10.1016/j.ecoser.2019.101046.
Sterner, R.W., Reinl, K.L., Lafrancois, B.M., Brovold, S., Miller, T.R., 2020b. A first assessment of cyanobacterial blooms in oligotrophic Lake Superior [WWW Document]. Limnol. Oceanogr. https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.1002/lno.11569 (accessed 10.23.20.
Suriano, Z.J., Leathers, D.J., 2017. Synoptic climatology of lake-effect snowfall conditions in the eastern Great Lakes region. Int. J. Climatol. 37, 4377–4389. https://doi.org/10.1002/joc.5093.
US Army Corps of Engineers, 2019. Weekly Great Lakes Water Level Update [WWW Document] accessed 6.21.19 https://www.lre.usace.army.mil/Missions/Great-Lakes-Information/Great-Lakes-Water-Levels/Water-Level-Forecast/Weekly-Great-Lakes-Water-Levels/, .
Van Cleave, K., Lenters, J.D., Wang, J., Verhamme, E.M., 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. https://doi.org/10.4319/lo.2014.59.6.1889.
Wang, J., Bai, X., Hu, H., Clites, A., Colton, M., Lofgren, B., 2012. Temporal and spatial variability of Great Lakes Ice Cover, 1973–2010*. J. Clim. 25, 1318–1329. https://doi.org/10.1175/2011JCLI4066.1.
Wilcox, D.A., Thompson, T.A., Booth, R.K., Nicholas, J.R., 2007. Lake-level variability and water availability in the Great Lakes (No. 1311), Circular. U.S. Geological Survey. https://doi.org/10.3133/cir1311.
Woolway, R.I., Kraemer, B.M., Lenters, J.D., Merchant, C.J., O'Reilly, C.M., Sharma, S., 2020. Global lake responses to climate change. Nat. Rev. Earth Environ. 1 (8), 388–403. https://doi.org/10.1038/s43017-020-0067-5.

Wuebbles, D., Cardinale, B., Cherkauer, K., Davidson-Arnott, R., Hellmann, J., Infante, D., Johnson, L., de Loe, R., Lofgren, B., Packman, A., Seglenieks, F., Sharma, A., Sohngen, B., Tiboris, M., Vimont, D., Wilson, R., Kunkel, K., Ballinger, A., 2019. An Assessment of the Impacts of Climate Change on the Great Lakes. Environmental Law and Policy Center, Chicago, IL.

Zobel, Z., Wang, J., Wuebbles, D.J., Kotamarthi, V.R., 2017. High-resolution dynamical downscaling ensemble projections of future extreme temperature distributions for the United States. Earths Future 5, 1234–1251. https://doi.org/10.1002/2017EF000642.