Title: Using Fuzzy Cognitive Mapping to Assess the Impacts of Climate Change on Great Lakes Ecosystem Services

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Abstract

The ecosystem services the Great Lakes provide are imperative in sustaining human well-being and economic viability. To better understand the consequences of climate change and to develop effective means of adapting to them, it is critical that we improve our understanding of the links between climate change and ecosystem services. Validated quantitative models are the best way to project such impacts, however, time, data, and model limitations often make this approach implausible. Alternatively, fuzzy cognitive maps (FCM) can be used to encode expert knowledge about interactions among ecosystem components, which then translates that subjective, qualitative data into predictions of the effects of management on an ecosystem. Leveraging interdisciplinary methodology, we predicted which ecosystem services might be at risk and through which pathways climate change will act on provision of those services. Our study found that cultural services such as recreational fishing, boating, and winter recreation are most likely to be negatively impacted whilst birding is expected to have a positive increase. Respondents predicted that supporting/regulating services may increase, with carbon sequestration showing the largest increase largely due to increased primary productivity. Provisioning services saw mixed results with drinking water, wild rice productivity, and commercial shipping recording an increase while commercial fishing showed a negative impact to declining ice cover.

Key words: Ecosystem service, Climate change, Great Lakes, fuzzy cognitive mapping

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Introduction

Globally, ecosystems provide a suite of valuable services on which humans depend for food, economic prosperity, inspiration, stability, and enjoyment (Millennium Ecosystem Assessment, 2005). In the Laurentian Great Lakes (hereafter the Great Lakes), ecosystems dampen diurnal and annual temperature swings, an important service in an era of temperature increases and changes to variability (Notaro et al., 2013). However, ecosystems are already contending with multiple environmental stressors, such as habitat loss, water pollution, invasive species, and over-harvesting. The cumulative effect of these stressors, in concert with a rapidly changing climate, is expected to disrupt ecosystem processes and services (Nelson et al., 2013; Cardinale et al., 2012; Côté et al., 2016). Although some news media reports describe the Great Lakes as a potential “climate refuge” (i.e. Schneider, 2021), climate change projections predict increased temperatures by as much as 4.0 degrees Celsus and increased annual precipitation by as much as 16.5% by the middle of the century (Zhang et al., 2020). Studies suggest that the distribution, extent, and composition of ecosystems are vulnerable to gradual changes in temperature or precipitation and climate related disturbances (Locatelli, 2016). The negative effect of climate change on ecosystem functions could ultimately degrade the services and economic value they provide.

The Great Lakes basin consists of more than 94,000 square miles of freshwater surface area, one of the greatest concentrations of aquatic ecosystems on Earth (Wuebbles et al., 2019). An estimated 40 million people living in the Great Lakes drainage basin depend on the region’s waters for their livelihoods and economy (EPA, 2019). However, climate change threatens Great Lakes ecosystem services through increases in air and water temperature, and through a variety of impacts on precipitation and hydrology including decreased snowpack and changing seasonality and intensity of rainfall (Mortsch & Quinn, 1996; Hayhoe et al., 2010; d’Orgeville et al., 2014; Zhang et al., 2020). For example, climate change effects endanger the fisheries of the Great Lakes through changes to thermal habitat, runoff, and ice cover, and may impact commercial shipping through changes to lake levels (Collingsworth et al., 2017; Marchand et al., 1989; Millerd, 2005). Direct human actions similarly imperil ecosystem services in the region. Habitat fragmentation, active and legacy biological and chemical pollution, timber harvesting, mining, and negligent, accidental introductions of invasive species continue to threaten Great Lakes ecosystem services (Collingsworth et al., 2017; Kling et al., 2003; Wuebbles et al., 2019; Rothlisberger et al., 2012; Li et al., 2018; Hartig et al., 2020).

Provisioning Services

Provisioning services are the ability of the ecosystem to provide some type of extractable product that is useful or necessary for humans (MEA, 2005). For the Great Lakes ecosystem, this can include a wide range of products and resources, including municipal drinking water, commercial fish, wild rice, and suitable conditions for cost-effective commercial shipping (Allan et al., 2017).

One of the most easily identifiable provisioning ecosystem services of the Great Lakes is access to vast amounts of high-quality freshwater. In 2019, the total daily withdrawal of water for the Great Lakes-St. Lawrence River basin was 38,854 million gallons per day largely for use in power generation, but also for municipal drinking water and agriculture (GLC, 2019). The intensification of inorganic fertilizer use and increased urban development combine with increased precipitation and warming temperatures from climate change to increase the occurrence of harmful algal blooms (HABs) and threaten the provisioning of drinking water (Smith et al., 2015; Carmichael & Boyer, 2016; Watson et al., 2016). Commercial fishing is another important provisioning ecosystem service that the Great Lakes provide, particularly for the Canadian side, but for both the United States and Canada, commercial landing dockside value has decreased since the late 1980s/early 1990s (Brenden et al., 2011). However, fisheries in the region (commercial, tribal, and recreational) still support 75,000 jobs and are valued at $7 billion annually (Great Lakes Fisheries Commission, n.d.).

Climate change impacts water temperatures, changing the thermal habitat of the lakes often reducing available habitat for coldwater fish species but possibly increasing habitat for warm water species (Collingsworth et al., 2017). The introduction of invasive species, like sea lamprey and dreissenid mussels similarly threaten fisheries (Christie, 1974; Hudson & Ziegler, 2014). Wild rice provided an important source of subsistence for Native Americans in the Great Lakes prior to European colonization, served as an important trade good in the early years of European settlements, and continues to be important as a commodity for Non-Native groups and as a cultural symbol for Native groups (Drewes & Silbernagel, 2005; Drewes & Silbernagel, 2012). Since the 1900s, the number of watersheds containing wild rice has dropped by 32% due to a combination of land-use change and climate change (Drewes & Silbernagel, 2012). Finally, the lakes provide cost-effective shipping for 230 million metric tons of cargo a year, valued at over $100 billion (Chamber of Marine Commerce, n.d.). Climate change driven alterations to lake levels endanger this industry, with low water levels being particularly consequential (Marchand et al., 1988; Millerd, 2005; Millerd, 2011)

Cultural Services

Cultural ecosystem services provide non-material benefits to humans (MEA, 2005). Often, cultural ecosystem services refer to areas of spiritual, cultural, or religious importance, but the term can also refer to recreational experiences like hiking, fishing, ecotourism, or photography (MEA, 2005). To quantify these ecosystem services, previous research in the Great Lakes focused on measures of sport fishing effort, recreational boat use, winter recreation, and birding activity (Chin et al., 2018; Allan et al., 2017).

Throughout United States waters, recreational fishing provides a substantial economic boost to Great Lakes coastal communities, more so than commercial fishing. Research using surveys of Michigan anglers suggests that the value of walleye to anglers, or the angler's willingness to pay value, is as high as $23 per fish, while some species of salmon may be valued between $40 and $65, or even as high as $80 per fish (Melstrom & Lupi, 2013). These values are higher than a past valuation using similar methodology, suggesting that per fish values are increasing, despite decreasing angler participation (Dann et al., 2004; Melstrom & Lupi, 2013). Climate change threatens to warm the Great Lakes, and in Lake Erie specifically, changing temperatures may squeeze coldwater fish between too warm upper layers of the lake in the summer and hypoxic, but cold bottoms (Collingsworth et al., 2017). However, fish are mobile and may shift in ranges in response to warming waters from climate change (Alofs et al., 2014). Contrary to the possible effects on recreational fisheries, the warmer temperatures may present increased opportunities for the summer tourism sector, including recreational boat use (Dawson & Scott, 2010). However, climate change may impact water levels on the Great Lakes, and stable water levels are important for continued access to existing docks and other infrastructure (Bergmann-Baker et al., 1995; Connelly et al., 2007; McCole & Joppe, 2014). Great Lakes coastal wetlands provide important habitat for waterfowl and migratory birds (Sierszen et al., 2012). Climate change driven alterations to water levels may impact the extent and composition of wetland vegetation, impacting the diversity of birds (Riffell et al., 2001). However, previous research suggests that areas with high density of recreational birding already experience substantial anthropogenic stress, suggesting that other factors beyond the quality of bird habitat, such as proximity to population centers, play a role in the provisioning of recreational birding opportunities (Allan et al., 2015).

Supporting/Regulating Services

Supporting services are the processes on which all other ecosystem services depend. These services often lack direct impacts on human activity; however, impairment of supporting services has implications for all other ecosystem services on which they rely. (MEA, 2005). Key supporting services for aquatic ecosystems include functions such as nutrient cycling and habitat formation. Regulating services refer to the "benefits obtained from the regulation of ecosystem processes," (MEA, 2005). Regulating services include things such as water quality maintenance and carbon sequestration (MEA, 2005).

Our analysis combined these service categories because they are difficult to untangle in some cases. For example, nutrient cycling plays a major role in the quality of water both directly and through algae blooms, while habitat availability and carbon sequestration are entwined due to the role of wetlands in both services, among other connections (Carmichael & Boyer, 2016; Braun & Theuerkauf, 2021). In the Great Lakes, coastal wetlands provide habitat for waterfowl and sportfish and play a role in nutrient cycling and carbon sequestration (Wilson et al., 2005; Sierszen et al., 2012; Hohman et al., 2021). Nutrient cycling may also be impacted by sediments that remove total nitrogen but act as a source of biologically available nitrogen and phosphorus (Boedecker et al., 2020). Climate change may impact nutrient cycling through changes to wetland vegetation that process nutrient runoff, or through changes to precipitation that may release nutrients accumulated in sediments (Wilson et al., 2005; Sierszen et al., 2012). Climate change may also impact supporting and regulating services through changes to lake levels. Changes to lake levels may alter the vegetative composition and extent of habitat available to a variety of species, including sport fish (Midwood & Chow-Fraser, 2011). Changes to lake levels may also impact erosion, further affecting the total carbon storage and extent in crucial coastal habitats (Braun & Theuerkauf, 2021).

Climate change may increase the value of one service while hindering another (Allan et al., 2017). Using cultural ecosystem services as an example, warming air and water temperatures that result from climate change may degrade the fishery of cold-water sport species (e.g., salmon), but higher numbers of warm days may increase boat and beach use (Collingsworth et al., 2017; Dawson & Scott, 2010). For other services, direct management action may benefit one service while hurting another. For example, dam/lock practices that prioritize high water levels for boating may reduce the shallow water habitat needed by wild rice, further highlighting the tradeoffs that exist in managing ecosystem services (Angradi et al., 2016). Understanding and communicating the tradeoffs that exist between ecosystem services is an integral component of effectively working with stakeholders to maximize benefits while minimizing detriments of restoration and conservation activities (Steinman et al., 2017).

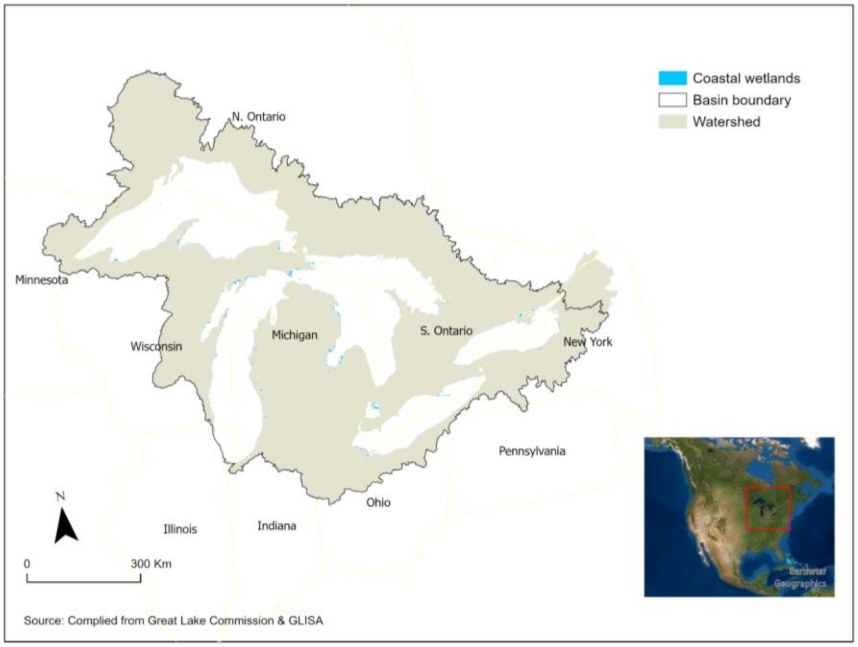
Goal of this Study

We aim to evaluate the impacts of climate change on Great Lakes ecosystem services using a model built based on the collection of expert knowledge. Our analysis seeks to use a semi-quantitative method (fuzzy cognitive mapping) to forecast which ecosystem services might be most strongly impacted by climate change and through which pathways. Many aspects of Great Lakes ecosystem services are well-studied; however, past work has not thoroughly established a model projecting the mechanisms for impacts of global climate change on the delivery of ecosystem services. Similarly, climate change impacts are not well-studied mechanistically on a basin-wide scale. Fuzzy cognitive mapping (FCM) has previously been employed in the Great Lakes region to predict the effects of management actions on the Lake Erie ecosystem, but our analysis seeks to examine the climate change aspect of anthropogenic influence region-wide (Hobbs et al., 2002). Our work alters the traditional FCM framework of in-person workshops due to pandemic constraints. Our survey-based analysis seeks to gather a diverse range of expert opinion from the region to examine pathways through which ecosystem services may be affected to help guide future research.

Methods

Study area

The geographic purview of the study includes Great Lake spanning across eight states in the United states and one Canadian province- Ontario, including many tribal, county, and city jurisdictions. Our research primarily focuses on biophysical feedback in Great Lakes coastal zones and connecting channels.The Great Lakes contain twenty percent of all freshwater on the planet's surface. Lake Superior is the largest and coldest lake in the system, with the least populated shoreline while Lake Huron is the second largest and coldest lake in the system. Lake Michigan is the third largest of the Great Lakes, with an estimated population of eight million people living along its shores.



Source: Complied from Great Lake Commission & GLISA

Figure 1: Map showing Great Lake watershed and political boundaries

The Great Lakes industry contributes $5.5 trillion to the economy, makes up nearly one-third of the combined U.S. and Canada GDP, and provides more than 43.4 million jobs (World Business Chicago, 2015). The basin is a major reservoir of biodiversity, containing the world's largest collection of freshwater coastal dunes, which provides habitat for over 4,000 species of plants, fish, and wildlife, as well as a source of drinking water for more than 24 million people (Government of Ontario, 2012). Shipping on the Great Lakes supports over 60,000 jobs and generates between $3 and $5 billion per year in the United States and Canada (Martin Associates, 2018). It is estimated that a 1,000-foot cargo ship must unload 270 tons of freight for every inch that the water level drops which influences the cost of goods being delivered. Additionally, the tourism of sport fishing generates $4 billion annually. Every year almost 65 million pounds of fish are caught in the Great Lakes contributing $1 billion to the regional economy (Rau et al., 2020).

Overview

Our approach utilized expert opinion through online surveys to quantify a conceptual model of the strength of relationships between climate change and ecosystems services present in Great Lakes environmental systems. Survey results were organized through Fuzzy Cognitive Mapping, which allows for the translation of conceptual maps into a semi-quantitative mental model that shows the strengths of relationships within a system network. The FCM approach analyzes people's perception about a system, while comparing and contrasting different groups of stakeholders (Ozesmi & Ozesmi, 2004). Advantages of FCM for ecological modeling include the ability to include abstract and aggregate variables in models, the ability to model relationships that are unknown with certainty, and the ability to model complex relationships with many feedback loops. This approach has been utilized successfully to assess perceptions of climate models among experts. This data is quantifiable and can be analyzed and compared between groups included in the survey (Halbrendt, 2014).

Specific ecosystem services and climate change variables have been discussed at length individually or in subsets within the literature. However, the specific connections between climate change and ecosystem services have not been modeled in the Great Lakes. To provide a means of estimation for these connections in our survey, we first constructed a conceptual map through a literature review.

Fuzzy Cognitive Maps

The Fuzzy Cognitive Maps (FCM) used in our survey were constructed through a literature review of ecosystem services with a preference for those occurring within the Great Lakes watershed. This literature review provided variables identified as potentially impactful for each ecosystem service. Changes in surface air temperature and precipitation were considered as the primary measurable impacts of climate change in the Great Lakes region.

Previous studies that used FCM involved survey participants in the creation of mental models or synthesized group models based on individual mental maps. (e.g., Gray, 2012; Özesmi & Özesmi, 2004). These general concept maps have previously been assembled to create in-depth surveys of stakeholders based on information collected from face-to-face interviews. (Halbrendt, 2014). Our study sought a similar approach by developing maps for surveys. We opted for a literature review instead of a preliminary survey as it was also difficult to conduct surveys in person due to the ongoing Covid-19 restrictions. We were also concerned that conducting the survey in two phases could negatively impact our response rate. Surveys that begin with a FCM also reduced the time it took to take the survey and eliminated potential scheduling complications that would result from arranging meetings with stakeholders over virtual conference calls.

Our method also allowed participants to complete the survey at a time of their own discretion.

Literature was quantified by searching Google Scholar and the University of Michigan Library for articles discussing ecosystem services under specific keywords. These keywords were used in conjunction with other terms from different categories (Table 1). Ecosystem services were categorized under two tiers. Tier 1 followed the general terminology as described by the Millennium Ecosystem Assessment while Tier 2 consisted of specific types of ecosystem services that fell under Tier 1 categories. This was done so as to include search results that discussed ecosystem services without mention of a broader framework.

Table 1. Literature review keywords and phrases.

Geographic Extent	Great Lakes, Lake Superior, Lake Michigan, Lake Huron, Lake Erie, Lake Ontario
Ecosystem Services (Tier 1)	Provisioning, Cultural, Supporting and Regulating
Ecosystem Services (Tier 2)	**Provisioning:** Food, Fiber, Biomass, Fuel, Freshwater
	Cultural: Recreational, Ecotourism, Spiritual, Aesthetics, Cultural, Educational, Spiritual
	Supporting: Nutrient cycling, Soil formation, Primary production, Water cycle, Habitat provisioning, Secondary Production
	Regulating: Climate moderation, Carbon sequestration, Air quality, Pollination, Disease and Hazard control, Erosion control, Water purification

Studies were compiled into a spreadsheet (see Appendix, Literature Review: Great Lakes ES Tracking) organized by geographic extant, ecosystem services (Tiers 1 & 2), and climate scenarios. Reviewed literature was also categorized by geographic extent in order to ensure coverage varied across the Great Lakes basin. The drivers of each ecosystem service were categorized as independent and dependent variables for each study. The relationships between drivers, although described in the literature, have not been quantified in their linkages to climate change (specifically, precipitation and temperature changes). For example, although changes in water temperature are known to impact nutrient cycling (Sierszen et al., 2012), the precise degree in which temperature controls for this service is unknown. Each map was assembled with interconnected variables but without strength indicators for the relationship between each variable.

Much of the research discussed had a large geographic extent covering the entire basin with about a quarter of studies specifically evaluating services within Lake Erie. Lake Michigan and Lake Huron were also well represented with Lakes Superior and Ontario covered the least.

Preliminary email interviews were conducted with academic stakeholders to review and make amendments to the FCM. Those who provided input into the final map design were later excluded from the later survey.

A FCM was considered complete if it included: 1. All of the primary variables discussed in the literature as impacting the related ecosystem service 2. All of the variables within the system network had a pathway in relation to changes in temperature or precipitation.

Survey Creation

Our survey sought to quantify perceptions among those possessing expert knowledge of the Great Lakes system, so it was not made available to the general public or shared within public spaces. We solicited > 300 individuals in conservation and science-based industries. Potential survey respondents were identified as those dealing with environmental systems in the United States and within Great Lakes Watershed in: Academic research, Government research/regulation, Nonprofits, or Business/Industry.

Respondents self-identified which of these categories their work fit into. However, it should be noted that some survey respondents gave feedback that they did not fit into any of these particular categories. Each respondent also indicated which of the five Great Lakes they were most familiar with.

The survey was created using Qualtrics survey software (Qualtrics, Provo, UT). This software was selected for its user-friendly interface and because it records data from each respondent anonymously. Qualtrics also grants users the option to eliminate location markers and IP addresses from the survey results which preserves the anonymity of the survey. This was helpful for us in receiving an institutional review board (IRB) exemption as such ethical considerations were required before conducting the survey.

For each question, respondents were asked to identify the strength of a relationship among variables in a premade mental model using a visual analog slider scale. Results were collected on a continuous scale of -1 to 1 with 0 indicating a lack of relationship between variables. Respondents were also asked to rank each section by its importance using the same visual analog scale. This was designed to account for the possibility of strong relationships between variables despite a lack of impact in relation to the affected ecosystem service.

Respondents indicated which category of ecosystem service they were most familiar with from a selection of cultural, regulating, provisioning, supporting services. A survey was considered complete if the respondent completed all of the questions from an ES category. Participants had the option of completing one or more ES categories. Incomplete surveys were excluded from the results.

Fuzzy Cognitive Modeling Scenarios & Statistical Analysis

Results from the survey were compiled into the software Mental Modeler (Gray et al., 2013). This software is optimized for analyzing data from FCM. An augmented matrix was created using the regular mean of all survey results for each map to represent a given value for each connection in the model. The mean was chosen as it controls for disagreement among survey responses. If a connection receives lots of negative and positive responses the mean will display a value closer to zero. This minimizes the role of variables with a lot of expert disagreement in the overall results and allows for more certain and stronger values to have a greater impact. Using the mean in model analysis also ensures that strong variables demonstrate expert consensus. The mean also minimizes the impact of outliers by drawing these values closer to the consensus mean.

The mental modeler software adds and normalizes this matrix to display the net impact on each ecosystem service. The model was run a single time for each FCM and returned final results in a consistent way. FCM is semi-quantitative and the results are not expected to be normally distributed.

This method mimics previous literature in which survey respondents compiled their maps into a single map following an in-person discussion. (Özesmi, 2004) Our results mimic this process but rather compiled the means of each respondent independently.

After creating the maps in Mental Modeler, we made scenarios for a 0.5 unit change in the climate drivers and examined how this changed the relative value of the response variable.

Results

Survey Respondent Career and Lake Expertise Demographics

Demographic information on which lakes are most studied, and the professions of survey respondents provides the first perspective of climate change impact on great lakes ecosystem services. The category of Academic Research had the greatest number of respondents with twenty and the second most identified category was Government-regulatory with 13 respondents (Table 2). Business and Industry along with Government-legislatives both had the fewest number of respondents with only one response for each of those categories respectively (Table 2). With regards to which lake respondents most closely identified their work, Lake Michigan had the greatest number of respondents with 14 (Table 2). Out of the remaining four lakes, Lake Onatrio had the fewest with no respondents. A further breakdown of profession types with lake expertise is shown in Table 2.

