BRIDGING GAPS IN INFORMATION: STRATEGIES FOR IMPROVING NATURAL RESOURCE MANAGEMENT IN A CHANGING CLIMATE

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ABSTRACT

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The Great Lakes region has an abundance of natural resources that are ecologically and socioeconomically valuable yet threatened by changing climate. To effectively address impacts of climate change within the Great Lakes region will require managers to mitigate the causes of climate change as well as adapt to current threats and to future changes in both social and ecological systems. This thesis addresses those needs by providing natural resource managers with strategies to increase support for climate change mitigation policies and by providing them with information on how social and ecological systems may change with changing climate so that they can develop and apply novel management strategies. Results from Chapter 1 show that while Michigan conservation organizations vary in their current engagement with climate change issues and in their willingness to increase engagement with their membership depending on perceived barriers, every organization expressed interest in receiving more information on how climate change will affect the state's fish and wildlife populations. In Chapter 2, we characterized how resilient Michigan river fish habitat may be to anticipated changes in climate. Our results indicate that while cumulative resilience is generally higher in the Upper Peninsula and in the Northern Lower Peninsula, resilient streams are also found in the Southern Lower Peninsula, suggesting that managers have opportunities in every part of the state for protecting and/or improving stream resiliency to changing climate. Collectively, outcomes of this research offer managers new information and strategies for mitigating and adapting to climate change, ultimately facilitating the sustainable management of natural resources in a changing climate.

To my parents Dan and Roberta Tracy, my partner Thomas Connor,
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PREFACE

The research chapters in this thesis have been prepared and formatted for publication. Therefore, there is some repetition in concept, study site descriptions, and methods among chapters.

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OVERVIEW

Altered atmospheric conditions have resulted in rising air temperatures and changes in the amount, form, and frequency of precipitation events across the globe, and projections indicate that such changes will continue (IPCC 2018). The Great Lakes region has been disproportionately affected by changes in climate compared to the rest of the U.S. Notably, mean annual air temperature has increased by 1.6°F since 1960, and annual precipitation has increase 10% over the last century (USGCRP 2018, Wuebbles et al. 2019). These changes will ultimately impact distributions and abundances of ecologically and economically valuable fish and wildlife populations found throughout the Great Lakes region as well as the people that rely on them (Kunkel et al. 2013, Wuebbles et al. 2019).

While managers in the Great Lakes region have invested heavily in protecting natural resources from current threats, much less has been done to protect them from the future threat of climate change. To effectively address the impacts of climate change will require managers to mitigate the causes of climate change as well as to adapt to current and future changes in both social and ecological systems (Liu et al. 2007, Ostrom 2009). To help in addressing these needs, the goal of my thesis is to provide natural resource managers with strategies to increase support for climate mitigation policies and actions and to provide them with information on how social and ecological systems may change with changing climate so that they can apply novel management practices.

To mitigate the causes of climate change, the Intergovernmental Panel on Climate Change (IPCC) has recommended adoption of policies and actions that reduce the flow of greenhouse gases into the atmosphere either by limiting emissions, promoting the use of clean energy, or enhancing carbon sinks such as forests (IPCC 2018). However, increased support from the public is essential for climate-friendly policies to be implemented or for conservation practices to be adopted. In the United States, hunters and anglers constitute a large and diverse group of individuals who could provide substantial support for climate change policy and mitigation efforts. Conservation organizations are groups primarily composed of hunters and anglers focused on conservation of fish and wildlife for the purposes of sustaining hunting and angling opportunities, and they may be in a unique position to strategically engage their members on issues of climate change.

Based on the role that conservation organizations could play in mobilizing members around climate change initiatives, the goal of Chapter 1 was to develop strategies to increase organizational engagement with their membership on climate change. We began by interviewing individuals in leadership roles in Michigan-based conservation organizations to gather baseline data on how engaged conservation organizations are currently in climate change and to identify perceived or real barriers to increasing engagement that exist within these organizations. Based on participant responses, we then made recommendations for strategies that organizations could use to overcome these barriers. Results from this Chapter 1 also informed the need for Chapter 2 based on participant requests for more Michigan-focused research on effects of climate change on fish and wildlife populations and their habitats.

In addition to mitigating the causes of climate change, natural resource managers need information on how fish and wildlife populations and the habitats that support them may change in response to changing climate so they can prioritize the protection or restoration of these resources. Currently, observational studies that document responses of fish and wildlife to changes in climate (e.g., Hari et al. 2006, Isaak et al. 2010, Ward et al. 2015) and predictive studies that model predicted impacts of climate change on their habitats (e.g., Herb et al. 2016, Van Zuiden et al. 2016) are the two primary types of information that managers can use to better understand how fish and wildlife habitat and populations may change with changing climate. However, such efforts to do not specifically address the natural factors that make fish and wildlife habitats and populations resilient to changes in climate.