Table 2: Cross-tabulation of the respondent's identified profession with the

Lake/Profession	Academic Research	Business & Industry	Government - legislative	Government - regulatory	Not for Profit	Lake Total
Erie	4	1	1	5	1	12
Huron	1	0	0	2	0	3
Michigan	9	0	0	4	1	14
Superior	6	0	1	2	1	10
Ontario	0	0	0	0	0	0
Profession Total	20	1	2	13	3	n = 39

Fuzzy Cognitive Mapping Results

The results of the fuzzy cognitive modeling analysis are divided by the ecosystem service type (regulating/supporting, cultural, etc.). Most ecosystem services had multiple drivers identified that impact the delivery of that service and that would likely be altered by the effects of climate change. Each specific ecosystem service we analyzed considering how the individual drivers influence the outcome and the combined outcome with all the drivers included. The impacts on intermediate variables can be viewed in the supplementary materials. The assumed importance of each variable connection as assigned by survey respondents was also collected and can be viewed in the appendix.

Provisioning Services

Within the provisioning ecosystem services category there were four services analyzed including commercial fishing, drinking and municipal water, shipping and transportation, and wild rice yields. The response rate for individual arrow weights in the provisioning service conceptual maps ranged from a minimum of four responses to a maximum of eight responses. The conceptual map for drinking and municipal water had the greatest overall response rate while shipping and transportation had the lowest overall response rate.

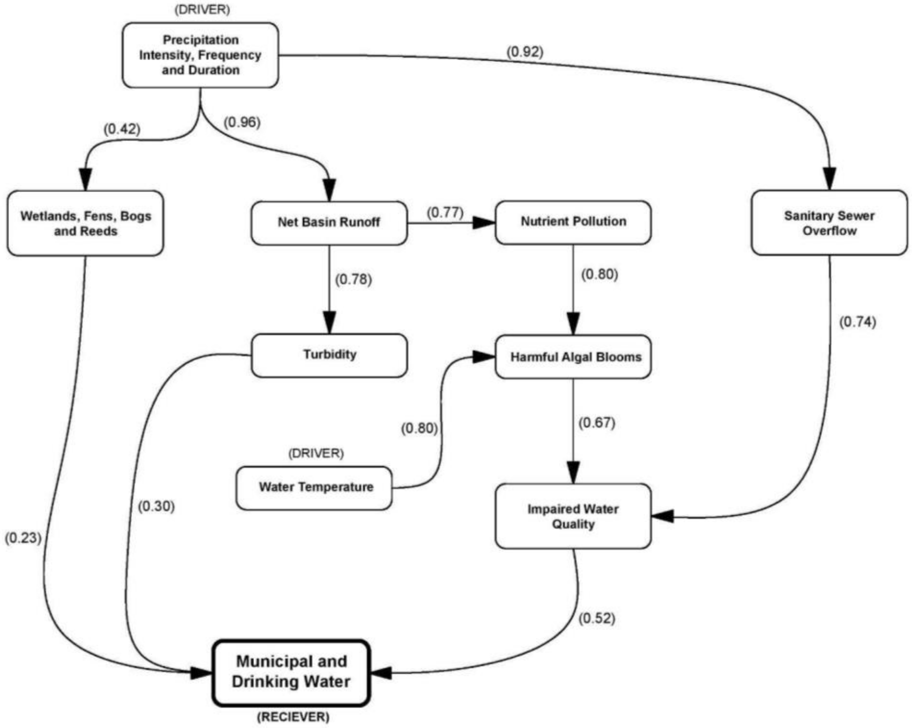


Figure 2. The drinking and municipal water conceptual map showing the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each arrow. The response rate for variables within the drinking and municipal water conceptual map ranged from a minimum of six responses to a maximum of eight responses.

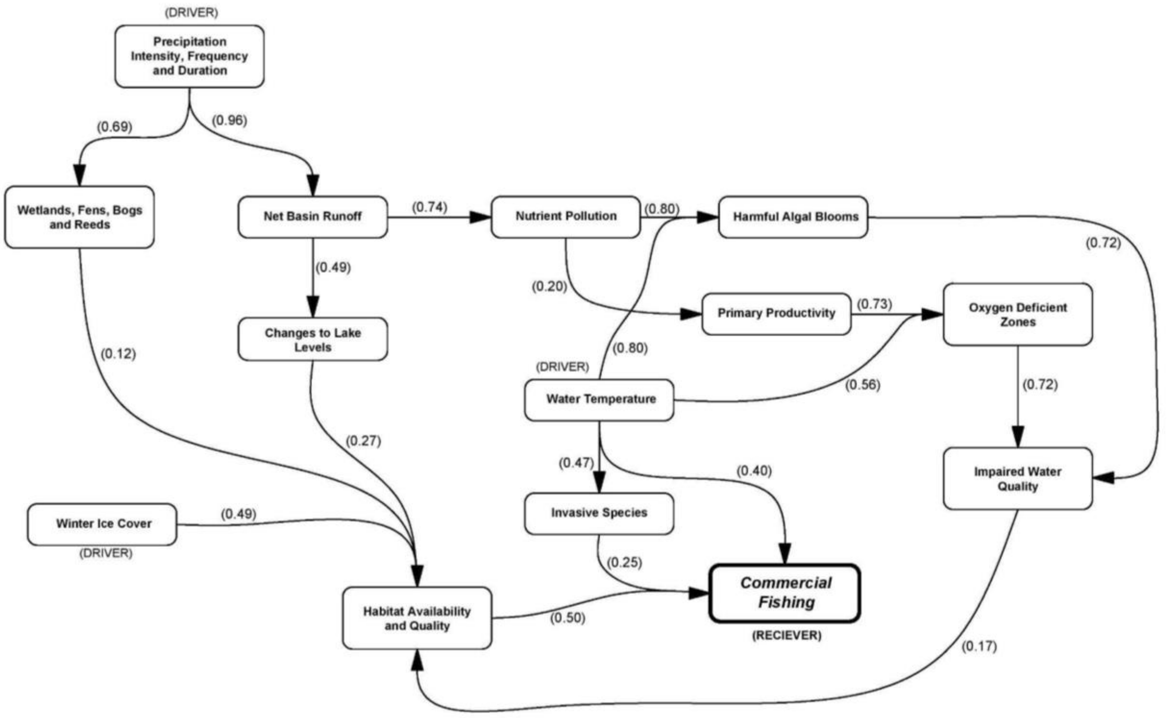


Figure 3. The commercial fishing conceptual map showing the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each arrow. The response rate for variables within the commercial fishing conceptual map ranged from a minimum of 4 responses to a maximum of 5 responses.

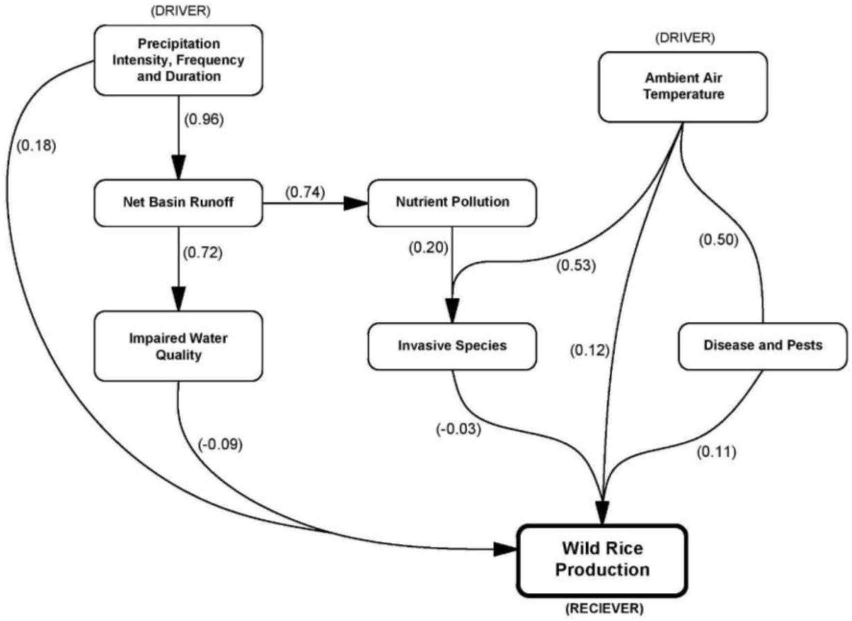


Figure 4. The wild rice production conceptual map showing the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each arrow. The response rate for variables within the wild rice production conceptual map ranged from a minimum of 5 responses to a maximum of 8 responses.

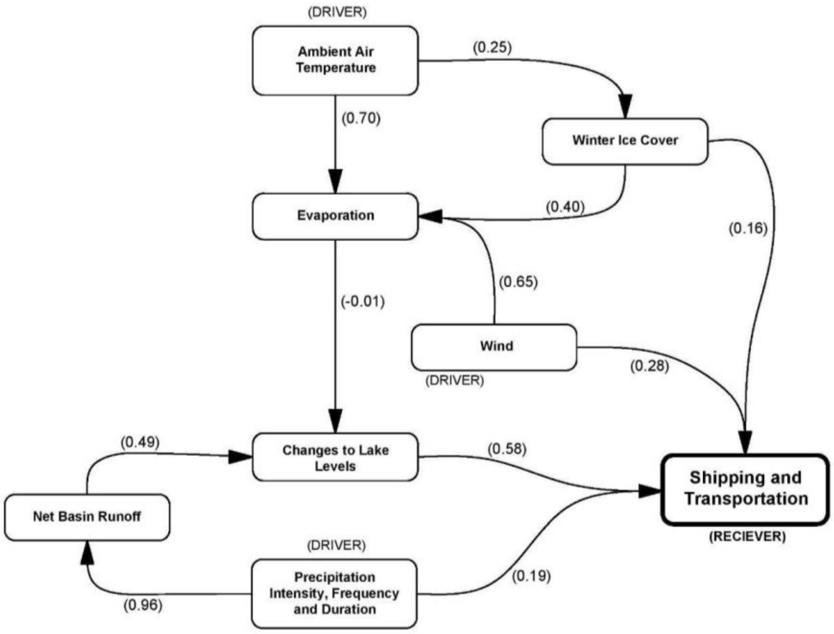


Figure 5. The shipping and transportation conceptual map showing the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each arrow. The response rate for variables within the shipping and transportation conceptual map ranged from a minimum of 4 responses to a maximum of 5 responses.

Drinking and Municipal Water

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity and (2) water temperature. The driver that had the greatest impact, considering the effects of climate change, on drinking and municipal water was precipitation frequency, duration, and intensity. With increased precipitation frequency, duration, and intensity there was an increase by a value of 0.34 in the delivery/quality of drinking and municipal water. The other driver of water temperature resulted in an increase in the delivery of habitat quality and availability by a value of 0.13. With both of the driver variables included in the scenario there will be an increase in the delivery/quality of drinking and municipal water by a value of 0.39 (Table 3).

Commercial Fishing

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, (2) winter ice cover, and (3) water temperature. The driver that had the greatest impact, considering the effects of climate change, on commercial fishing services was water temperature. With an increase in water temperature, there was an increase of 0.29 in the delivery/quality of commercial fishing services. An increase in precipitation intensity, frequency and duration had the next great impact with a resulting increase in the delivery of commercial fishing services by 0.12. A decrease in winter ice cover led to a decrease in the delivery of commercial fishing by a value of 0.06. When all three drivers were included in the scenario there was a 0.01 decrease in commercial fishing services (Table 3).

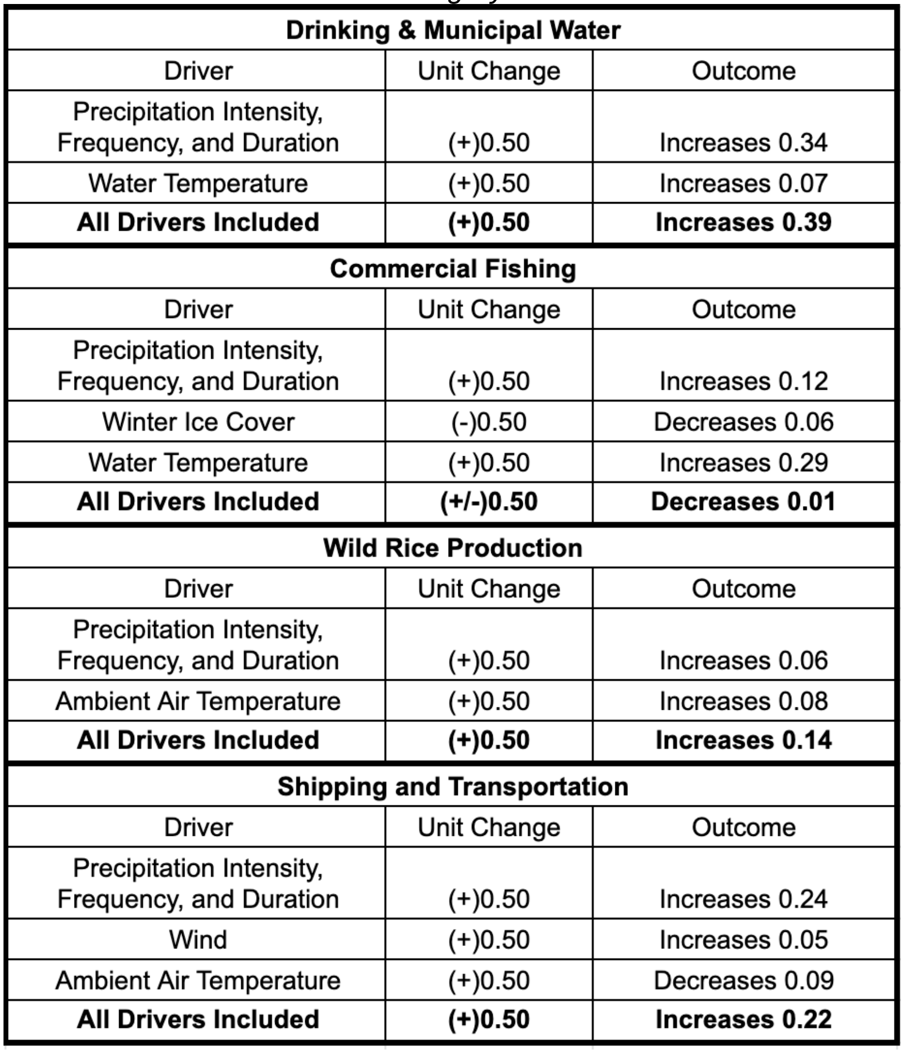
Wild Rice Production

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, and (2) ambient air temperature. The driver that had the greatest impact, considering the effects of climate change, on wild rice production services was ambient air temperature. With increased ambient air temperature there was an increase by a value of 0.08 in the delivery/quality of wild rice production services. When increased, the other driver variable of precipitation frequency, duration, and intensity led to an increase in the delivery of wild rice production services by a value of 0.06. When considering both driving variables there is an increase in the delivery of wild rice production by a value of 0.14 (Table 3).

Shipping and Transportation

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, (2) wind, and (3) ambient air temperature. The driver that had the greatest impact, considering the effects of climate change, on shipping and transportation services was precipitation frequency, duration, and intensity. With increased precipitation frequency, duration, and intensity there was an increase by a value of 0.24 in the delivery/quality of shipping and transportation services. The driver variable with the next greatest impact was the water temperature. With an increase in ambient air temperatures, there was an increase in the delivery of shipping and transportation services by a value of 0.09. The final driver that was analyzed, with the least impact being felt from climate change is wind. With an increase in wind as a result of climate change, there is a decrease in the delivery of shipping and transportation services by a value of 0.09. When considering all three driving climate variables there is a decrease in the delivery of shipping and transportation by a value of 0.22 (Table 3).

Table 3. The manipulated driver variable, the unit change, and the outcome of all scenarios for each ecosystem service analyzed within the cultural services category.



Drinking & Municipal Water

Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.34
Water Temperature	(+)0.50	Increases 0.07
All Drivers Included	**(+)0.50**	**Increases 0.39**

Commercial Fishing

Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.12
Winter Ice Cover	(-)0.50	Decreases 0.06
Water Temperature	(+)0.50	Increases 0.29
All Drivers Included	**(+/-)0.50**	**Decreases 0.01**

Wild Rice Production

Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.06
Ambient Air Temperature	(+)0.50	Increases 0.08
All Drivers Included	**(+)0.50**	**Increases 0.14**

Shipping and Transportation

Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.24
Wind	(+)0.50	Increases 0.05
Ambient Air Temperature	(+)0.50	Decreases 0.09
All Drivers Included	**(+)0.50**	**Increases 0.22**

Cultural Services

Within the cultural ecosystem services category, there were four services analyzed including sport fishing, recreational boating, winter recreation, and birding opportunities. The response rate for intermediate variables in the cultural service conceptual maps ranged from a minimum of eight responses to a maximum of eighteen responses. The conceptual map for sport fishing had the greatest overall response rate while birding opportunities had the lowest overall response rate.

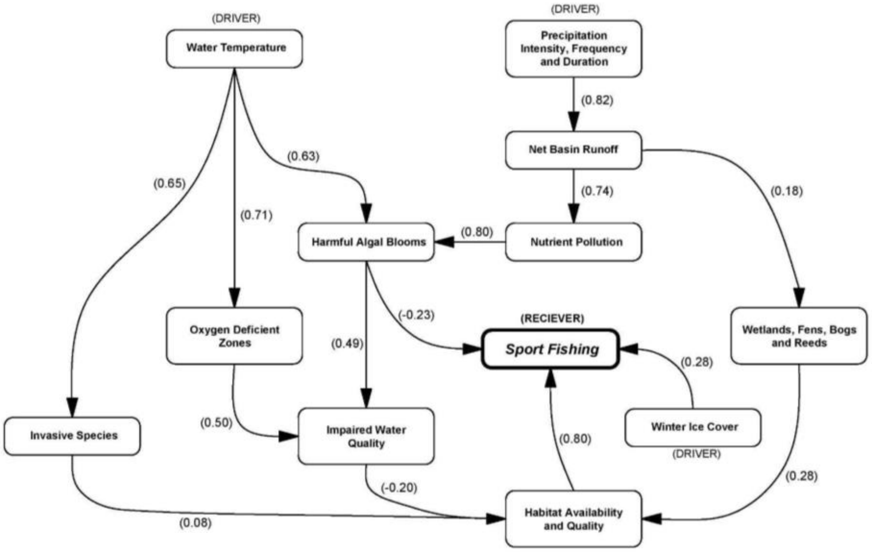


Figure 6. The sport fishing conceptual map shows the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each connection. The response rate for variables within the sport fishing conceptual map ranged from a minimum of 15 responses to a maximum of 18 responses.

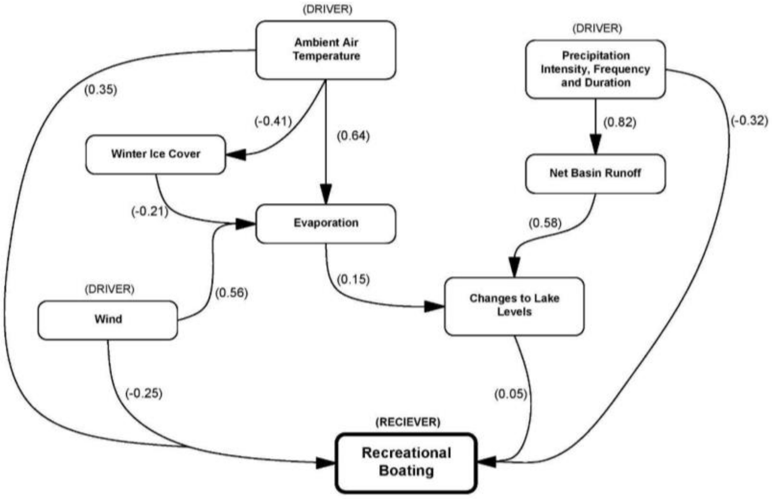


Figure 7. The recreational boating conceptual map shows the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to connection. The response rate for variables within the recreational boating conceptual map ranged from a minimum of 11 responses to a maximum of 17.

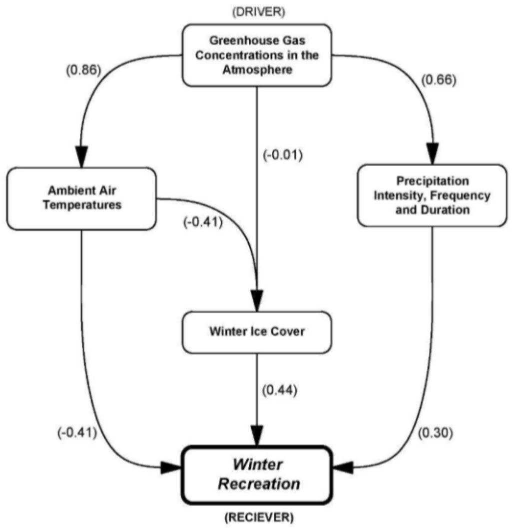


Figure 8. The winter recreation conceptual map shows the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each connection. The response rate for variables within the winter recreation conceptual map ranged from a minimum of 12 responses to a maximum of 15.

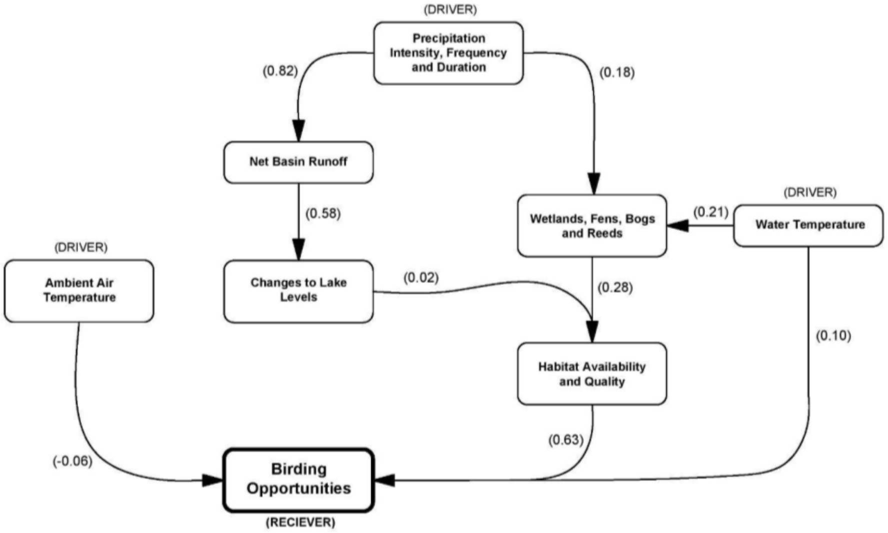


Figure 9. The birding opportunities conceptual map shows the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each connection. The response rate for variables within the birding opportunities conceptual map ranged from a minimum of 8 responses to a maximum of 13 responses.

Sport Fishing

The sport fishing conceptual map shows the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each connection. The driver variables that were altered to reflect the implications of climate change on sport fishing were (1) precipitation frequency, duration, and intensity, (2) water temperature, and (3) winter ice cover. The driver that had the greatest impact, considering the effects of climate change, on sport fishing services was winter ice cover. With decreased winter ice cover there was a decrease by a value of 0.14 in the delivery/quality of sport fishing services. The driver variable with the next greatest impact was the water temperature. With an increase in water temperatures, there was a decrease in the delivery of sport fishing services by a value of 0.10. The final individual driver that was analyzed was precipitation frequency, duration, and intensity and had the least impact being felt from climate change. With an increase in the frequency, duration, and intensity of precipitation as a result of climate change, there is a decrease in the delivery of sport fishing services by a value of 0.05. While we explored how these individual drivers impact the delivery of sport fishing services, realistically they will all be playing an interactive role at any given time. When considering all three driver variables there is a decrease in the delivery of sport fishing by a value of 0.27 (Table 4).

Recreational Boating

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, (2) ambient air temperature, and (3) wind. The driver that had the greatest impact, considering the effects of climate change, on recreational boating services was ambient air temperature. With increased ambient air temperatures there was an increase by a value of 0.18 in the delivery/quality of recreational boating services. The next strongest effect of a driver on recreational boating was precipitation frequency, duration, and intensity. With an increase in frequency, duration, and intensity there was a decrease in the delivery of recreational boating services by a value of 0.15. For the driver variable of wind, an increase in wind results in a decrease in recreational boating services by 0.12. When all three driver variables are included in a single scenario there was a decrease of 0.09 in recreational boating services (Table 4).

Winter Recreation

Only atmospheric greenhouse gas concentration was altered to reflect the implications of climate change. With increased atmospheric greenhouse gas concentrations, there was a decrease in the delivery/quality of winter recreation by a value of 0.15 (Table 4).

Birding Opportunities

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, (2) ambient air temperature, and (3) water temperature. The driver that had the greatest impact, considering the effects of climate change, on birding opportunities was water temperature. With increased water temperatures there was an increase by a value of 0.07 (Table 4) in the delivery/quality of birding opportunities. Both other drivers had an equal magnitude of effects but in opposite directions. With an increase in precipitation frequency, duration, and intensity there was an increase in the delivery of birding opportunities by a value of 0.03 (Table 4). With an increase in ambient air temperature, there was a decrease in delivery/quality of birding opportunities by 0.03 (Table 4). With all three drivers included in a single scenario, there was an increase in birding opportunities by a value of 0.06.

Table 4. The manipulated driver variable, the unit change, and the outcome of all scenarios for each ecosystem service analyzed within the cultural services category.

Sport Fishing		
Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Decreases 0.05
Water Temperature	(+)0.50	Decreases 0.10
Winter Ice Cover	(-)0.50	Decreases 0.14
All Drivers Included	**(+/-)0.50**	**Decreases 0.27**
Recreational Boating		
Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Decreases 0.15
Ambient Air Temperature	(+)0.50	Increases 0.18
Wind	(+)0.50	Decreases 0.12
All Drivers Included	**(+)0.50**	**Decreases 0.09**
Winter Recreation		
Driver	Unit Change	Outcome
Atmospheric GHG Concentrations	(+)0.50	Decreases 0.15
All Drivers Included	**(+)0.50**	**Decreases 0.15**
Birding Opportunities		
Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.03
Ambient Air Temperature	(+)0.50	Decreases 0.03
Water Temperature	(+)0.50	Increases 0.07
All Drivers Included	**(+)0.50**	**Increases 0.06**

Supporting/Regulating Services

Within the supporting/regulating ecosystem services category, there were three services analyzed including nutrient cycling, carbon sequestration, and habitat quality and availability. The response rate for individual arrow weights in the supporting/regulating service conceptual maps ranged from a minimum of seven responses to a maximum of twenty responses. The conceptual map for nutrient cycling had the greatest overall response rate while habitat quality and availability had the lowest overall response rate.

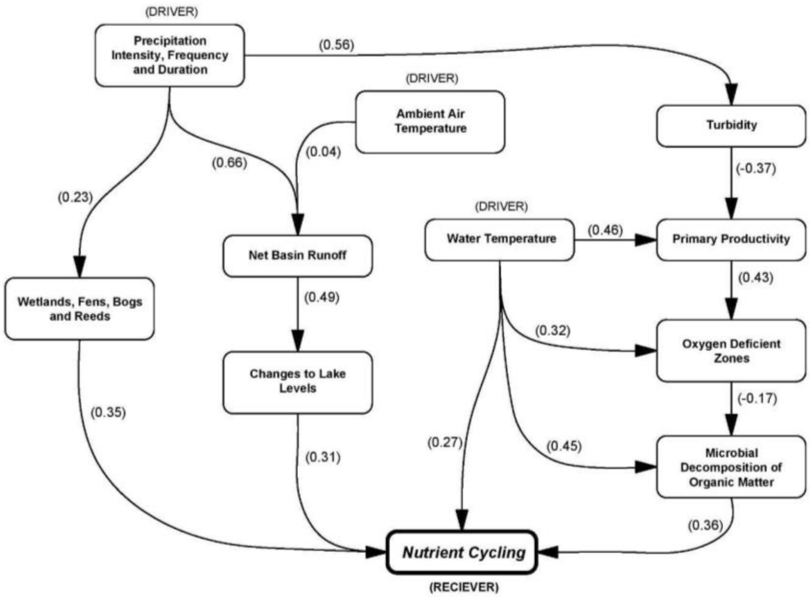


Figure 10. The nutrient cycling conceptual map showing the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each connection. The response rate for variables within the nutrient cycling conceptual map ranged from a minimum of 14 responses to a maximum of 20.

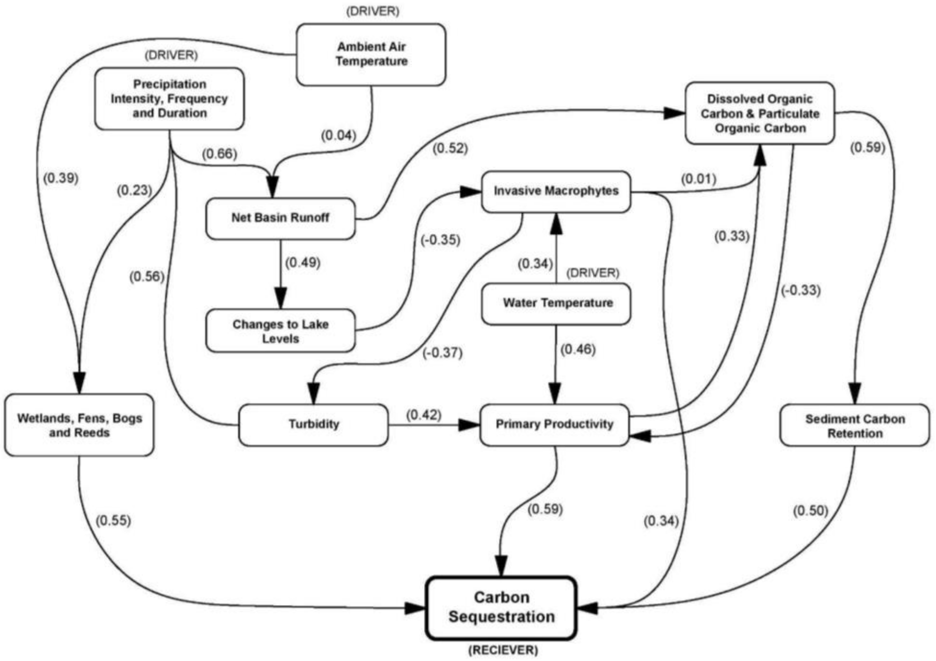


Figure 11. The carbon sequestration conceptual map showing the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each arrow. The response rate for variables within the nutrient cycling conceptual map ranged from a minimum of 7 responses to a maximum of 14.

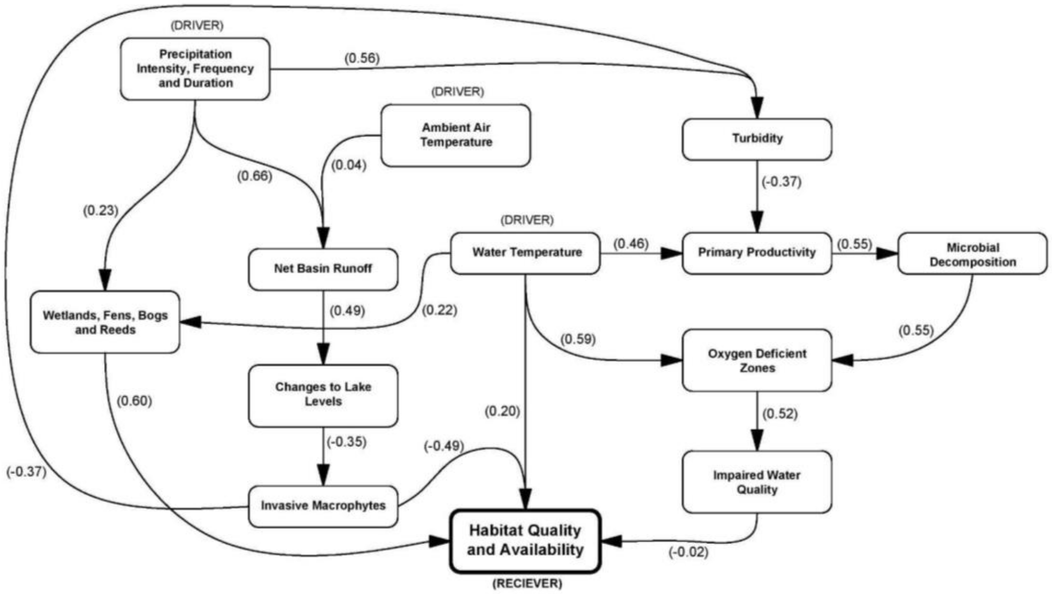


Figure 12. The habitat quality and availability conceptual map showing the drivers and intermediate variables that were included in the analysis with the averaged weights from the survey assigned to each arrow. The response rate for variables within the habitat quality and availability conceptual map ranged from a minimum of 7 responses to a maximum of 12 responses.

Nutrient Cycling

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, (2) ambient air temperature, and (3) water temperature. The driver that had the greatest impact, considering the effects of climate change, on nutrient cycling was water temperature. With increased water temperatures there was an increase by a value of 0.20 (Table 5) in the delivery/quality of nutrient cycling. The next strongest effect of a driver on nutrient cycling was precipitation frequency, duration, and intensity. With an increase in precipitation frequency, duration, and intensity there was an increase in the delivery of nutrient cycling by a value of 0.09 (Table 5). In the scenario where ambient air temperature alone was manipulated, there was not a strong enough correlation between variables to have an impact on nutrient cycling. This is likely because the weight from ambient air temperature to net basin runoff, which is an upstream factor to nutrient cycling, was relatively small (0.04).

Carbon Sequestration

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, (2) ambient air temperature, and (3) water temperature. The driver that had the greatest impact, considering the effects of climate change, on carbon sequestration was water temperature. With increased water temperatures there was an increase by a value of 0.18 (Table 5) in the delivery/quality of carbon sequestration. Both other drivers had equal strength effects on carbon sequestration. With an increase in precipitation frequency, duration, and intensity there was an increase in the delivery of carbon sequestration by a value of 0.11 (Table 5). With an increase in water temperature, there was an increase in delivery/quality of carbon sequestration by 0.11 (Table 5).

Habitat Quality and Availability

The driver variables that were altered to reflect the implications of climate change were (1) precipitation frequency, duration, and intensity, (2) ambient air temperature, and (3) water temperature. The driver that had the greatest impact, considering the effects of climate change, on habitat quality and availability was water temperature. With increased water temperatures there was an increase by a value of 0.16 (Table 5) in the delivery/quality of habitat quality and availability. The next strongest effect of a driver on habitat quality and availability was precipitation frequency, duration, and intensity. With an increase in precipitation frequency, duration, and intensity there was an increase in the delivery of habitat quality and availability by a value of 0.13 (Table 5). Again, in the scenario where ambient air temperature alone was manipulated, there was not a strong enough correlation between variables to have an impact on habitat quality and availability. This is likely because the weight from ambient air temperature to net basin runoff, which is an upstream factor to nutrient cycling, was relatively small (0.04).

Table 5. The manipulated driver variable, the unit change, and the outcome of all scenarios for each ecosystem service analyzed within the supporting/regulating services category.

Nutrient Cycling		
Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.09
Ambient Air Temperature	(+)0.50	0.00
Water Temperature	(+)0.50	Increases 0.20
All Drivers Included	**(+)0.50**	**Increases 0.29**
Carbon Sequestration		
Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.11
Ambient Air Temperature	(+)0.50	Increases 0.11
Water Temperature	(+)0.50	Increases 0.18
All Drivers Included	**(+)0.50**	**Increases 0.40**
Habitat Quality and Availability		
Driver	Unit Change	Outcome
Precipitation Intensity, Frequency, and Duration	(+)0.50	Increases 0.13
Ambient Air Temperature	(+)0.50	0.00
Water Temperature	(+)0.50	Increases 0.16
All Drivers Included	**(+)0.50**	**Increases 0.28**

Discussion

Great Lakes ecosystems provide many services that support the ongoing functioning of these landscapes, provide cultural benefits and economic opportunities. It is important to understand how the delivery of these ecosystem services will be impacted by the onset of climate change. The purpose of this paper is to identify to what extent certain ecosystem services will be impacted and to what degree. Our results indicate that the impacts of climate change may increase many of the underlying drivers of these ecosystems, ultimately increasing the delivery of these services. The ecosystem services that displayed the greatest potential increase included carbon sequestration, drinking and municipal water and nutrient cycling. The services that showed the most potential for a decrease included winter recreation, sport fishing and recreational boating. The scenarios that we ran to determine these results considered these ecosystem services from a fundamental perspective and did not consider the conditions that individual or native species may require. The services that we identified to have the greatest impact as a result of climate will need further investigation to determine how individual species will respond.

The Fuzzy Cognitive Mapping (FCM) method provides a semi-quantitative perspective on the impacts of climate change on ecosystem service quality/delivery in the Great Lakes. These perspectives can be used to provide guidance on where there is disagreement or uncertainty within the Great Lakes research and management community. We will discuss the implications of the results in an attempt to understand the mechanism that drives those outcomes and how these results can be used to guide future research.

A limitation of this study is that the dependencies among some of the drivers are not modeled. For example, water temperature and winter ice cover are influenced by ambient air temperature; however, these dependencies are manually prescribed based on consensus that are widely accepted (e.g., increase in ambient air temperature accompanies warmer water temperature and less winter ice cover). An exception is GHG increase, which is set as an upstream driver of precipitation frequency and ambient air temperature in the model. We also assumed these unit changes are the same across the drivers (i.e., ±0.5). Modeling exact changes caused by one driver to the others is a highly complex problem that requires a more complicated approach such as regional climate modeling and is not within the scope of this study.

Provisioning Services

Great lakes have been adversely affected by anthropogenic stressors that are impacting aquatic ecosystems across the globe and more recently, climate change has emerged as an additional stressor to fish populations and fisheries in these large lakes. From our analysis, it was observed that commercial fishing was negatively impacted by the modification in climate attributes. In particular, the model was more sensitive towards the decreasing ice cover than to increasing temperature or precipitation. Studies have shown that water temperatures and ice cover in the Great Lakes can be affected by rising air temperatures and increased downward longwave radiation. By reducing wave action in shallow areas, ice cover can influence the physical conditions for fish whose eggs incubate during the winter (Collingsworth et al., 2017). Meanwhile, the rising temperature affects the concentration of dissolved oxygen in surface water, which has a seasonal and daily cycle. Under such scenarios, solubility of oxygen will be limited, and prevalence of hypoxia can induce additional stress on fish, meanwhile it provides an opportunity for invasive fishes to dominate. In sum, climate change will have a negative impact on commercial cold-water species by reducing their habitat for growth, inducing interspecific competition, and invasive species. Despite these findings, predicting how the diminishing ice cover will change as the world warms and in particular for cold water dwellers will require more research.

The most notable of provisioning services is the provisioning of clean water for drinking and other municipal-scale extractive activities. The Great Lakes-St. Lawrence Basin provides 38,854 million gallons per day for extraction going to various activities including drinking water and thermoelectric cooling (GLC, 2019). In our conceptual map for drinking and municipal water, there are two major pathways through which climate change can affect the provisioning of this service, through total supply and through quality of supply. The strongest pathway through which drinking and municipal water was affected was through impaired water quality (0.52). In our conceptual maps, impaired water quality stemmed from two upstream factors, harmful algal blooms and sewer overflows. Harmful algal blooms are projected to increase with the effects of climate change through two pathways, increased precipitation, and increased water temperatures both represented in our conceptual diagrams and studied in the literature (Michalak et al., 2013). However, the prevalence of harmful algal blooms is not solely determined by climate change driven effects; nutrient pollution from conventional agriculture also plays a key role in increases to harmful algal blooms (Michalak et al., 2013).

Our analysis did not include other anthropogenic effects beyond those resulting from climate change, so changes to agricultural practices were not included. However, agricultural nutrient increases/reductions are hard to separate from climate change, as increased precipitation also increases runoff, moving more nutrients from the land to the lakes (Michalak et al., 2013). Our conceptual maps agree with this finding, with net basin runoff having a strong positive effect on nutrient pollution (0.77) and nutrient pollution having a strong positive effect on harmful algal blooms (0.80). Our maps did not focus too heavily on aspects of total water supply, as more recent analyses do not project the strong reductions in net basin supply that earlier models did (Mailhot et al., 2019; Croley, 1990). Small changes to probabilities of extrema could increase the likelihood of municipal water intake extensions, but these extensions have also occurred in the past as Great Lakes water levels are historically highly variable (Mailhot et al., 2019; Changnon, 1993).

Our findings suggest that wild rice production is likely to be equally affected by changes to precipitation and changes to temperature. However, the overall magnitude of climate change impacts on wild rice production was relatively small. This suggests that other factors may be at play in the noted decline of wild rice throughout the Great Lakes region (Drewes & Silbernagel, 2012). Wild rice production is dependent on water levels, with high water levels drowning the crop, and low water levels encouraging production but limiting access for harvest (Drewes & Silbernagel, 2012). Further, stable water levels may encourage dominance by invasive species like *Phragmites australis* (Wilcox & Nichols, 2008). Our model did not explicitly include changes to water level, despite their importance to wild rice yield, because more recent models of long-term water levels in the Great Lakes do not predict dramatic changes to water levels from climate change (Notaro et al., 2015; Mailhot et al., 2019). The relatively small effect of climate change factors suggests that human actions on the environment may be of crucial importance for sustaining wild rice production. Given the importance of water levels, management actions at dams and locks that prioritize high water levels may drown wild rice in Great Lakes-connected coastal wetlands (Drewes & Silbernagel, 2012; Angradi et al., 2016). In smaller wetlands throughout the region, local scale land-use change may be the most important factor in the extent and quality of wild rice habitat available (Jennings et al., 2003). Although wild rice production in our model was not particularly affected by climate change, climate change may still exacerbate the current downward trend resulting from a myriad of factors including regional land use change and human impacts on hydrology (Drewes & Silbernagel, 2012).

Our analysis suggests that climate change will most likely impact commercial shipping through changes to precipitation. Survey respondents indicated that changes to precipitation could result in a modest increase in commercial shipping (0.22). Commercial shipping interests prefer high water levels that allow for the full loading of vessels without concerns for draft. Our conceptual map for commercial shipping contained two of the key components that determine water levels in the Great Lakes, evaporation and precipitation/runoff. Survey respondents indicated that changes in precipitation through runoff had a higher impact on lake levels (0.49) than changes in evaporation (-0.01). By increasing precipitation as predicted in recent climate change forecasts for the region (Zhang et al., 2020), our model predicts an increase in commercial shipping. Early models for long-term water levels in the Great Lakes predicted decreased water levels (Croley, 1990; Hartmann, 1990; Mortsch & Quinn, 1996). However, these models often overpredicted changes to evapotranspiration, and later models correcting for this found modest decreases, no change, or possibly increases to water levels (Lofgren et al., 2011; Music et al., 2015). Our model included ice cover, wind, and precipitation directly as factors that influence commercial shipping, but the strength of each effect was small compared to the effect of lake levels. Past studies included reductions in ice cover and extended shipping seasons as a possible means of recouping losses from reduced lake levels; however, given more recent projections of long-term lake levels, risky ice-season shipping may not be required despite decreasing trends in ice cover duration (Marchand et al., 1988; Mason et al., 2016).

Cultural Services

The Great Lakes provide an immense cultural value to people through the delivery of ecosystem services that provide natural or emotional enjoyment. In our analyses the cultural services were limited to sport fishing, recreational boating, winter recreation and birding opportunities. There are countless cultural services that the Great Lakes provide but we limited it to these options as we felt they are some of the more broadly utilized cultural services.

Sport fishing is an extremely important aspect of the culture and economy of the Great Lakes basin. The economic value of sport fishing alone supports a large portion of the tourist market in the Great Lakes. It is estimated that the value of sport fishing within the Great Lakes is in the range of $393 million to $1.47 billion per year (Poe et al., 2013). With this in mind, it is alarming that the results of our FCM show a decrease (-0.27) in the delivery/quality of sport fishing as a result of the impacts of climate change. This is a result of many of the intermediate variables in the conceptual model for sport fishing being assigned negative values by the survey respondents. Variables that were identified as negatively impacting sport fishing are the same variables that will negatively impact the success of fishes as a whole. These negative variables included oxygen deficient zones, harmful algal blooms and impaired water quality. These results align well with the prevailing literature on the success of fish species in the Great Lakes. Many of these effects are compounding with each other, further exacerbating the impact of fishes. For example, harmful algal blooms which are detrimental to fish through the release of neurotoxins such as Anatoxin-a, and Microcystin among others (Heisler et al., 2008). Harmful algal blooms also increase the rate of oxygen deficiency of the Great Lakes. When the climate drivers of water temperature and precipitation were manipulated individually in the FCM scenarios they both resulted in an increase in the harmful environmental factors of oxygen deficiency, harmful algal blooms and impaired water quality. The climate variable that had the greatest impact on the delivery of sport fishing ecosystem service was a decrease in winter ice cover. This could be explained by the importance that winter ice cover has on the recruitment success of popular sport fishing species such as whitefish and perch (Brown et al., 1993; Farmer et al., 2015). While increased water temperatures can cause increased growth rates and sizes of temperature fish, the shorter, warmer winters are harmful to their reproductive cycle and may negate any assumed benefits of increased summer water temperatures (Farmer et al., 2015). Another more simple explanation is that decreased ice cover provides less opportunity for ice fishing in general as the winter season makes up a large portion of the Great Lakes sport fishery season. Winter ice cover was as a driving variable or an intermediate variable in multiple of our conceptual models, in each instance that it was included, the impact of climate change led to a decrease in the value of winter ice cover (recreational boating -0.2; winter recreation -0.17). Not all of the variables that were included in the conceptual models were identified to have likely negative impacts. Survey respondents indicated that variables such as wetlands which benefit from increased precipitation have a positive impact on the delivery of sport fishing ecosystem services. Even the presence of invasive species had a positive impact on sport fishing. This could be explained by the fact that this model did not consider only the impact on native fisheries, as there is sport fishing value derived from non-native species (Cambray, J. A., 2003). The sport fisheries of the Great Lakes provide not only a great leisure and spiritual service through sport fishing, it is also an important tourism source. With this in mind, we recommend that future research should focus on understanding which fish species will be the most impacted by this decrease in sport fishing delivery. In addition, it should be identified which species will be the most impacted, either positively or negatively and how this will impact the sport fishing industry in the Great Lakes. A further understanding of how decreases in ice cover and increases in precipitation and water temperature impact sport fisheries will also have greater implications on other ecosystem services related to fish as well and can have wider implications in the success of Great Lakes fisheries.

In the conceptual model assessing winter recreation, increased greenhouse gas (GHG) concentrations were the only driver variable, with increased ambient temperature and increased precipitation/intensity as intermediate variables. With an increase in atmospheric GHG concentrations there was a negative response (-0.15) in the delivery of winter recreation ecosystem services. This again was largely due to a resulting decrease in winter ice cover. With this conceptual map the driving variable that was manipulated in the climate change scenario was GHG concentrations rather than ambient air temperature and/or precipitation intensity, frequency and duration. This allowed us to assess how the respondents would correlate the affect climate change may have on these variables. For both ambient air temperature and precipitation intensity, frequency and duration, the survey respondents assigned strongly positive values, 0.86 and 0.66 respectively. This indicates that the survey respondents believe that increased GHG concentrations will result in increased ambient air temperatures and an increase in precipitation intensity, duration and frequency. This aligns closely with the scientific consensus that increased temperatures allow the atmosphere to hold more moisture, increasing the intensity and frequency of rainfall (Hanrahan et al., 2021). A variable that the respondents felt would positively impact the delivery of winter recreation ecosystem services was precipitation intensity, duration and frequency. This could be interpreted that increases in precipitation during the winter months as snowfall will increase the delivery of winter recreation but it should be noted that there is also an increase in ambient temperatures as well, meaning precipitation during the winter months may actually be in the form of rain rather than snow.

For the ecosystem service of recreational boating, the FCM analysis showed the decreased winter ice cover actually led to an increase in recreational boating. Overall though, there was a decrease in the delivery/quality of recreational boating ecosystem services. Considering the driving factors of precipitation intensity, duration and frequency, ambient air temperature and wind, there was a negative response of recreational boating to the likely impacts of climate change. This was most significantly attributed to increased precipitation intensity, duration and frequency (-0.15) leading to fewer recreational boating opportunities. The second largest controlling factor was the expected increase in wind leading to less favorable conditions for recreational boating (-0.12).

The only cultural service analyzed in this study that showed an increase in the delivery/quality in the face of climate change was the ecosystem service of bird watching enjoyment and opportunities. One aspect of birding that feels these positive increases in the rate at which birds sing. Most birds sing from within or atop clumps of dense vegetation, increased water temperatures and increased rainfall both contribute to increased vegetation growth (Møller, 2011). Wetlands with increased water extent also see increased species richness and populations of marsh bird species (Hohman et al., 2021). Alternatively a resulting decrease in birding opportunities from increased ambient air temperatures (0.03). This negative impact of increased ambient temperatures could be attributed to the negative impact that changing temperature has on the timing of migration for some bird species (Donnelly et al., 2009). Alternatively, there is some literature that increased temperatures lead to larger, faster developing eggs in birds which could lead to an increase in the success and strength of bird reproduction (Boersma, 1982). It is worth noting that this increase in birding opportunities does not consider the preferences or needs of any particular species, only the underlying conditions that support bird populations and reproductive success. While some species may see an increase in success, more sensitive species may see a decrease. We recommend further research into how individual species will respond to these changes identifying which may respond positively and which may respond negatively. This should keep consider any tradeoffs that may occur with increased air temperature which was identified as negatively influencing birding opportunities.

Supporting/Regulating Services

In our FCM analysis of how climate change may impact nutrient cycling delivery in the Great Lakes we considered precipitation intensity, duration and frequency, ambient air temperature and water temperatures. Overall, considering all of the drivers with the implications of climate change there was a positive increase in the delivery/quality of nutrient cycling in the Great Lakes. We observed that increases in water temperature resulted in the greatest impact on nutrient cycling with a positive response (0.20). Water temperature is known to accelerate the rate of nutrient cycling in lakes, especially eutrophic lakes (Yindong et al., 2021). Again it is important to keep in mind that we are only investigating the fundamental delivery of nutrient cycling delivery, not the implications of increased delivery. In lakes that are already eutrophic, an increase in nutrient cycling can compound these issues. Seasonal spikes in nutrient loading that correlate with increased water temperatures can lead to worse algal blooms which have repercussions of their own (Yindong et al., 2021).

Precipitation intensity, duration and frequency also showed a positive response (0.09) to the effects of climate change. This could be attributed to an increase in precipitation intensity, duration and frequency leading to wetlands that have a larger extent and increased interspersion (Hohman, 2021). This can benefit nutrient cycling by increasing the residence time for water in wetlands and slower moving allowing for sediments to settle out (Baskar et al., 2014). Wetlands are an incredibly effective and important actor in cycling and removing nutrients, from both natural and now human sources (Williams, 1985). With an increase in wetland area as a result of increased rainfall, there should be greater rates of nutrient cycling. In addition, wetlands of the Great Lakes depend on cyclical changes in water levels to function effectively and increases in precipitation intensity, duration and frequency may help maintain these cycles (Mortsch, 1998). There are a few caveats to keep in mind though, the first of which is the tremendous impact the land use changes have on the area of wetlands. The Great Lakes basin has seen average wetland losses of 50% since European settlement with some areas exceeding 90% (Hecnar, 2004). As humans realize how crucial wetlands are to the sustaining of our coastal and inland ecosystems there has been a push to replace the lost natural wetlands with manufactured wetlands. While engineered wetlands will bring back some of the benefits that natural wetlands provide, they function much less effectively (Mortsch, 1998). The possible increase in nutrient cycling that climate change may provide can only be utilized if existing wetlands are protected and are allowed to experience the seasonal variations in water levels. In addition, man made wetlands do provide the benefits of natural wetlands to a lesser extent, further research should be completed on how to increase the efficiency of these manufactured wetlands.

Carbon sequestration is a particularly relevant ecosystem service in modern ecosystems. Ecosystems, especially aquatic ecosystems, are notable sources of carbon storage but it will be important moving forward to understand how they will respond to climate change. Under the influence of climate change, many types of ecosystems may revert to releasing carbon rather than capture it (Duffy et al., 2021). Overall, considering the climatic effects of climate change there was a positive increase in the delivery/quality of carbon sequestration services. The climate driver that had the greatest influence on carbon sequestration considering the implications of climate change was water temperature. With elevated water temperatures there was a positive response in the delivery of carbon sequestration. When looking at the values assigned to the conceptual model by repondants, much of this increase in carbon sequestration can be attributed to the strong positive response increased water temperatures have on primary productivity. In aquatic ecosystems, warming water increases carbon specific primary productivity (Williams et al., 1997). Survey respondents identified carbon sequestration to see the greatest positive response to climate change compared to any of the ecosystem services we investigated. While completing the literature review we determined there is a gap in research regarding carbon sequestration in the Great Lakes, especially considering climate change. We recommend further research to identify where carbon sequestration will be increasing both spatially and what mechanism will be sequestering this carbon.

Another crucially important supporting service for the Great Lakes is habitat quality and availability. This is a foundation for the success of the flora and fauna that inhabit these ecosystems. The quality and availability of habitat is not only important for individual species but for the delivery of other ecosystem services as a whole. To assess the impact that climate change may have on the delivery of habitat quality and availability three drivers were manipulated. These include precipitation intensity, duration and frequency, ambient air temperatures and water temperatures. Considering the impacts of climate change on all three drivers, there was an increased response (0.28) in the delivery of habitat quality and availability. A factor that leads to this possible increase in habitat quality and availability is the increase in wetlands, bogs, fens and reeds. Great Lakes wetlands naturally experience changes in water levels and flourish when there is variation in input (Mortsch, 1998). With increased rainfall frequency, duration and intensity this should provide a benefit the the function of these as valuable habitat. Again, as mentioned about nutrient cycling, human alteration of wetlands limits their ability to function and may negate any potential benefits. If wetlands are not able to have this variation in water levels due to diking or the complete filling in then this can lead to a permanent loss of that habitat (Prince et al., 1992). Another aspect of increased rainfall, leading to increased water levels is the impact it has on invasive species. *Phragmites australis* has become a perisiant threat to the quality and availability of habitat in the Great Lakes, and our model accounts for that threat with the variable of invasive macrophytes being assigned a value of -0.49 by repondants. Species like *Phragmites australis* are intolerant to flooding, so increased water levels will aid in making conditions less favorable for that invasive species (Mauchamp et al., 2001). While *Phragmites australis* will suffer from having their roots submerged, this alone will not eradicate the problem. Flooding in addition to other methods of suppression such as spraying or burning are also necessary (Utah Counties Weed Supervisor, 2022). An important note is that this conceptual model does not account for the habitat needs of any particular species. There is a wide range of conditions that different species inhabit, while habitat conditions may become more favorable for one species it likely will become less favorable for another. This could lead to changes in community composition and ecosystem diversity. Further research needs to be done to identify specifically which species are going to benefit from altered conditions and which will suffer. In addition, the continued management and removal of detrimental invasive macrophytes should continue.

Conclusion

A cognition model, such as FCM, depicts a system in a way that closely resembles how humans perceive it, as a result, even a non-professional audience can understand the model, and each parameter has a recognizable meaning. The goal of the study was to develop a conceptual model that combines a holistic view of the ecosystem, its processes, and multiple ecosystem services. It promotes interdisciplinarity by integrating different disciplines and fields of knowledge, as well as a horizontal relationship between scientists and local actors. In terms of ecology, the models are a significant step forward in our understanding of how top-down and bottom-up processes influence the regulation of key ecosystem services. The usefulness of an FCM model as a tool for exploring future scenarios will improve as the relationships in the model are substantiated or revised based on comparisons to process-based models. FCM can be used to easily communicate with policymakers and land managers in order to assist them in making long-term decisions. In addition, these models can be useful in guiding large, basin wide decisions in which the implications are difficult to study. The results of this study are meant to provide a broad, basin wide assessment of how climate change will impact multiple ecosystem services. Ecosystem services such as drinking and municipal water, sport fishing, commercial fishing and carbon sequestration have all been identified as seeing the greatest impacts as a result of climate change. The next steps we recommend are to further identify species or spatially explicit changes that will occur. As the implications of climate change evolve over time it may be beneficial to replicate this study with updated variables or weights assigned.

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Appendix

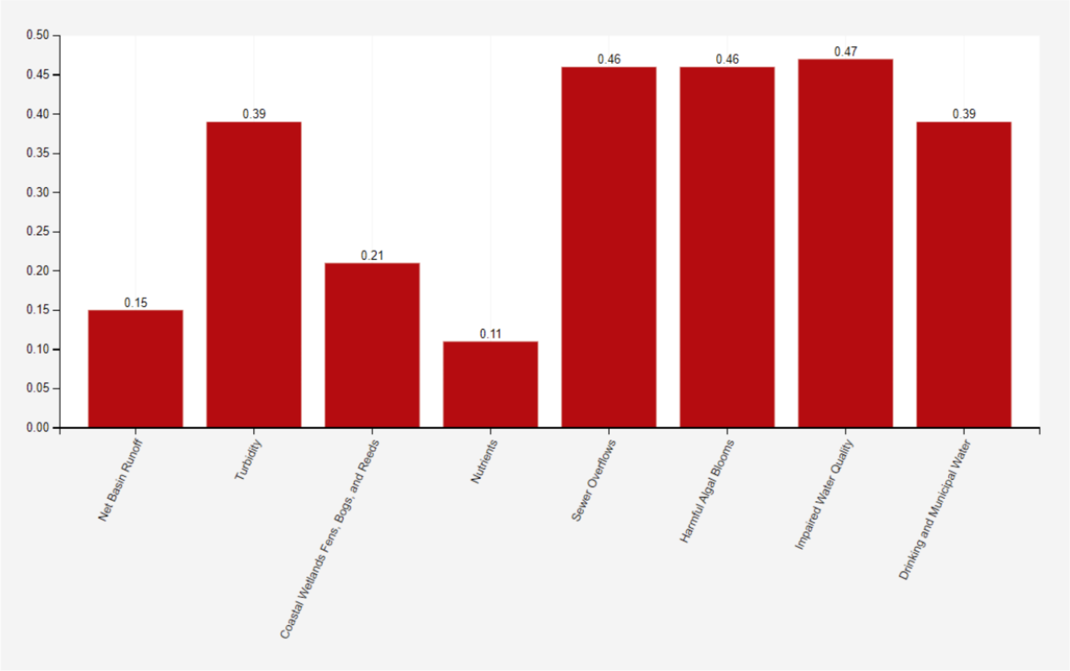


Figure A1. Drinking and Municipal Water FCM output.

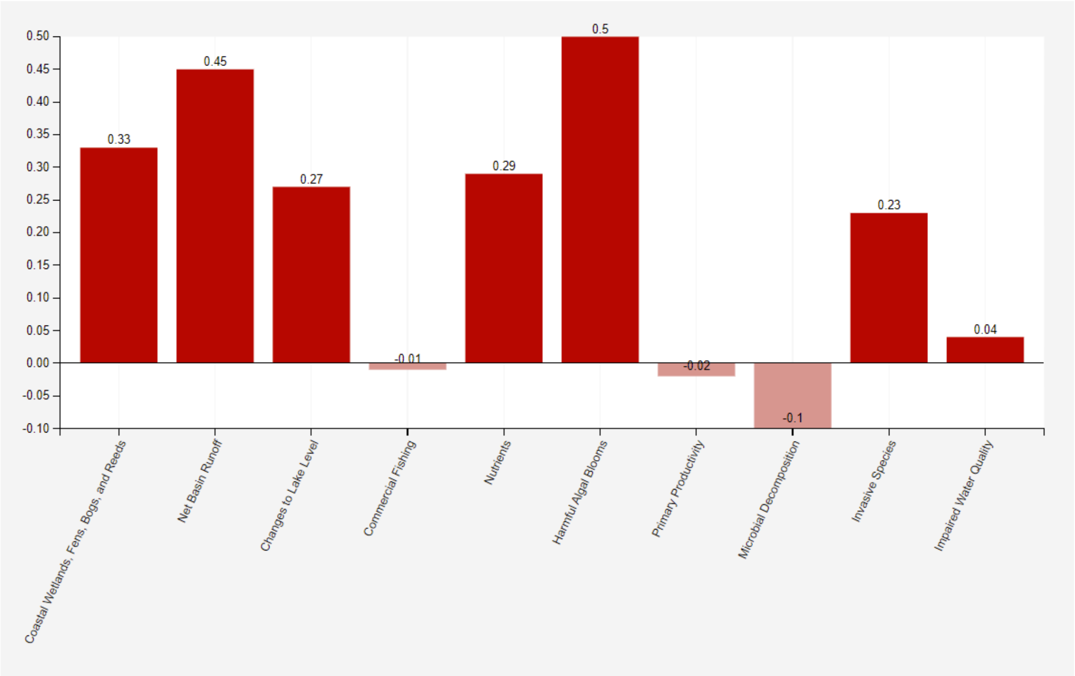


Figure A2. Commercial Fishing FCM output.

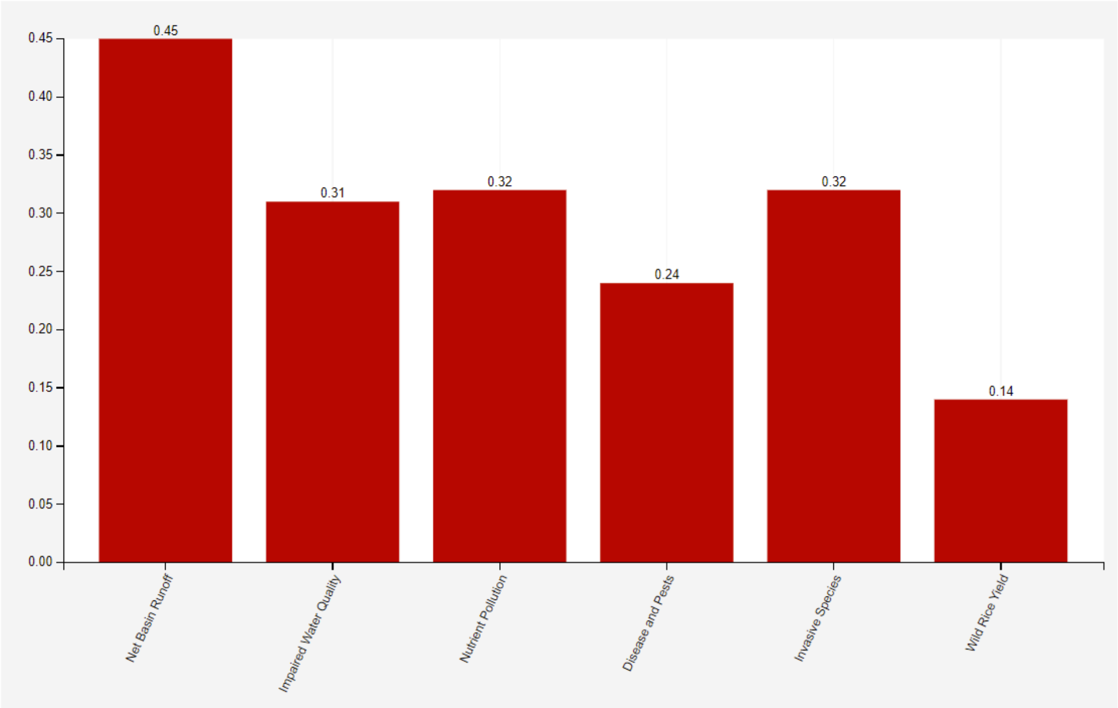


Figure A3. Wild Rice Production FCM output.

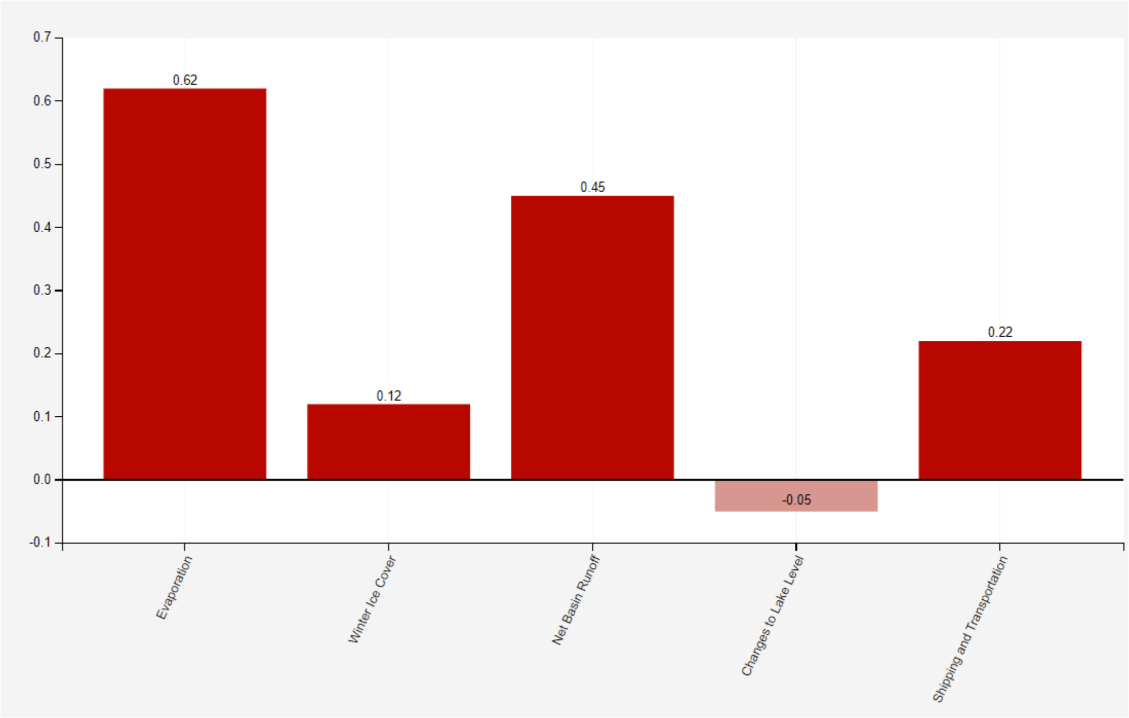


Figure A4. Shipping and Transportation FCM output.

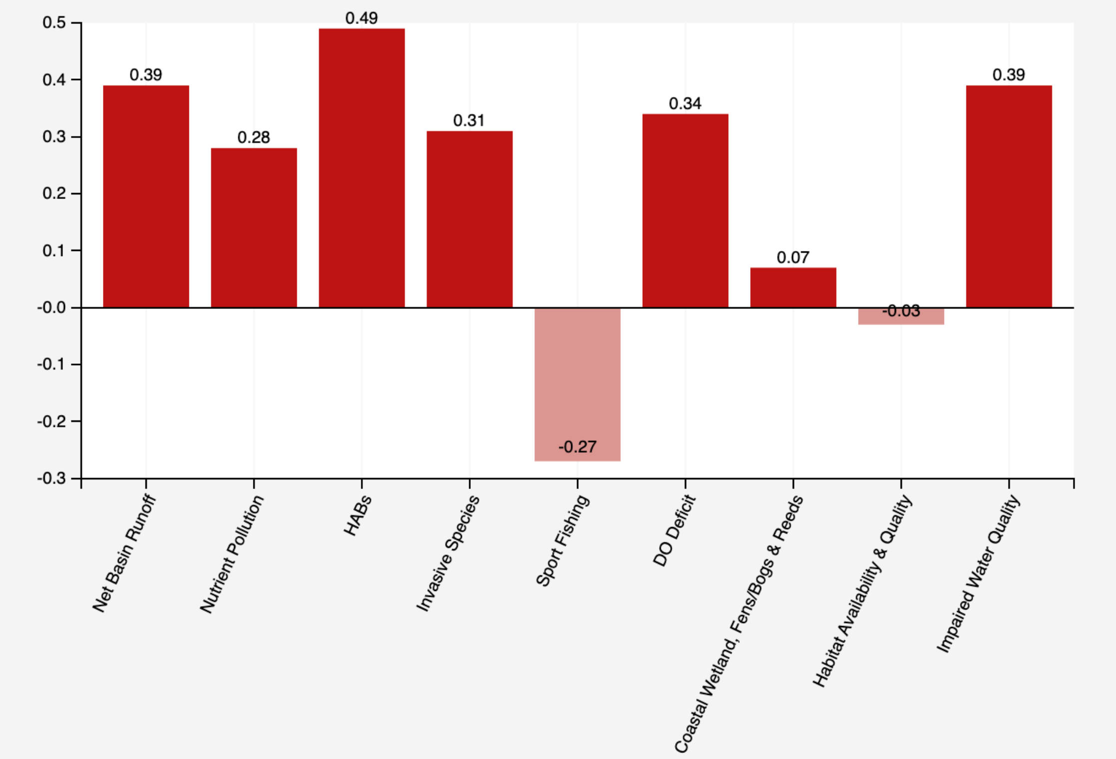


Figure A5. Sport Fishing FCM output.

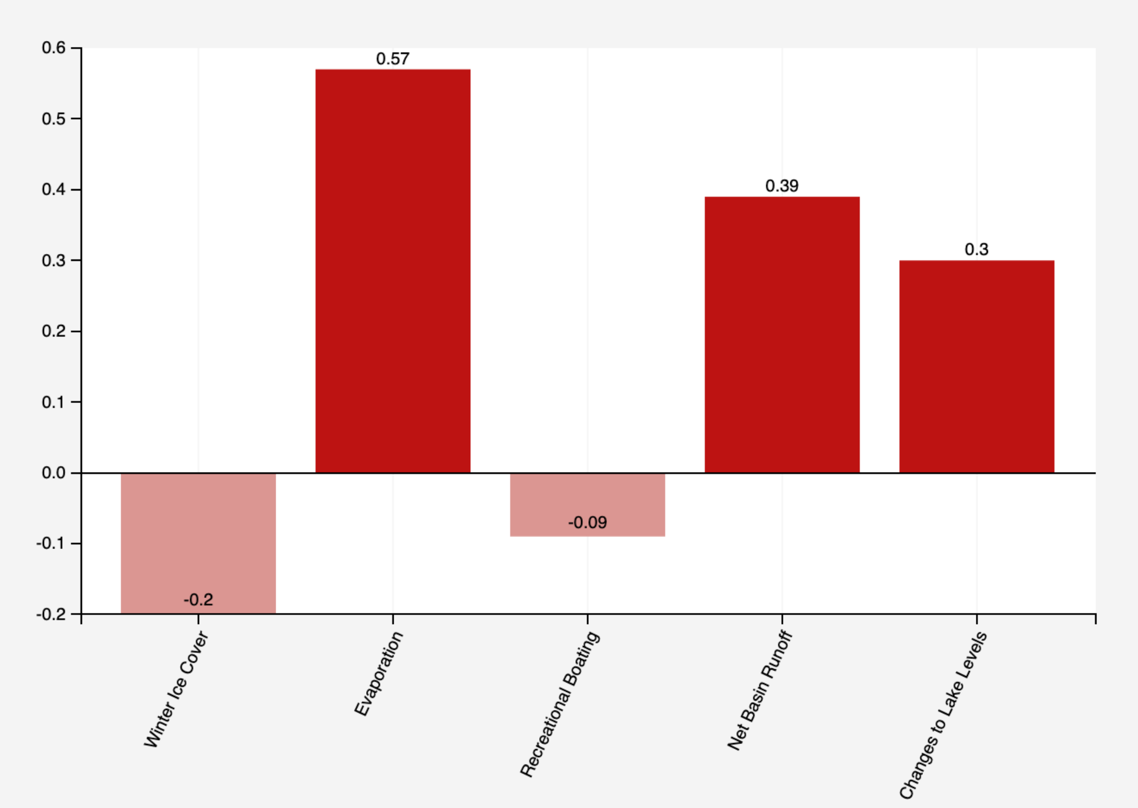


Figure A6. Recreational Boating FCM output.

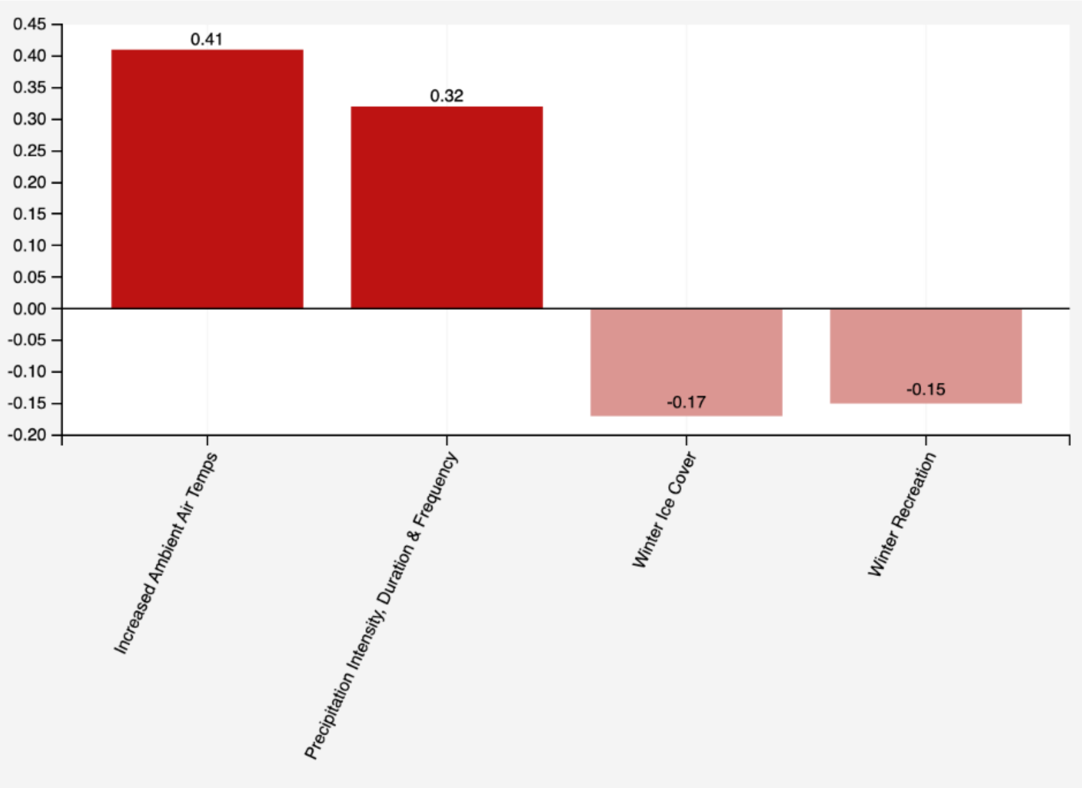


Figure A7. Winter Recreation FCM output.

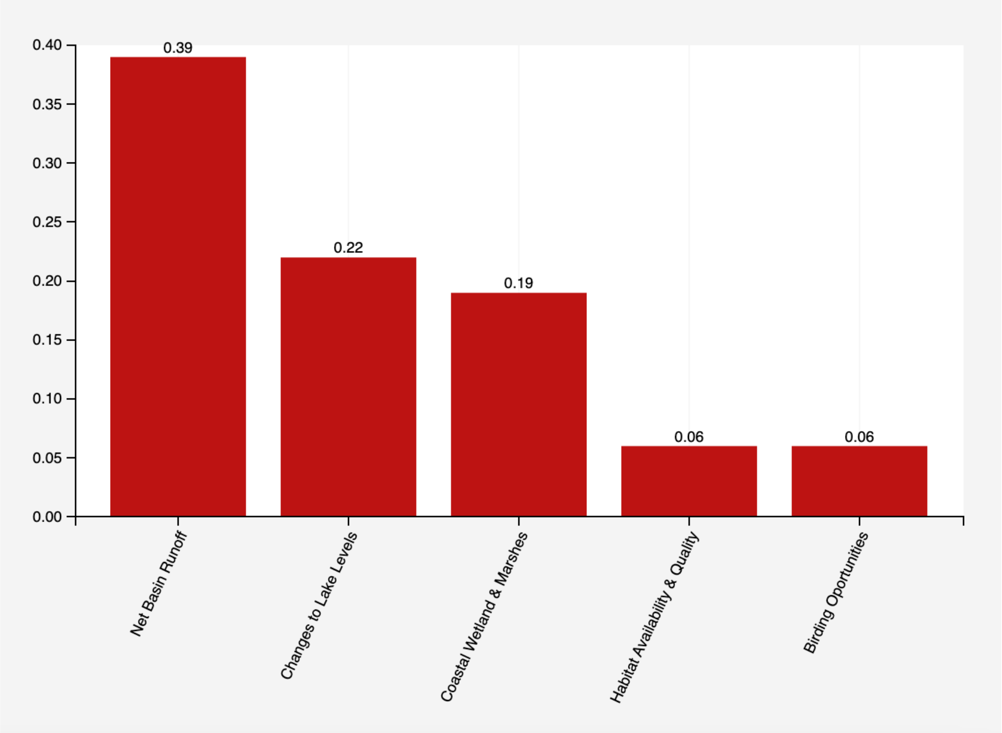


Figure A8. Briding Opportunities FCM output.

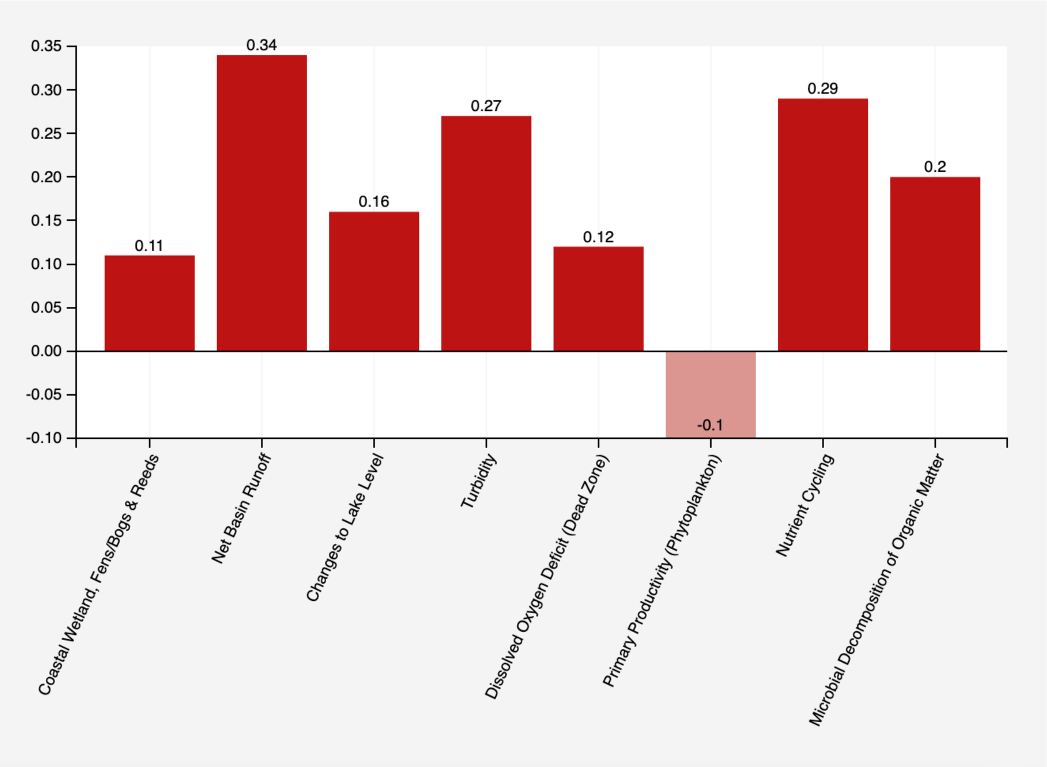


Figure A9. Nutrient Cycling FCM output.

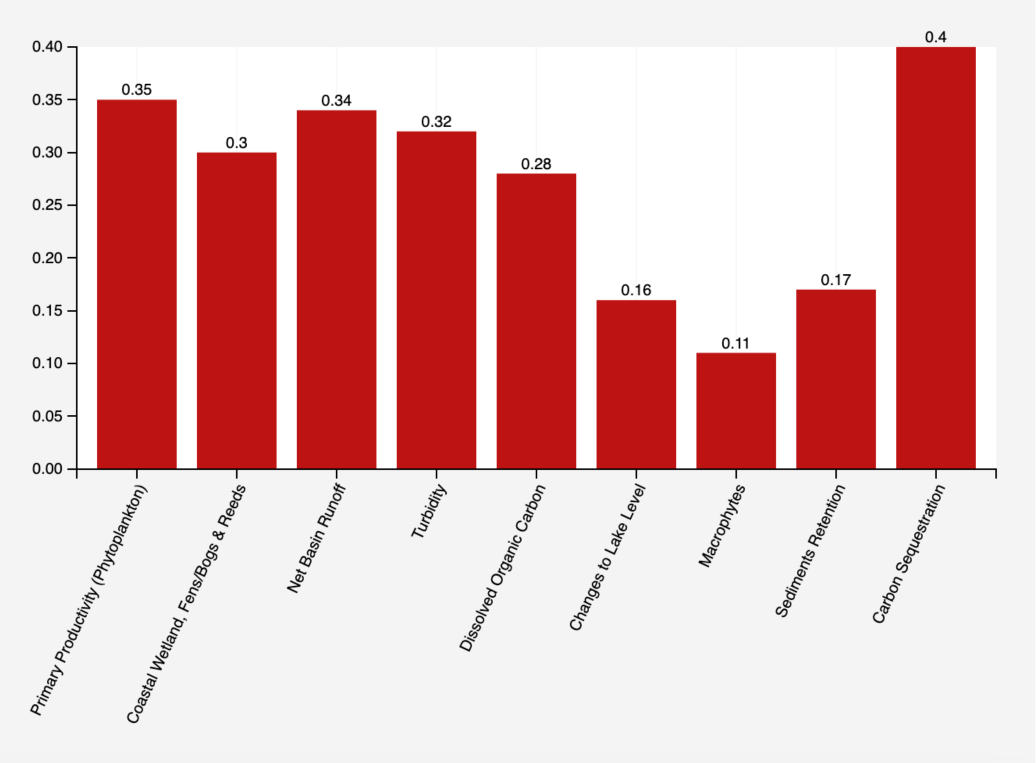


Figure A10. Carbon Sequestration FCM output.

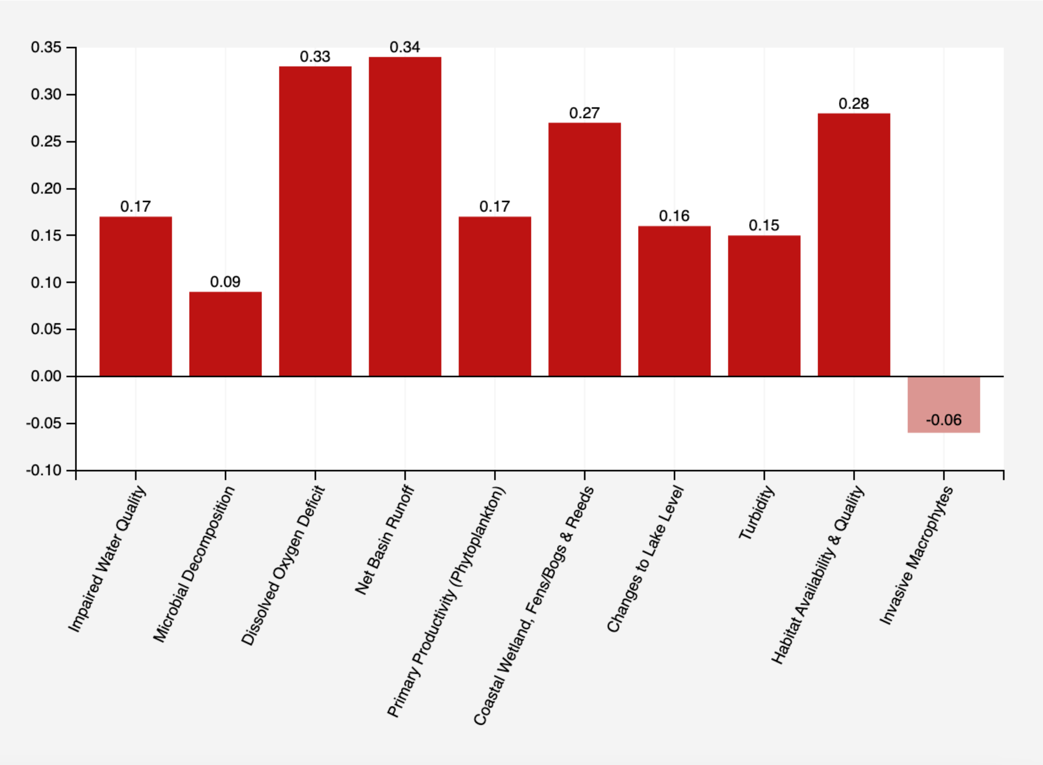
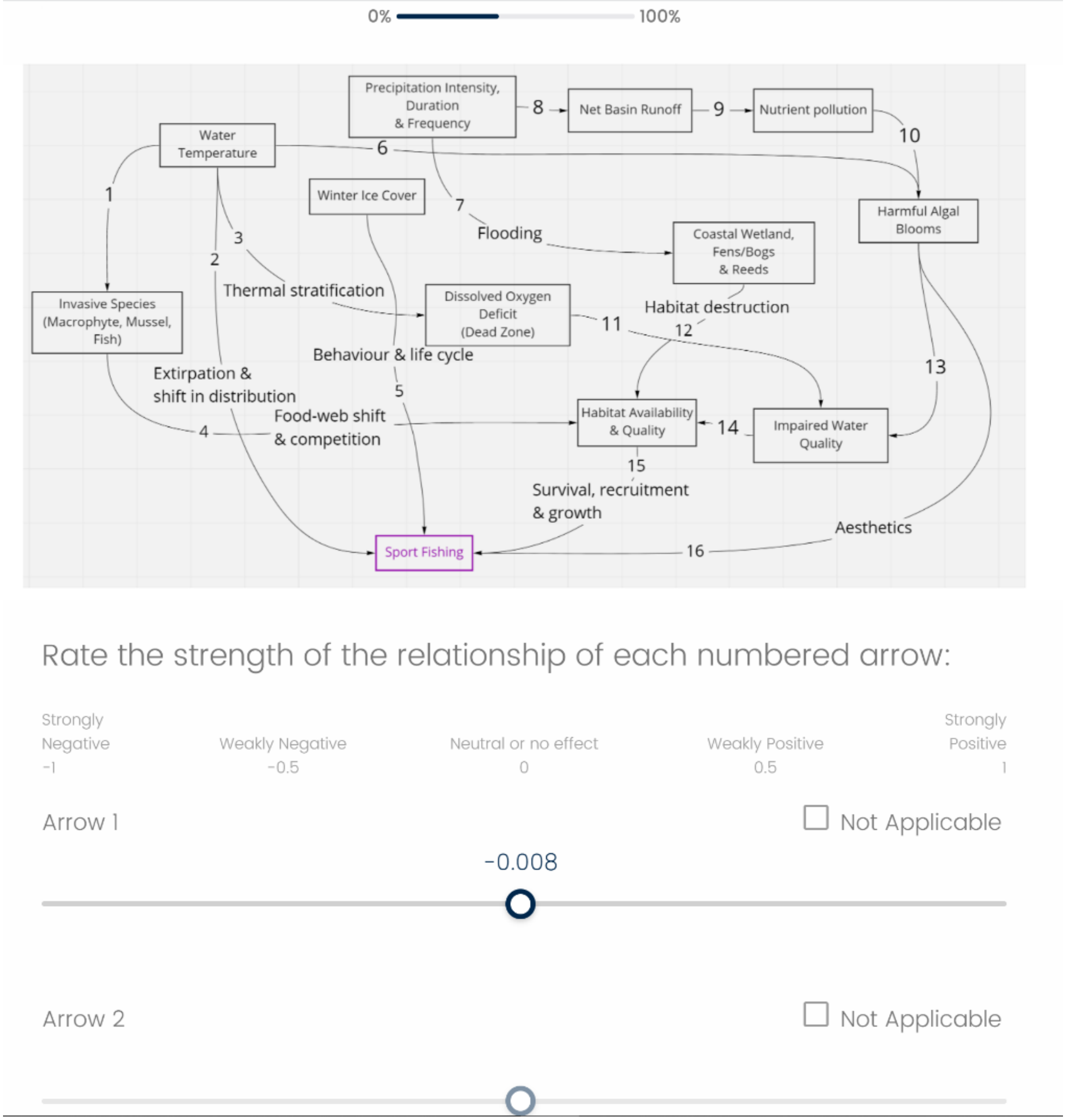


Figure A11. Habitat Availability and Quality FCM output.



Rate the strength of the relationship of each numbered arrow:

Strongly Negative	Weakly Negative	Neutral or no effect	Weakly Positive	Strongly Positive
-1	-0.5	0	0.5	1

Arrow 1 ☐ Not Applicable

-0.008

Arrow 2 ☐ Not Applicable

Figure A12. Example page from professional survey.

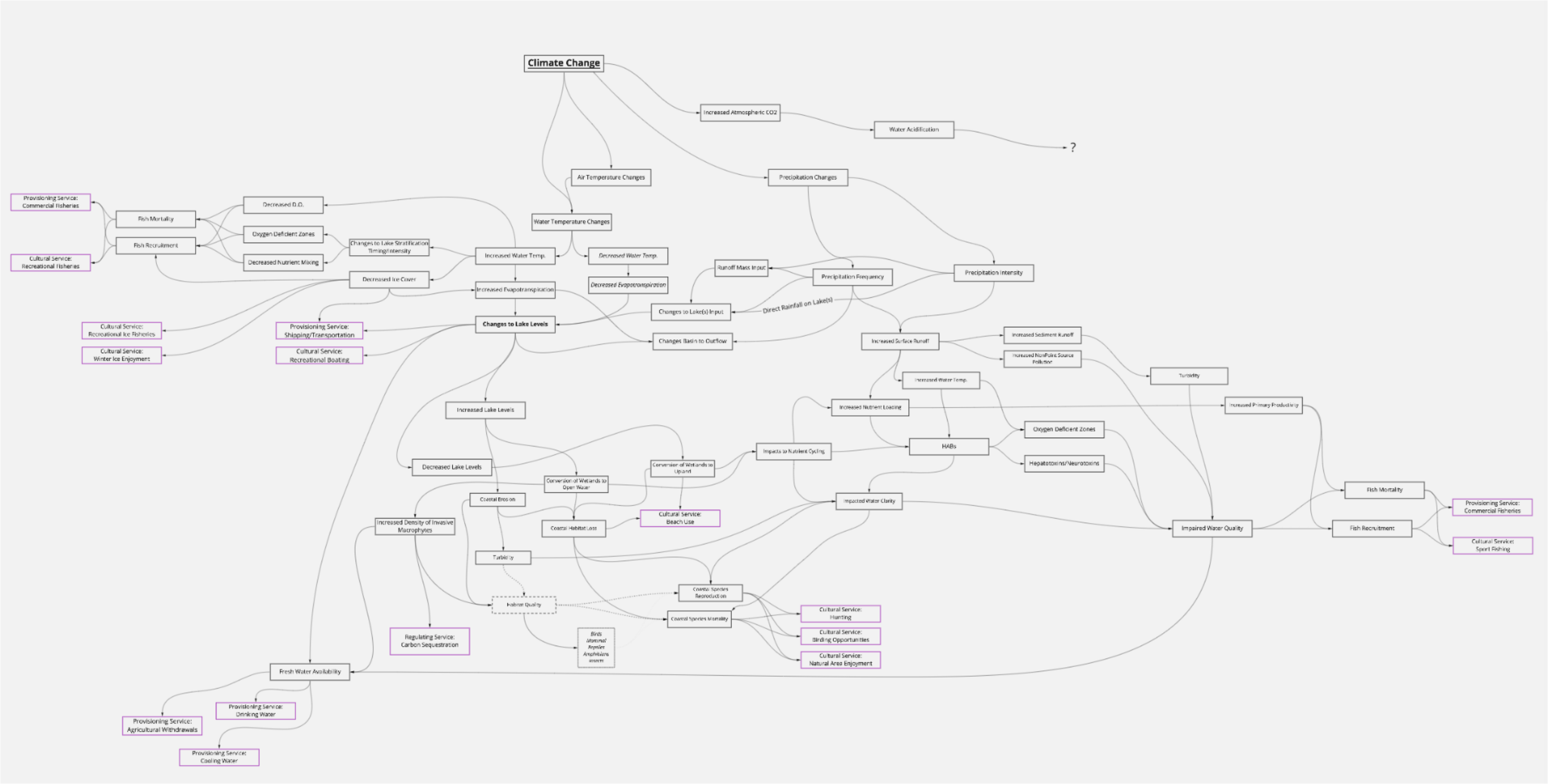


Figure A13. Complete original conceptual model.

	Article Title	Author	Publication date	Volume and Page number	Research Question/Objective	Geographic extent	Location	Ecosystem services (Tier 1)	Ecosystem services (Tier 2)	Method	Independent Variables	Dependent Variables	Key Findings (Quantified)	Climate Change	Notes	Link
1	Near-Decadal Oscillation of Water Levels and Mercury Bioaccumulation in the Laurentian Great Lakes Region	Watras et al.	2020	Volume?, p. 82-89	They investigated the potential cause(s) and trends in bioaccumulation in two pelagic piscivores (Walleye, Sander vitreus and Common Loon, Gavia immer)	Great Lakes	Upper Great Lakes, Wisconsin specifically	Regulating	Water quality	Analysis of 150-250 lakes in northern wisconsin and samples of loons and walleye from these locations. Compared to a record of water levels from 1942-2019.	Water level	Mercury concentration in walleye, common loon	Mercury levels oscillate decadely with water levels. Rising waters under climate change could obscure the benefits of reduced mercury emissions. No valuation of the service, quantification in terms of mercury concentration in fish	Retrospective analysis of climate change effects on water levels		https://pubs.acs.org/doi/full/10.1021/acs.estlett.9b00772?casa_token=JWiqZe2Ks8sAAAAA:kYmqUCVOJEdKJdL811AaDQEEkHdlfA8-pobSmO0eTrNhd6y44suXFDupAJ9SVLsq9YJjTlWmd1N1Iw
1	Near-Decadal Oscillation of Water Levels and Mercury Bioaccumulation in the Laurentian Great Lakes Region	Watras et al.	2020	Volume?, p. 82-89	They investigated the potential cause(s) and trends in bioaccumulation in two pelagic piscivores (Walleye, Sander vitreus and Common Loon, Gavia immer)	Great Lakes	Upper Great Lakes, Wisconsin specifically	Cultural	Recreational	Analysis of 150-250 lakes in northern wisconsin and samples of loons and walleye from these locations. Compared to a record of water levels from 1942-2019.	Water level	Mercury concentration in walleye, common loon	Mercury levels oscillate decadely with water levels. Rising waters under climate change could obscure the benefits of reduced mercury emissions. No valuation of the service, quantification in terms of mercury concentration in fish	Retrospective analysis of climate change effects on water levels		https://pubs.acs.org/doi/full/10.1021/acs.estlett.9b00772?casa_token=JWiqZe2Ks8sAAAAA:kYmqUCVOJEdKJdL811AaDQEEkHdlfA8-pobSmO0eTrNhd6y44suXFDupAJ9SVLsq9YJjTlWmd1N1Iw
2	Coastal Bluff Evolution in Response to a Rapid Rise in Surface Water Level	Krueger et al.	2020	125, issue 10, p. ?	They studied the effects of unprecedented rising water levels on the stability of three bluffs on the Lake Michigan shore of wisconsin	Lake Michigan	Wisconsin shore of Lake Michigan	Regulating	Erosion control	Developed models from drone photographs to depict the stability of surfaces and the movement of unstable surfaces	Water level	Instability of surfaces, rate of movement of unstable surfaces, duration of instability	Instability will travel up coastal bluffs, and the crests may continue eroding for up to a decade after water levels lower and stabilize. Quantified as rate of movement of unstable surfaces, no valuation	Current state analysis of climate change effects on water levels		https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019JF005428
3	Development of a multi-scale wetland Resilience Index from muskellunge nursery habitat in Georgian Bay, Lake Huron	Weller & Chow-Fraser	2019	103, 212-225	Record low water levels led to low recruitment of muskellunge. Some sites had none, while other sites remained active. They sought to understand the resiliency of some nursery habitat to sustained low water levels.	Lake Huron	Georgian Bay Lake Huron	Supporting	Habitat Provisioning	GIS analysis using existing wetland layers, digital elevation model, to analyze bathymetry and slope and other characteristics. Compared the hydrogeomorphic features of sites that were resilient to sustained low water levels and those that weren't, then they tried to create a resiliency index of habitat	Bathymetry, Slope	Resiliency Index	Substrate slope, depth, and site exposure are key variables that are primarily linked to aquatic vegetation structure which in turn is important for nursery habitat of muskellunge. Quantification as habitat resiliency, no valuation	Current state analysis of climate change effects on water levels	This is really supporting services through habitat provisioning, but the authors really framed it as being important for cultural services through recreational fisheries, so I will index it as both	https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S1470160X19302249?via%3Dihub#b0170
3	Development of a multi-scale wetland Resilience Index from muskellunge nursery habitat in Georgian Bay, Lake Huron	Weller & Chow-Fraser	2019	103, 212-225	Record low water levels led to low recruitment of muskellunge. Some sites had none, while other sites remained active. They sought to understand the resiliency of some nursery habitat to sustained low water levels.	Lake Huron	Georgian Bay Lake Huron	Cultural	Recreational	GIS analysis using existing wetland layers, digital elevation model, to analyze bathymetry and slope and other characteristics. Compared the hydrogeomorphic features of sites that were resilient to sustained low water levels and those that weren't, then they tried to create a resiliency index of habitat	Bathymetry, Slope	Resiliency Index	Substrate slope, depth, and site exposure are key variables that are primarily linked to aquatic vegetation structure which in turn is important for nursery habitat of muskellunge. Quantification as habitat resiliency, no valuation	Current state analysis of climate change effects on water levels	The authors framed this paper through recreational fisheries, so I dual indexed it	https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S1470160X19302249?via%3Dihub#b0170
4	Changes in aquatic vegetation and fish communities following 5 years of sustained low water levels in coastal marshes of eastern Georgian Bay, Lake Huron	Midwood & Chow-Fraser	2011	18, p. 93-105	How do changing water levels, in this case sustained low water levels in Eastern Georgian Bay, affect the diversity of the plants in wetlands? How do these changes affect fish species richness?	Lake Huron	Eastern Georgian Bay	Supporting	Habitat Provisioning	Used satellite images and water level records to analyze the changes in four vegetation types in wetlands, used fyke net samples of fish populations	Water level	Vegetative Diversity (Four categories)	Sustained low water levels have resulted in an increase in high density floating vegetation and a decrease in low density floating vegetation. Similarly, they found that low water levels resulted in a decrease in emergent and submerged aquatic vegetation and an increase in terrestrial meadow vegetation. No valuation, in units specific to aquatic vegetation	Retrospective analysis of climate change effects of water levels	The authors looked at water level effects on vegetation and then vegetation effects on fish diversity	https://onlinelibrary-wiley-com.proxy.lib.umich.edu/doi/full/10.1111/j.1365-2486.2011.02558.x
4	Changes in aquatic vegetation and fish communities following 5 years of sustained low water levels in coastal marshes of eastern Georgian Bay, Lake Huron	Midwood & Chow-Fraser	2011	18, p. 93-105	How do changing water levels, in this case sustained low water levels in Eastern Georgian Bay, affect the diversity of the plants in wetlands? How do these changes affect fish species richness?	Lake Huron	Eastern Georgian Bay	Cultural	Recreational	Used satellite images and water level records to analyze the changes in four vegetation types in wetlands, used fyke net samples of fish populations	Water level	Species richness of fish	Sustained low water levels have resulted in an increase in high density floating vegetation and a decrease in low density floating vegetation. These changes correlated with a decrease in species richness. No valuation, in units of species richness	Retrospective analysis of climate change effects of water levels	The authors looked at water level effects on vegetation and then vegetation effects on fish diversity	https://onlinelibrary-wiley-com.proxy.lib.umich.edu/doi/full/10.1111/j.1365-2486.2011.02558.x
~~5~~	~~A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes~~	~~Sierszen et al~~	~~2012~~	~~15(1):92–106~~	~~What is the value of Great Lakes coastal wetlands as related to nutrient retention, sediment retention and wildlife habitat?~~	~~Great Lakes~~	~~Entire Great Lakes but also broken out into individual lake basins.~~	~~Supporting~~	~~Nutrient Cycling~~	~~Extrapolation of retention rates from other studies applied to great lakes GLCW areas.~~	~~Wetland Extent~~	~~Nutrient Retention~~	~~Basin-wide, coastal wetlands may retain nearly 4000 tonnes P and 53,000 tonnes N per year.~~	~~Wetlands may provide the ES of climate regulation by means of carbon sequestration.~~		~~http://www.glisaclimate.org/media/Sierszen%20et%20al%20%282012%29%20A%20review%20of%~~
~~5~~	~~A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes~~	~~Sierszen et al~~	~~2012~~	~~15(1):92–107~~	~~What is the value of Great Lakes coastal wetlands as related to nutrient retention, sediment retention and wildlife habitat?~~	~~Great Lakes~~	~~Entire Great Lakes but also broken out into individual lake basins.~~	~~Provisioning~~	~~Wildlife Habitat~~	~~Review of multiple wetland studies and inventories.~~	~~Wetland Extent~~	~~Number of species that depend on wetland presence and extent~~	~~30 species of waterfowl, 155 breeding bird species, and 55 species of reptiles and amphibians are supported by coastal wetland habitats across the Basin. Nearly all sport and commercial Great Lakes fish species use coastal wetlands for life-cycle functions, and Great Lakes food webs are supported by wetland export of young sport and forage fish.~~		~~Biological responses indicate declines in the wildlife and fishery services with increasing levels of anthropogenic disturbance.~~	~~http://www.glisaclimate.org/media/Sierszen%20et%20al%20%282012%29%20A%20review%20of%20selected%20ecosystem%20services%20provided%20by%20coastal%20wetlands%20of%20the%20Laurentian%20Great%20Lakes.pdf~~
6	Carbon Fixation Trends in Eleven of the World's Largest Lakes: 2003–2018	Sayers, Michael; Bosse, Karl; Fahnenstiel, Gary; Shuchman, Robert.	2020	12(12)	Can the primary production and carbon sequestration of large lakes around the world be quantified using remotely sensed data?	Other	Global, includes each of the Great Lakes individually	Regulating	Carbon Sequestration	Remote sensing of chl a production, water temp, other variables that play a role in the estimation of primary production	Chl a, water temp, light extinction coefficients	Primary production, carbon fixation	Primary production ranged from around 236 mg of C per square meter per day in Lake Huron to around 1175 in Lake Erie. This resulted in a range of carbon sequestration from 2.1 Tg of Carbon per year to 11 tg of carbon per year. No valuation, in units of TgC/year for carbon sequestration	Retrospective, climate change effects on water temperature from 2003 to 2018		https://www-proquest-com.proxy.lib.umich.edu/docview/2470563676?pq-origsite=%requestingapplication%
7	A PGIS-based climate change risk assessment process for outdoor recreation and tourism dependent communities	Bitsura-Meszaros, Karly; Seekamp, Erin; Davenport, Mae; Smith, Jordan W	2019	11(12)	What aspects of the natural and built environments do stakeholders believe are most susceptible to the effects of climate change?	Lake Superior	North shore of Lake Superior (Minnesota section)	Cultural	Recreational	Participatory GIS in three stages, pre-survey, focus group, post survey	Location	Vulnerability to climate change	Stakeholders are most concerned about the effects of climate change in relation to ski resorts and wildfires. In pre-surveys, stakeholders were concerned about the impacts of fluctuating water levels on marinas and safe harbors. Although participants were concerned about the impacts of water levels on harbors, the perceived severity of these was rated as low. Participants believed wildfires and low snowfalls/ice cover to be the most severe impacts. No valuation.	Future vulnerability through various impacts including water levels, temperatures, ice cover		https://www-proquest-com.proxy.lib.umich.edu/docview/2322229199/fulltext/F6F708C214D844DCPQ/1?accountid=14667
8	Mapping Floating and Emergent Aquatic Vegetation in Coastal Wetlands of Eastern Georgian Bay Lake Huron	Midwood, J and Chow-Fraser, P	2010	30: 1141-1152	Can an object-based analysis method be used to accurately classify wetlands in the Great Lakes from remote sensing imagery? What percentage of wetlands in Georgian Bay are potential fish habitat?	Lake Huron	Eastern Georgian Bay	Supporting	Habitat Provisioning	Object based analysis, process tree classification of wetlands into 3 (or 4 including dry meadows) categories	Color, shape of object	Type of habitat	IKONOS imagery and object-based analysis can be used to classify wetlands with a greater than 85% accuracy rate using process tree classification. They found that an average wetland in the south-eastern half of Georgian Bay contained 1.6 ha of visible fish habitat and 6.3 ha of potential fish habitat. This amounts to 230.4 ha of VFH and 907.2 ha of PFH in the south-eastern half of Georgian Bay total under 2002 water levels. No valuation, in units of ha of VFH and PFH.	Current state (2002) analysis of the effects of climate change on water levels		https://link-springer-com.proxy.lib.umich.edu/content/pdf/10.1007/s13157-010-0105-z.pdf
9	Coastal Wetland Support of Great Lakes Fisheries: Progress from Concept to Quantification	Trebitz et al	2015	144:352–372	What is the biomass of fishes and subsequent fishery valuation that depends of coastal wetlands?	Great Lakes	Entire Great Lakes	Provisioning	Fisheries Production	Analyses of patterns for fishery-relevant, wetland-using fish species relies primarily on data from 58 GLCWs surveyed via electrofishing over the summers of 2002–2004	Location/Exte	richness and diversity	Wetlandusing species are estimated to make up half the biomass and 60% of the dollar value of the fish landed commercially and 80% of the fish numbers harvested recreationally.	Climate change not mentioned but anthropogenic stressors do play a significant role.	A few key habitat characteristics (e.g., vegetation structure) are broadly predictive of the types of sport and panfish present, with more degraded GLCWs generally supporting abundant but lower-value taxa (rough-fish species) and less degraded GLCWs supporting fewer but higher-value taxa (sport and panfish species).	https://derekogle.com/NCNRS349/modules/aaaSpeakers/Trebitz_Hoffman_TAFS2015.pdf
10	Area and Habitat Relationships of Birds in Great Lakes Coastal Wet Meadows	Riffell et al	2001	4: 492–507	What are the relationships of birds to patch area and habitat characteristics specially related to Great Lakes coastal wetlands?	Lake Huron	Northern Lake Huron Coastal Wetlands	Supporting	Bird Habitat	Observational transects completed in a varying characteristic wetlands.	Extent/characteristics	richness and diversity	Nine species were positively associated with increasing wet meadow area, which underscores the importance of large wetlands to avian conservation in the region. Habitat quality also had a positive correlation to species diveristy and richness.			
11	Projecting the effects of agricultural conservation practices on stream fish communities in a changing climate	Fraker, M.E., Keitzer, S.C., Sinclair, J.S., Aloysius, N.R., Dippold, D.A., Yen, H., Arnold, J.G., Daggupati, P., Johnson, M.-V.V., Martin, J.F., Robertson, D.M., Sowa, S.P., White, M.J., Ludsin, S.A.	2020	747	How will climate change affect the composition of stream fish communities? How will various ACP scenarios impact the effect of climate change?	Lake Erie	Western Lake Erie Basin (Streams)	Supporting	Habitat Provisioning	APEX, SWAT and Stream fish distribution (boosted tree regression? *Ask Mike!*)	Climate change scenario (emissions pathway), temperature, agricultural conservation programs	Suitable habitat for stream fish	For most species climate change outweights the effects of ACPs. More extreme climate change will reduce habitat for large fish, cool water fish (recreational fisheries). Small benthic fish with opportunistic life histories are likely to benefit from a warming climate. Somewhat counterintuitively, ACPs could actually worsen this shift and speed it up. Effects of climate change on recreationally important species may be obscured by the increase in habitat for warm water periodic or opportunistic species. No valuation, measured in terms of km's of suitable habitat	RCP4.5 and RCP8.5		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0048969720346416?via%3Dihub

Literature Review: Great Lakes ES Tracking

	Article Title	Author	Publication date	Volume and Page number	Research Question/Objective	Geographic extent	Location	Ecosystem services (Tier 1)	Ecosystem services (Tier 2)	Method	Independent Variables	Dependent Variables	Key Findings (Quantified)	Climate Change	Notes	Link
11	Projecting the effects of agricultural conservation practices on stream fish communities in a changing climate	Fraker, M.E., Keitzer, S.C., Sinclair, J.S., Aloysius, N.R., Dippold, D.A., Yen, H., Arnold, J.G., Daggupati, P., Johnson, M.-V.V., Martin, J.F., Robertson, D.M., Sowa, S.P., White, M.J., Ludsin, S.A.	2020	747	How will climate change affect the composition of stream fish communities? How will various ACP scenarios impact the effect of climate change?	Lake Erie	Western Lake Erie Basin (Streams)	Cultural	Recreational	APEX, SWAT and Stream fish distribution (boosted tree regression? *Ask Mike!*)	Climate chan	Suitable habitat for st	For most species climate change outweights the effects of ACPs. More extreme climate change will reduce habitat for large fish, cool water fish (recreational fisheries). Small benthic fish with opportunistic life histories are likely to benefit from a warming climate. Somewhat counterintuitively, ACPs could actually worsen this shift and speed it up. Effects of climate change on recreationally important species may be obscured by the increase in habitat for warm water periodic or opportunistic species. No valuation, measured in terms of km's of suitable habitat, change in suitable habitat for recreationally important species.	RCP4.5 and RCP8.5		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0048969720346416?via%3Dihub
12	Great Lakes coastal fish habitat classification and assessment	Kovalenko, K. E., Johnson, L. B., Riseng, C. M., Cooper, M. J., Johnson, K., Mason, L. A., McKenna, J., Sparks-Jackson, B.L., Uzarski, D. G.	2018	44(5): 1100-1109	What factors dictate presence/absence of fish in the Great Lakes? How does fish habitat relate to areas of anthropogenic stress?	Great Lakes	Split into two ecoregions, north and south	Supporting	Habitat Provisioning	Used existing fish presence data from Great Lakes Environmental Indicators project and basin-wide indicators like temperature, turbidity, to create a presence/absence model for fish and compared this to maps of existing anthropogenic stressors.	Temp, warm season days, turbidity	Presence/absence	In the northern Great Lakes, temperature is the feature that determines habitat suitability for fish, in the southern Great Lakes chlorophyll a concentration, turbidity, and wave height were the factors that predicted presence or absence. Invasive species density correlated with chlorophyll a and inorganic turbidity. Areas of high diversity and areas with preferred habitat overlapped with anthropogenic stressors. No valuation, predicts presence absence throughout the Great Lakes under certain conditions. Also maps where important areas are compared to stressor indices.	Anthropogenic stressors but no climate change		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0380133018301308?via%3Dihub
12	Great Lakes coastal fish habitat classification and assessment	Kovalenko, K. E., Johnson, L. B., Riseng, C. M., Cooper, M. J., Johnson, K., Mason, L. A., McKenna, J., Sparks-Jackson, B.L., Uzarski, D. G.	2018	44(5): 1100-1109	What factors dictate presence/absence of fish in the Great Lakes? How does fish habitat relate to areas of anthropogenic stress?	Great Lakes	Split into two ecoregions, north and south	Cultural	Recreational	Used existing fish presence data from Great Lakes Environmental Indicators project and basin-wide indicators like temperature, turbidity, to create a presence/absence model for fish and compared this to maps of existing anthropogenic stressors.	Temp, warm season days, turbidity	Presence/absence	In the northern Great Lakes, temperature is the feature that determines habitat suitability for fish, in the southern Great Lakes chlorophyll a concentration, turbidity, and wave height were the factors that predicted presence or absence. Invasive species density correlated with chlorophyll a and inorganic turbidity. Areas of high diversity and areas with preferred habitat overlapped with anthropogenic stressors. No valuation, predicts presence absence throughout the Great Lakes under certain conditions. Also maps where important areas are compared to stressor indices.	Anthropogenic stressors but no climate change		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0380133018301308?via%3Dihub
13	Protecting local water quality has global benefits	Downing, J.A., Polasky, S., Olmstead, S.M., Newbold, S.	2021	12, 2709	What is the present value of the global cost of methane emissions driven by eutrophication in lakes?	Other	Global, but Lake Erie as a case study	Regulating	Climate change moderation	Integrated assessment models and used the social cost of methane (and social cost in CO2e) developed by the US interagency working group.	Methane aversion pathways, discount rates, emissions growth	Social cost of methane emissions from lakes	A 40% reduction in P loading to Lake Erie would generate about $3.1 billion in averted costs using the social cost of methane and a 3% discount rate, this is an order of magnitude larger than the estimated benefits for anglers or beach closures. Globally, estimated costs range from $7.5 trillion to $81 trillion between 2015 and 2050. Averting new emissions from lakes or allowing only small amounts of growth would save between $0.66–24 trillion.	Contribution to climate change rather than an effect of climate change, although warming temps would contribute to eutrophication		https://www.nature.com/articles/s41467-021-22836-3#Sec6
14	Valuing Lake Erie Beaches Using Value and Function Transfers	Palm-Forster, L., Lupi, F., and Chen, M.	2016	45(2): 270-292	What is the value of beaches in the Western Lake Erie basin? How much would be lost from beach closures due to HABs? What the shortcomings of each valuation method used?	Lake Erie	Western Lake Erie Basin	Cultural	Recreational	Two benefit transfer methods were used, value-transfer and function transfer to estimate beach demand as trips and to estimate elasticity as change in trips.	Days closed, population nearby, alternatives available, temperature, travel cost, etc	Trips taken to the beach, value of each trip in dollars (WTP), value of the beach total, lost value from closures	Function transfer results in a WTP of $15.91 for a single day trip to the beach, value transfer results in a WTP of $18.08. Entire season single beach closures result in a loss of $2.21 million (value transfer) or $1.96 million (function transfer). A regional closure of all 67 western/central basin Lake Erie beaches would result in a loss of between $1.16 million (value transfer) and $2.394 (function transfer) million per day. A closure of half the Lake Erie beaches studied would result in a welfare loss of between $574,000 and $744,000 per day. A closure of just 6 would result in a loss of $233,000 and $259,000 per day.	Increased eutrophication from climate change and agricultural runoff	In the first part (single beach) value transfer yielded higher estimates of welfare loss, in regional closures, function transfer yielded higher estimates of welfare loss.	https://www.cambridge.org/core/services/aop-cambridge-core/content/view/7118CA96FF77278C3EFE464055E8F720/S2372261416000151a.pdf/div-class-title-valuing-lake-erie-beaches-using-value-and-function-transfers-div.pdf
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688	What is the spatial distribution, variability and delivery of ES for the Lake Erie Basin and their co-occurance?	Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>2 km2)	Provisioning	Commercial fisharies	Spatail statistics	Port landing (	Average annual herv	Port landings are greatest in Ohio waters of the WB and across all three basins in Ontario waters		Timeframe 2000-2010	http://dx.doi.org/10.1016/j.jglr.2017.06.001
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688		Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>25, 000)	Provisioning	Water use	Spatail statistics	Public water	Gallons of water per	Detroit, MI; Toledo and Cleveland, OH; Erie, PA; and Buffalo, NY are greatest users of Lake Erie and SCDRS water for public water supply, Detroit Edison's Monroe Plant is the single largest user of surface water for thermoelectric cooling followed by Detroit Edison St. Clair and Belle River plants and Brighton Beach		Timeframe 2013 / 2014	
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688		Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>25, 000)	Supporting	Habitat (Bird)	Spatail mapping, feature to point	Point data fro	Coastal biodiversity s	Area within St. Clair River, Lake St. Clair and the Detroit River and along the southern shoreline of the Western basin up to Point Pelee are important bird areas			
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688		Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>25, 000)	Supporting	Biodiversity (Terrestrial and Coastal)	Rescaling of biodiversity significance scores based on minimum and maximum, and aggregated for each unit	Lake Erie Co	Coastal wetland biod	Northwest portion of Lake St. Clair in Michigan, along much of the U.S shoreline, and at Rondeau Point had highest scores for coastal wetland biodiversity, Vicinity of Lower Portage River and Cedar Creek, number of Ontario sites including the Canard River, Rondeau Point, the area just west of Long Point recorded highest values for coastal terrestrial biodiversity		Timeframe 2010 / 2012	
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688		Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>25, 000)	Cultural	Spot fishing	Summarized data on number and locations of private as well as charter boat by individual reporting districts	Recreational	Private and charter re	Anglers fishing from private boats in both U.S.and Canada across the five lakes and connecting waters totaled 15.3 million angler hours, of which Lake Erie and the St. Clair River, Lake St. Clair and the Detroit River contributes about half of that total		Timeframe 2010	
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688		Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>25, 000)	Cultural	Boating	Regression estimates of the number of parking spaces using parking lot area, parking spaces was used as a proxy for boat launch locations	Marina locati	Number of boat slips	Lake Erie has 236 marinas with 39,975 boat slips, and 198 boat launches, containing over 9,133 parking spaces, more than any other Great Lakes, boating activity is concentrated in particular along the Detroit River, Lake St. Clair and shoreline of the WB			
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688		Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>25, 000)	Cultural	Beaches	Spatial statistics, summerization and clustering	Beach locatio	Visits per day, beach	Beach visitation is highest for urban centric beaches of Lake St. Clair, at multiple locations along the Ohio shoreline, Presque Isle, PA, and around Long Point, ON,		Timeframe 2007-2009	
15	Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services	Allan, J. D., Manning, N. F., Smith, S. D., Dickinson, C. E., Joseph, C. A., & Pearsall, D. R.	2017	43: 678-688		Lake Erie	Shorelines (4 subunits based on depth), shoreline counties (2-5 km buffer), urban or natural area (>25, 000)	Cultural	Recreational (Birding, park visitations)	Spatial statistics	Number of vis	Average annual visita	Parks situated along the southern shoreline of Lake Erie and within easy reach by urban populations, Belle Isle in Detroit, and the Lakefront and Euclid Reservations (formerly Cleveland Lakefront State Park) in Cleveland, represent the majority of annual visitation.		Timeframe 2005-2010 (US), 2008-2011 (CA)	
16	Ship-borne Nonindigenous Species Diminish Great Lakes Ecosystem Services	Rothlisberger et al	2012	15: 462–476	What is the economic impact of invasive species in the great lakes?	Great Lakes	Entire Great Lakes	Provisioning	Fisheries Production	Expert judgment and economic analysis	Invasive species presence	Impact of fisheries valuation	For the US waters, median damages aggregated across multiple ecosystem services were $138 million per year, and there is a 5% chance that for sportfishing alone losses exceeded $800 million annually.	Not considered	Highly based on expert opinion. US waters only.	https://link.springer.com/content/pdf/10.1007/s10021-012-9522-6.pdf
17	Using cultural ecosystem services to inform restoration priorities in the Laurentian Great Lakes	Allan et al	2015	13(8): 418–424	How can evaluationg cultural ES be used to prioritize restoration efforts?	Great Lakes	Entire Great Lakes	Cultural	Sport fishing, recreational boating, birding, beach use, and park visitation	Used agency reports, citizen science, and social media as data sources to quantify the spatial distribution of five recreational elements of cultural ES			Produced multiple maps showing the distribution and intensity of cultural ecosystem services throughout the GL.	not considered	Citizen science and PGIS used.	https://repository.library.noaa.gov/view/noaa/13712/noaa_13712_DS1.pdf
18	A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes	Sierszen, M. E., Morrice, J. A., Trebitz, A. S., & Hoffman, J. C.	2012	15: 92-106	How are coastal wetlands functions measured and quanitifed? What effect does anthropogenic stressors have on the measures?	Great Lakes		Provisioning	Fisharies	Presence/absence			Chequamegon Bay of Lake Superior is used by 50 species of fish; 37 for spawning, 12 for migration, and 49 as a nursery area		Invasive species continue to alter the ecology of the Great Lakes and cause significant economic damage to commercial and recreational fisheries	http://dx.doi.org/10.1080/14634988.2011.624970
18	A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes	Sierszen, M. E., Morrice, J. A., Trebitz, A. S., & Hoffman, J. C.	2012	15: 92-107	How are coastal wetlands functions measured and quanitifed? What effect does anthropogenic stressors have on the measures?	Great Lakes		Provisioning	Food (Wild rice)	Presence/absence					Threats to Wild Rice include reductions in water clarity associated with eutrophication or sediment loading, invasive plant species, and water level controls that reduce the water-level variability to which it is adapted	
18	A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes	Sierszen, M. E., Morrice, J. A., Trebitz, A. S., & Hoffman, J. C.	2012	15: 92-108	How are coastal wetlands functions measured and quanitifed? What effect does anthropogenic stressors have on the measures?	Great Lakes		Regulating	Carbon sequestration						No estimates providing carbon sequestration for GLCWs.	
18	A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes	Sierszen, M. E., Morrice, J. A., Trebitz, A. S., & Hoffman, J. C.	2012	15: 92-109	How are coastal wetlands functions measured and quanitifed? What effect does anthropogenic stressors have on the measures?	Great Lakes		Regulating	Coastal protection	Wetland extent			A stand of wetland plants 20 m wide attenuates waves by 40%		Lacustrine wetlands are naturally rare in Lake Superior and much reduced in the lower	
18	A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes	Sierszen, M. E., Morrice, J. A., Trebitz, A. S., & Hoffman, J. C.	2012	15: 92-111	How are coastal wetlands functions measured and quanitifed? What effect does anthropogenic stressors have on the measures?	Great Lakes		Supporting	Habitat (birds, amphibians, mammals)	Presence/absence			GLCWs supported an estimated total of 26,450 breeding pairs of Dabbling Ducks, the most common ducks using coastal wetlands. Organohalide contaminants are the most well documented anthropogenic stressors on bird populations in the Great Lakes.			

	Article Title	Author	Publication date	Volume and Page number	Research Question/Objective	Geographic extent	Location	Ecosystem services (Tier 1)	Ecosystem services (Tier 2)	Method	Independent Variables	Dependent Variables	Key Findings (Quantified)	Climate Change	Notes	Link
18	A review of selected ecosystem services provided by coastal wetlands of the Laurentian Great Lakes	Sierszen, M. E., Morrice, J. A., Trebitz, A. S., & Hoffman, J. C.	2012	15: 92-112	How are coastal wetlands functions measured and quanitifed? What effect does anthropogenic stressors have on the measures?	Great Lakes		Supporting	Water quality	Nutrient retention			Areal rates of total phosphotus retention through sedimentation and burial of particulate forms ranged from 191 tonn per yr (Lake Ontario) to 1,802 tonn per yr (Lake Michigan) whereas that for dissolved inorganic nitrogen ranged from 2,365 tonn N per yr to 22,327 tonn N per yr. Simialry, sediment retention efficiencies varied widle, estimates suggests that Old Woman Creek wetland retained 47% of incoming sediment between 1987 and 1997, with a sedimentation rate ranging from 0.4–1.0 cm yr−1	Flood or condition of high flow may resulting in the transport of several years of accumulated P to nearshore waters. Climatic and geologic characteristics may influence rates of nutrient and sediment retention		
19	Evaluating sediments as an ecosystem service in western Lake Erie viaquantification of nutrient cycling pathways and selected geneabundances	Boedecker et al	2020	46: 920-932	How can sediments be an ES by cycling nutrient in Lake Erie	Lake Erie	Western Lake Erie	Provisioning	Nutrient cycling	Water and soil core sampling,	Loading valu	Nutrient reduction	Sediment is a valuable method of nutrient reduction but its ability to reduce dissolved nutrient is inhibited by high HAB years and high levels of nutrient runoff.	Mentions that further study needs to take place including climate change as a factor, not considered in this study.		https://reader.elsevier.com/reader/sd/pii/S0380133020300885?token=D6136273FA0B98BBA12AE63CA3589F9A276F2D8401E161396A828F87D6A7968C76A06EEFD5DEF4AE6D7FAF7578BD0FA1&originRegion=us-east-1&originCreation=20210525162347
20	Forecasting the combined effects of anticipated climate change and agricultural conservation practices on fish recruitment dynamics in Lake Erie	David A. Dippold, Noel R. Aloysius, Steven Conor Keitzer, Haw Yen, Jeffrey G. Arnold, Prasad Daggupati, Michael E. Fraker, Jay F. Martin, Dale M. Robertson, Scott P. Sowa, Mari-Vaughn V. Johnson, Mike J. White, Stuart A. Ludsin	2020	65:1487–1508	How will changing climate and planned agricultural conservatio	Lake Erie	Western Lake Erie	Provisioning	Food (Commercial fisheries)	Precollected fish survey data, built a model of fish recruitment based on abiotic factors like winter severity, spring warming rate, Maumee TP loading	Climate change scenario (affects winter severity, spring warming rate), ACP (affects Maumee TP)	Age-0 abundance of each species	Walleye recruitment model only included winter severity, and all models resulted in reduced recruitment by the end of the forecast (2040s-2060s). In early years, recruitment was forecasted to be higher because of more variable winter temperatures. Yellow perch recruitment was diminished under all scenarios except for under RCP 8.5 with only critical farm acres treated under the ACPs. White perch recruitment is expected to go up or remain about the same under all ACPs and climate change scenarios.	RCP 4.5 and 8.5		https://onlinelibrary.wiley.com/doi/pdf/10.1111/fwb.13515
20	Forecasting the combined effects of anticipated climate change and agricultural conservation practices on fish recruitment dynamics in Lake Erie	David A. Dippold, Noel R. Aloysius, Steven Conor Keitzer, Haw Yen, Jeffrey G. Arnold, Prasad Daggupati, Michael E. Fraker, Jay F. Martin, Dale M. Robertson, Scott P. Sowa, Mari-Vaughn V. Johnson, Mike J. White, Stuart A. Ludsin	2020	65:1487–1508	How will changing climate and planned agricultural conservatio	Lake Erie	Western Lake Erie	Cultural	Recreation (Recreational Fisheries)	Precollected fish survey data, built a model of fish recruitment based on abiotic factors like winter severity, spring warming rate, Maumee TP loading	Climate change scenario (affects winter severity, spring warming rate), ACP (affects Maumee TP)	Age-0 abundance of each species	Walleye recruitment model only included winter severity, and all models resulted in reduced recruitment by the end of the forecast (2040s-2060s). In early years, recruitment was forecasted to be higher because of more variable winter temperatures. Yellow perch recruitment was diminished under all scenarios except for under RCP 8.5 with only critical farm acres treated under the ACPs. White perch recruitment is expected to go up or remain about the same under all ACPs and climate change scenarios.	RCP 4.5 and 8.5		https://onlinelibrary.wiley.com/doi/pdf/10.1111/fwb.13515
21	Ecosystem services of Earth's largest freshwater lakes	Robert W. Sternera, Bonnie Keeler, Stephen Polasky, Rajendra Poudela, Kirsten Rhudea, Maggie Rogers	2020	41	Comparing ecosystem services shared among large lakes	Other	Large Freshwater Lakes Worldwide	Provisioning	Fisheries Production	Reported commercial fisheries data and estimated recreational fishery data based on agency reports						https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S2212041619300658?via%3Dihub#s0105
21	Ecosystem services of Earth's largest freshwater lakes	Robert W. Sternera, Bonnie Keeler, Stephen Polasky, Rajendra Poudela, Kirsten Rhudea, Maggie Rogers	2020	41	Comparing ecosystem services shared among large lakes	Other	Large Freshwater Lakes Worldwide	Provisioning	Transportation	Tons of material unloaded						https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S2212041619300658?via%3Dihub#s0105
21	Ecosystem services of Earth's largest freshwater lakes	Robert W. Sternera, Bonnie Keeler, Stephen Polasky, Rajendra Poudela, Kirsten Rhudea, Maggie Rogers	2020	41	Comparing ecosystem services shared among large lakes	Other	Large Freshwater Lakes Worldwide	Provisioning	Water supply	Great Lakes Commission data on water withdrawls/usage						https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S2212041619300658?via%3Dihub#s0105
21	Ecosystem services of Earth's largest freshwater lakes	Robert W. Sternera, Bonnie Keeler, Stephen Polasky, Rajendra Poudela, Kirsten Rhudea, Maggie Rogers	2020	41	Comparing ecosystem services shared among large lakes	Other	Large Freshwater Lakes Worldwide	Cultural	Recreation/tourism	Flickr uploads per location	Photos taken	Recreational value				https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S2212041619300658?via%3Dihub#s0105
22	Mapping ecosystem service indicators in a Great Lakes estuarine Area of Concern	Angradi, T.R., Launspach, J.J., Bolgrien, D.W., Bellinger, B.J., Starry, M.A., Hoffman, J.C., Trebitz, A.S., Sierszen, M.E. and Hollenhorst, T.P.,	2016	42(3), 717-727	What is the spatial extent and distribution of ecosystem services in the St. Louis Estuary of Lake Superior?	Lake Superior	St. Louis Estuary	Cultural	Recreation (power boating, sailing, beach use, fishing)	Using biophysical data to map the service providing area of each service	Various biophysical indicators, also mapped effects of proposed restoration plans on the service providing areas	Service providing area (units of area) was the general mapped variable	The most widespread service was landscape views. Services tied to specific delivery areas (like shore-caught fish) comprised the smallest areas. Most areas have 3-7 services delivered of the 18 mapped (likely have more total, but only mapped 18). Spatial correlation was low, but esocid fish and wave attenuation areas cooccurred, as did power cruising, power boating, and sailing areas. Table five summarizes the total service providing area for each service.	No aspects of climate change, did look at planned habitat restoration projects for an AoC	Table 5 summarizes the extent of each service in the St. Louis Estuary	https://www.researchgate.net/profile/Brent-Bellinger/publication/301757266_Mapping_ecosystem_service_indicators_in_a_Great_Lakes_estuarine_Area_of_Concern/links/573256d508ae298602da3693/Mapping-
22	Mapping ecosystem service indicators in a Great Lakes estuarine Area of Concern	Angradi, T.R., Launspach, J.J., Bolgrien, D.W., Bellinger, B.J., Starry, M.A., Hoffman, J.C., Trebitz, A.S., Sierszen, M.E. and Hollenhorst, T.P.,	2016	42(3), 717-727	What is the spatial extent and distribution of ecosystem services in the St. Louis Estuary of Lake Superior?	Lake Superior	St. Louis Estuary	Regulating	Erosion control (wave energy attentuation)	Using biophysical data to map the service providing area of each service	Various biophysical indicators, also mapped effects of proposed restoration plans on the service providing areas	Service providing area (units of area) was the general mapped variable	The most widespread service was landscape views. Services tied to specific delivery areas (like shore-caught fish) comprised the smallest areas. Most areas have 3-7 services delivered of the 18 mapped (likely have more total, but only mapped 18). Spatial correlation was low, but esocid fish and wave attenuation areas cooccurred, as did power cruising, power boating, and sailing areas. Table five summarizes the total service providing area for each service.	No aspects of climate change, did look at planned habitat restoration projects for an AoC	Table 5 summarizes the extent of each service in the St. Louis Estuary	https://www.researchgate.net/profile/Brent-Bellinger/publication/301757266_Mapping_ecosystem_service_indicators_in_a_Great_Lakes_estuarine_Area_of_Concern/links/573256d508ae298602da3693/Mapping-ecosystem-service-indicators-in-a-Great-Lakes-estuarine-Area-of-Concern.pdf

	Article Title	Author	Publication date	Volume and Page number	Research Question/Objective	Geographic extent	Location	Ecosystem services (Tier 1)	Ecosystem services (Tier 2)	Method	Independent Variables	Dependent Variables	Key Findings (Quantified)	Climate Change	Notes	Link
22	Mapping ecosystem service indicators in a Great Lakes estuarine Area of Concern	Angradi, T.R., Launspach, J.J., Bolgrien, D.W., Bellinger, B.J., Starry, M.A., Hoffman, J.C., Trebitz, A.S., Sierszen, M.E. and Hollenhorst, T.P.,	2016	42(3), 717-727	What is the spatial extent and distribution of ecosystem services in the St. Louis Estuary of Lake Superior?	Lake Superior	St. Louis Estuary	Cultural	Aesthetics (water views)	Using biophysical data to map the service providing area of each service	Various biophysical indicators, also mapped effects of proposed restoration plans on the service providing areas	Service providing area (units of area) was the general mapped variable	The most widespread service was landscape views. Services tied to specific delivery areas (like shore-caught fish) comprised the smallest areas. Most areas have 3-7 services delivered of the 18 mapped (likely have more total, but only mapped 18). Spatial correlation was low, but esocid fish and wave attenuation areas cooccurred, as did power cruising, power boating, and sailing areas. Table five summarizes the total service providing area for each service.	No aspects of climate change, did look at planned habitat restoration projects for an AoC	Table 5 summarizes the extent of each service in the St. Louis Estuary	https://www.researchgate.net/profile/Brent-Bellinger/publication/301757266_Mapping_ecosystem_service_indicators_in_a_Great_Lakes_estuarine_Area_of_Concern/links/573256d508ae298602da3693/Mapping-ecosystem-service-indicators-in-a-Great-Lakes-estuarine-Area-of-Concern.pdf
22	Mapping ecosystem service indicators in a Great Lakes estuarine Area of Concern	Angradi, T.R., Launspach, J.J., Bolgrien, D.W., Bellinger, B.J., Starry, M.A., Hoffman, J.C., Trebitz, A.S., Sierszen, M.E. and Hollenhorst, T.P.,	2016	42(3), 717-727	What is the spatial extent and distribution of ecosystem services in the St. Louis Estuary of Lake Superior?	Lake Superior	St. Louis Estuary	Provisioning	Food (fish, wild rice)	Using biophysical data to map the service providing area of each service	Various biophysical indicators, also mapped effects of proposed restoration plans on the service providing areas	Service providing area (units of area) was the general mapped variable	The most widespread service was landscape views. Services tied to specific delivery areas (like shore-caught fish) comprised the smallest areas. Most areas have 3-7 services delivered of the 18 mapped (likely have more total, but only mapped 18). Spatial correlation was low, but esocid fish and wave attenuation areas cooccurred, as did power cruising, power boating, and sailing areas. Table five summarizes the total service providing area for each service.	No aspects of climate change, did look at planned habitat restoration projects for an AoC	Table 5 summarizes the extent of each service in the St. Louis Estuary	https://www.researchgate.net/profile/Brent-Bellinger/publication/301757266_Mapping_ecosystem_service_indicators_in_a_Great_Lakes_estuarine_Area_of_Concern/links/573256d508ae298602da3693/Mapping-ecosystem-service-indicators-in-a-Great-Lakes-estuarine-Area-of-Concern.pdf
22	Mapping ecosystem service indicators in a Great Lakes estuarine Area of Concern	Angradi, T.R., Launspach, J.J., Bolgrien, D.W., Bellinger, B.J., Starry, M.A., Hoffman, J.C., Trebitz, A.S., Sierszen, M.E. and Hollenhorst, T.P.,	2016	42(3), 717-727	What is the spatial extent and distribution of ecosystem services in the St. Louis Estuary of Lake Superior?	Lake Superior	St. Louis Estuary	Supporting	Habitat provisioning (birds, fish)	Using biophysical data to map the service providing area of each service	Various biophysical indicators, also mapped effects of proposed restoration plans on the service providing areas	Service providing area (units of area) was the general mapped variable	The most widespread service was landscape views. Services tied to specific delivery areas (like shore-caught fish) comprised the smallest areas. Most areas have 3-7 services delivered of the 18 mapped (likely have more total, but only mapped 18). Spatial correlation was low, but esocid fish and wave attenuation areas cooccurred, as did power cruising, power boating, and sailing areas. Table five summarizes the total service providing area for each service.	No aspects of climate change, did look at planned habitat restoration projects for an AoC	Table 5 summarizes the extent of each service in the St. Louis Estuary	https://www.researchgate.net/profile/Brent-Bellinger/publication/301757266_Mapping_ecosystem_service_indicators_in_a_Great_Lakes_estuarine_Area_of_Concern/links/573256d508ae298602da3693/Mapping-ecosystem-service-indicators-in-a-Great-Lakes-estuarine-Area-of-Concern.pdf
23	A Valuation Of Ecological Services In The Great Lakes Basin Ecosystem to Sustain Healthy Communities and a Dynamic Economy	Krantzberg, G., and Boer, C.	2006			Great Lakes	Ontario, Canada	Provisioning	Commercial Fishing				$35 million per year	Reduced summer water levels would diminish the recharge of groundwater supplies, cause small streams to dry up, and reduce the area of wetlands, resulting in poorer water quality and less habitat for wildlife. As lake levels drop, costs to shipping in the Great Lakes are likely to increase, along with costs of dredging harbours and channels and of adjusting docks, water intake pipes, and other infrastructure.	Lower water levels reduce spawning and breeding areas for native fish	
23	A Valuation Of Ecological Services In The Great Lakes Basin Ecosystem to Sustain Healthy Communities and a Dynamic Economy	Krantzberg, G., and Boer, C.	2006			Great Lakes	Great Lakes and St. Lawrence	Provisioning	Transportation				$2.2 - $3 billion		Lower water levels reduce the transportation/navigation abilities of commercial boats in the Great Lakes, decreases value of maritime transport	
23	A Valuation Of Ecological Services In The Great Lakes Basin Ecosystem to Sustain Healthy Communities and a Dynamic Economy	Krantzberg, G., and Boer, C.	2006			Great Lakes	Canada and USA	Cultural	Sport Fishing				$7.5 billion		Lower water levels reduce spawning and breeding areas for native fish. Polluted water reduces recreational enjoyment and willingness to participate in industry	
23	A Valuation Of Ecological Services In The Great Lakes Basin Ecosystem to Sustain Healthy Communities and a Dynamic Economy	Krantzberg, G., and Boer, C.	2006			Great Lakes	Canada	Cultural	Recreational Boating	Interpolated from US			$2.2 billion		Lower water levels reduce navigable pathways for leisure trips	
23	A Valuation Of Ecological Services In The Great Lakes Basin Ecosystem to Sustain Healthy Communities and a Dynamic Economy	Krantzberg, G., and Boer, C.	2006			Great Lakes	Canada	Cultural	Beaches				$200-$250 million		Too high/too low water levels reduce aesthetic value/ recreational abilities of beaches	
23	A Valuation Of Ecological Services In The Great Lakes Basin Ecosystem to Sustain Healthy Communities and a Dynamic Economy	Krantzberg, G., and Boer, C.	2006			Great Lakes	Canada	Supporting	Wetlands and Biodiversity				$70 billion			
24	Quantification of Historical Changes of Submerged Aquatic Vegetation Cover in Two Bays of Lake Ontario with Three Complementary Methods	Bin Zhu, Dean G. Fitzgerald, Susan B. Hoskins, Lars G. Rudstam, Christine M. Mayer, and Edward L. Mills	2007	33:122–135	How has submerged vegetation distribution and coverage changed over time in a bay of Lake Ontario?	Lake Ontario	Sodus Bay, Chaumont Bay	Regulating	Nutrient cycling, water purification	aerial photograph interpretation (API), hydroacoustics, rake sampling	Location	Time	The SAV coverage in Sodus Bay increased by 5% between 1972 and 1980 and by 35% between 1980 and 1999–2002 whereas the maximum depth of SAV colonization extended from 5.5 to 6.4 m during this period. In Chaumont Bay, the SAV coverage tripled while its maximum depth of occurrence increased from 5.1 to 6.1 m from 1982 to 2002.	not considered	Increased SAV will play a role in the increase in nutrients in the lake. Mussels also are playing a factor in increased water clarity. This clarity will play a role in the expansion of SAV.	
24	Quantification of Historical Changes of Submerged Aquatic Vegetation Cover in Two Bays of Lake Ontario with Three Complementary Methods	Bin Zhu, Dean G. Fitzgerald, Susan B. Hoskins, Lars G. Rudstam, Christine M. Mayer, and Edward L. Mills	2007	33:122–136	How has submerged vegetation distribution and coverage changed over time in a bay of Lake Ontario?	Lake Ontario	Sodus Bay, Chaumont Bay	Supporting	Habitat, food sources	aerial photograph interpretation (API), hydroacoustics, rake sampling	Location	Time	The SAV coverage in Sodus Bay increased by 5% between 1972 and 1980 and by 35% between 1980 and 1999–2002 whereas the maximum depth of SAV colonization extended from 5.5 to 6.4 m during this period. In Chaumont Bay, the SAV coverage tripled while its maximum depth of occurrence increased from 5.1 to 6.1 m from 1982 to 2002.	not considered	Increased SAV will play a role in the increase in nutrients in the lake. Mussels also are playing a factor in increased water clarity. This clarity will play a role in the expansion of SAV.	
25	Measuring the Net Economic Value of Recreational Boating as Water Levels Fluctuate	Nancy A. Connelly, Tommy L. Brown, Jonathan W. Brown	2007	43(4): 1016-1023	How does the net economic benefit of boating in Lake Ontario change due to lake levels?	Lake Ontario	Lake Ontario	Cultural	Recreational (Boat Use)	Direct expenditures, willingness to pay surveys, IMPLAN total economic impact analysis	Lake level, willingness to pay	Net economic benefit	Boaters spend $137 per day per boat which is $178 million total in 2002. If water levels were lower, during the month of August in particular, (244 ft in this analysis) about $8 million dollars could be lost in net economic benefits	Not considered, but fluctuations in water levels would be a result of climate change	This is interesting because it says that high water levels will cause losses too, but not on the same levels as the low water levels. Low water levels make it so floating and fixed docks don't work while high water levels only inundate fixed docks. High WTP values for yachts at marinas make the economic damage less.	https://onlinelibrary-wiley-com.proxy.lib.umich.edu/doi/full/10.1111/j.1752-1688.2007.00083.x
26	Associations between cyanobacteria and indices of secondary production in the western basin of Lake Erie	James H. Larson, Mary Anne Evans, Robert J. Kennedy, Sean W. Bailey, Keith A. Loftin, Zachary R. Laughrey, Robin A. Femmer, Jeff S. Schaeffer, William B. Richardson, Timothy T. Wynne, J. C. Nelson, Joseph W. Duris	2017	63(1): 232-243	What effect do cyanobacteria levels have on secondary production?	Lake Erie	Western Basin of Lake Erie	Supporting	Secondary production	Correlation coefficients between indices of secondary production and cyanobacteria levels	Indices of cyanobacteria production, microcystin concentration	Indices of secondary production (growth of unionid mussels, size of dresseinid mussels (young of year), mass of colonizing animals on a hester dendy sampler)	Cyanobacteria concentrations are loosely correlated with secondary production, but the toxins seem to have a larger effect.	Not considered, increasing climate change will increase cyanobacteria blooms		https://aslopubs-onlinelibrary-wiley-com.proxy.lib.umich.edu/doi/full/10.1002/lno.10733

Literature Review: Great Lakes ES Tracking

	Article Title	Author	Publication date	Volume and Page number	Research Question/Objective	Geographic extent	Location	Ecosystem services (Tier 1)	Ecosystem services (Tier 2)	Method	Independent Variables	Dependent Variables	Key Findings (Quantified)	Climate Change	Notes	Link
27	Linking Weather Patterns, Water Quality And Invasive Mussel Distributions In The Development And Application Of A Water Clarity Index For The Great Lakes	Ransibrahmanakul, Varis; Pittman, Simon J.; Pirhalla, Douglas E.; Sheridan, Scott C.; Lee, Cameron C.; Barnes, Brian B.; Hu, Chuanmin; Shein, Karsten	2018	120-123	What spatio-temporal trends exist in water clarity, and how do these trends correlate with trends of invasive mussel biomass?	Lake Michigan	Lake Michigan	Cultural	Aesthetics (water clarity)	Development of an index based on Moderate Resolution Imaging Spectroradiometer data	Mussel biomass, wind speed/direction	Turbidity (Kd, and chl a concentration)	Turbidity is associated with mussel biomass, but is likely confounded by unmeasured variables like runoff from land.	No measure of climate change		https://ieeexplore-ieee-org.proxy.lib.umich.edu/document/8518935
28	The effect of competition among three salmonids on dominance and growth during the juvenile life stage	Jessica A. Van Zwol, Bryan D. Neff, Chris C. Wilson	2012	21(4): 533-540	How would the reintroduction of Atlantic Salmon affect the growth of recreationally important non-native trout species in Lake Ontario/Lake Ontario Streams?	Lake Ontario	Lake Ontario and surrounding streams	Cultural	Recreational (growth of rec. important species)	Experimental semi-natural stream channels, measured growth of fish in presence of other species	Reach composition (presence or absence of salmon)	Fish growth rate, behavior	Brown trout were dominant and had the highest growth rate, even in the presence of Atlantic salmon	No measure of climate change		https://onlinelibrary-wiley-com.proxy.lib.umich.edu/doi/full/10.1111/j.1600-0633.2012.00573.x
29	Indirect management of invasive species through bio-controls: A bioeconomic model of salmon and alewife in Lake Michigan	Eli P.Fenichel, Richard D.Horan, James R.Bence	2010	32(4): 500-518	What is the optimal stocking strategy (maximum social benefit) for chinook salmon in Lake Michigan?	Lake Michigan	Lake Michigan	Cultural	Recreational (fishing)	Bioeconomic model	Salmon stock	Net social benefit, stock of alewives	The optimal stocking strategy for salmon to minimize damage from alewives and maximize the long term benefits of the chinook salmon fishery involves responsive stocking amounts and high data availability. Stocking should fluctuate in order to maximize benefits (more salmon stocked), minimize damages (alewives clogging drains, fouling beaches), and prevent extirpation of the now crucial forage fish.	No measure of climate change		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0928765510000229?via%3Dihub
30	Cumulative Habitat Impacts of Nearshore Engineering	Guy A. Meadows, Scudder D. Mackey, Reuben R. Goforth, David M. Mickelson, Tuncer B. Edil, Jonathan Fuller, Donald E. Guy, Lorelle A. Meadows, Elizabeth Brown, Stephanie M. Carman, Dale L. Liebenthal	2005	31(1): 90-112	How does nearshore engineering affect habitat availability and quality in the Great Lakes?	Great Lakes	6 study sites, 4 on Lake Michigan, 2 on Lake Erie	Supporting	Habitat provisioning	Sediment samples, sonar scans, biological sampling	Water level, sediment type, nearshore engineering	Erosion rate, sediment composition of the nearshore benthic environment, biological composition of the nearshore environment	Nearshore engineering changes the rate of erosion, bluff recession. It also may contribute to a benthic environment more conducive to colonization by introduced aquatic vegetation.	No measure of climate change, took place during a period of falling water levels		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0380133005702926?via%3Dihub
31	Repeated large-scale mechanical treatment of invasive Typha under increasing water levels promotes floating mat formation and wetland methane emissions	Olivia F. Johnson; AbhaPanda; Shane C. Lishawa; Beth A.Lawrence	2021	790	How do mechanical control methods for Typha affect the formation of floating mats and the emissions of methane?	Lake Huron	Cheboygan Marsh	Supporting	Nutrient cycling	3 treatments (crushing, harvesting, control) measured carbon fluxes and estimated above ground biomass	Treatment	Above ground biomass, carbon flux, net ecosystem production	Treated plots of typha grow back with less aboveground biomass. Treated plots, specifically harvested plots, also had higher methane flux rates. Treated plots promoted the formation of floating mats.	Rising water levels during the study period		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0048969721029910?via%3Dihub
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32	Evaluating sediments as an ecosystem service in western Lake Erie via quantification of nutrient cycling pathways and selected gene abundances	Ashlynn R. Boedecker; Desi N.Niewinski; Silvia E.Newell; Justin D.Chaffin; Mark J.McCarthy	2020	46(4): 920-932	What role do sediments play in the cycling of nitrogen in the western basin of Lake Erie?	Lake Erie	Western Basin	Supporting	Nutrient cycling	Sediment cores, water sampling, functional gene analysis	Sediment cor	N flux, N transformati	Sediments remove up to about a third of TN in the western basin. Sediments, however, may be a source of biologically available N and ortho-P, both of which help to sustain HABs.	2 year period, but HABs may be a result of climate change.		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0380133020300885?via%3Dihub
33	Lake hydrodynamics intensify the potential impact of watershed pollutants on coastal ecosystem services	Lucas Gloege; Galen A McKinley; Robert J Mooney; J David Allan; Matthew W Diebel; and Peter B McIntyre	2020	15: 6	How do the hydrodynamics of lakes endanger the delivery of ecosystem services?	Lake Michigan	Plumes of 11 rivers, around the lake	Provisioning	Freshwater (municipal uptakes)	Massachusetts Institute of Technology general circulation model, chose three representative ecosystem services	Pollutant load, service usage	Cumulative stress days	High cumulative stress days may be a result of in lake physics rather than solely a result of high loading from rivers. In lake physics, notably the thermal bar in Lake Michigan, prevent the dispersal of pollutants away from the shore and concentrate them in the nearshore areas. The thermal bar also plays a role in the spread of pollutants down the shore along areas of high importance for ecosystem service delivery.	No measure of climate change		https://www.researchgate.net/publication/339895256_Lake_hydrodynamics_intensify_the_potential_impact_of_watershed_pollutants_on_coastal_ecosystem_services
33	Lake hydrodynamics intensify the potential impact of watershed pollutants on coastal ecosystem services	Lucas Gloege; Galen A McKinley; Robert J Mooney; J David Allan; Matthew W Diebel; and Peter B McIntyre	2020	15: 6	How do the hydrodynamics of lakes endanger the delivery of ecosystem services?	Lake Michigan	Plumes of 11 rivers, around the lake	Cultural	Beaches	Massachusetts Institute of Technology general circulation model, chose three representative ecosystem services	Pollutant load, service usage	Cumulative stress days	High cumulative stress days may be a result of in lake physics rather than solely a result of high loading from rivers. In lake physics, notably the thermal bar in Lake Michigan, prevent the dispersal of pollutants away from the shore and concentrate them in the nearshore areas. The thermal bar also plays a role in the spread of pollutants down the shore along areas of high importance for ecosystem service delivery.	No measure of climate change		https://www.researchgate.net/publication/339895256_Lake_hydrodynamics_intensify_the_potential_impact_of_watershed_pollutants_on_coastal_ecosystem_services
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34	Periphyton bioconcentrates pesticides downstream of catchment dominated by agricultural land use	R.C.Rooney; C. Davy; J.Gilbert; R.Prosser; C. Robichaud; C. Sheedy	2020	702	What is the role of periphyton in the removal of pesticides from the water column in agricultural catchments?	Lake Erie	Rondeau Bay/Rondeau Provincial Park	Regulating	Water purification	Water, sediment, and periphyton samples	Location, type of sample	Pesticide concentration, bioconcentration factor	20/161 pesticides tested for were found in higher levels in periphyton than the ambient environment. For some pesticides, this concentration may be as high as 20 times the ambient concentrations. Periphyton seemingly provide the ecosystem service of pesticide removal, but they may be a mechanism for legacy pollutants to enter the aquatic foodweb as well.	No measure of climate change		https://www-sciencedirect-com.proxy.lib.umich.edu/science/article/pii/S0048969719344638?via%3Dihub
35	Invasive species removal increases species and phylogenetic diversity of wetland plant communities	Shane C. Lishawa; Beth A. Lawrence; Dennis A. Albert; Daniel J. Larkin; Nancy C. Tuchman	2019	9(11): 6231-6244	Which invasive species removal methods restore the diversity of a site most effectively?	Great Lakes	Lake Huron and the St. Mary's River	Provisioning	Genetic diversity	Three distinct treatments, measured species richness	Treatment (harvest, mow, removal, control), type of wetland (emergent marsh, wet meadow)	Species richness, litter, typha cover	Invasive typha covers a larger area in the emergent marsh. All three methods reduced typha cover in the emergent marsh. Harvesting resulted in increased species richness in all zones.	No measure of climate change, lake levels at low levels during study though		https://onlinelibrary-wiley-com.proxy.lib.umich.edu/doi/full/10.1002/ece3.5188
36	Short-term impacts of Phragmites management on nutrient budgets and plant communities in Great Lakes coastal freshwater marshes	Kristin E. Judd & Steven N. Francoeur	2018	27:55-74	How does the removal of invasive species affect the ability of wetlands to retain nutrients and uptake carbon?	Lake Erie	Detroit River International Wildlife Refuge	Regulating	Carbon sequestration	Aerial treatments of phragmites patches with broad spectrum herbicides, measured species richness, diversity, plant productivity, and nutrient uptake	Treatment group	Species richness, diversity, aboveground net primary productivity, % C, N, P	Herbicide treatments significantly reduce net primary productivity, nitrogen uptake, and phosphorus uptake. Scaled to the western basin of Lake Erie, this accounts for 24 × 103 kg of phosphorus and 159 × 103 kg of nitrogen.	No measure of climate change		https://link-springer-com.proxy.lib.umich.edu/article/10.1007/s11273-018-9643-6
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37	Identifying and Eliminating Sources of Recreational Water Quality Degradation along an Urban Coast	Meredith B. Nevers, Murulee N. Byappanahalli, Dawn Shively, Paul M. Buszka, P. Ryan Jackson, Mantha S. Phanikumar	2018	47(5): 1042-1050	What are the dominant sources of e.coli at an urban beach? How can these sources be minimized resulting in fewer beach closures and improved water quality?	Lake Michigan	Grand Calument Area of Concern	Cultural	Recreational	Water samples for qPCR analysis. Trained canine gull deterrents	Location, treatment (control vs. dogs)	Source of e.coli, e. coli density	Gulls represent a significant source of e.coli contamination at Lake Michigan beaches, and in the study area, trained canines present a possible short term solution.	No measure of climate change, although rainfall listed as major contributor to e.coli densities. Increased rainfall is possible with increasing climate change		https://acsess-onlinelibrary-wiley-com.proxy.lib.umich.edu/doi/full/10.2134/jeq2017.11.0461
38	Use of Fish Telemetry in Rehabilitation Planning, Management, and Monitoring in Areas of Concern in the Laurentian Great Lakes	J. L. Brooks, C. Boston, S. Doka, D. Gorsky, K. Gustavson, D. Hondorp, D. Isermann, J. D. Midwood, T. C. Pratt, A. M. Rous, J. L. Withers, C. C. Krueger & S. J. Cooke	2017	60: 1139-1154	How can fish telemetry data be incorporated into rehabilitation and management plans?	Great Lakes	7 AoCs using telemetry data	Supporting	Habitat Provisioning	7 distinct case studies, analyzed how telemetry data helped there.	Location	Residence time, habitat use	Recreationally and commercially important fish use deeper water habitat than originally planned for restoration in Lake Ontario. Lake Sturgeon rely on the St. Clair River for spawning, and restoration work seeking to benefit lake sturgeon should build reefs in that area. In Lake Superior, young sturgeon use the Garden River, a frequent target of lampricide treatments. This suggests that maybe lampricide treatments should target other areas to reduce mortality.	No measure of climate change	Didn't really quantify any ecosystem services, but provided mentions of studies that did in isolated instances.	https://link-springer-com.proxy.lib.umich.edu/article/10.1007/s00267-017-0937-x

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39	Climate change as a long-term stressor for the fisheries of the Laurentian Great Lakes of North America	Paris D. Collingsworth, David B. Bunnell, Michael W. Murray, Yu-Chun Kao, Zachary S. Feiner, Randall M. Claramunt, Brent M. Lofgren, Tomas O. Höök & Stuart A. Ludsin	2017	27(2): 363-391	How will climate change affect the fisheries of the Great Lakes?	Great Lakes	Great Lakes wide	Cultural	Recreational (Fishing)	Review article			Warmer temperatures will likely increase the potential for positive growth of warmwater and coolwater species at the expense of some coldwater species. Longer periods of stratification in the summer will likely occur along with longer periods of bottom hypoxia in productive lakes.	Temperature and precipitation changes mostly		https://link-springer-com.proxy.lib.umich.edu/article/10.1007/s11160-017-9480-3#Abs1