To address this need, the goal of Chapter 2 was to estimate the resilience of fish habitat in Michigan streams to changing climate. Because ecosystem resilience is a multi-faceted property affected by a variety of physical and biological habitat features, our first two objectives were to identify a set of variables that may promote resilience and then create sub-indices to characterize different aspects of resilience. Finally, we integrated individual sub-indices into one cumulative resilience score to show a composite estimate of stream resilience.

Michigan was chosen as the study region for this project due to its abundance of natural resources that support a thriving hunter and angler community (Calantone et al. 2019). These include four Great Lakes, more than 11,000 inland lakes and over 36,000 miles of rivers for angling, and 8 million acres of forests, grasslands, and wetlands for public hunting land and wildlife watching (MDNR 2018). Together these habitats support a diversity of ecologically and socioeconomically valuable fish and wildlife populations including cold, cool, and warm water fisheries as well as both boreal and temperate wildlife species. These valuable species draw hunters and anglers from across the country and contribute \$11.2 billion annually to Michigan's economy (Calantone et al. 2019). Michigan hunters and anglers are also politically active and have collectively influenced and supported policies at the regional, state, and national levels which benefit fish and wildlife conservation. Collectively, outcomes of this research will provide managers with information and strategies for mitigating and adapting to climate change, ultimately facilitating the sustainable management of natural resources in a changing climate

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CHAPTER 1: OVERCOMING BARRIERS: STRATEGIES FOR INCREASING CONSERVATION ORGANIZATION ENGAGMENT WITH MEMBERSHIP ON CLIMATE CHANGE

ABSTRACT

The Great Lakes region has been disproportionately affected by changes in climate, and these changes will ultimately impact distributions and abundances of the region's ecologically- and economically-valuable fish and wildlife populations. While policies and actions that mitigate impacts of climate change have been proposed by organizations such as the United Nations and Intergovernmental Panel on Climate Change, increased support from the public is essential for their implementation. Hunters and anglers constitute a large and diverse group of individuals who could provide substantial support for climate change policy and mitigation efforts. Conservation organizations are groups primarily composed of hunters and anglers focused on the conservation of fish and wildlife for the purpose of sustaining hunting and angling opportunities, and may be in a unique position to engage their members on issues of climate change. In light of this, the goal of our study was to develop strategies to increase organizational engagement with their membership on climate change. We first interviewed individuals in leadership roles in conservation organizations to gather baseline data on how engaged these organizations currently were in climate change issues. We then identified perceived or real barriers to engagement within these organizations and their memberships. Finally, we used this information to make recommendations for strategies that organizations can use to increase their engagement with members in climate change issues. Collectively, we found that while Michigan conservation organizations vary in their current engagement with climate change issues and in their willingness to increase engagement with their membership depending on perceived barriers, interest in receiving more information on how climate change will affect the state's fish and

wildlife populations was unanimous across all organizations sampled. Ultimately, this study provides conservation organizations with information and strategies that will enable them to increase their engagement in climate change, potentially leading to increased hunter and angler support for climate change policy and mitigation.

INTRODUCTION

Global concentrations of atmospheric greenhouse gases including carbon dioxide, methane, and nitrous oxide have increased substantially since the mid-1800s (IPCC 2018). Altered atmospheric conditions have resulted in rising air temperatures and changes in the amount, form, and frequency of precipitation events across the globe, and projections indicate that such changes will continue to intensify (IPCC 2018). The Great Lakes region has been disproportionately affected by global changes in climate compared to the rest of the country. Notably, mean annual air temperature has increased by 1.6°F (compared to a 1.2°F increase nationwide), and annual precipitation has increase 10% (compared to a 4% increase nationwide) over the last century (USGCRP 2018, Wuebbles et al. 2019). These changes will ultimately impact distributions and abundances of ecologically- and economically-valuable fish and wildlife populations found throughout the Great Lakes region (Kunkel et al. 2013, Wuebbles et al. 2019).

To effectively address these coming changes, international organizations including the Intergovernmental Panel on Climate Change (IPCC) and the United Nations (UN) have recommended that countries adopt policies and actions to mitigate impacts of climate change globally, nationally, and regionally, with the focus of such policies and actions including promoting clean energy, protecting and/or restoring habitats, and raising public awareness about climate change (UN 2015, IPCC 2018). However, in many countries, increased support from the public is essential for climate-friendly policies to be implemented or for conservation practices to be adopted. In the United States, one group that could be engaged to increase support for such efforts includes hunters and anglers. Hunters and anglers constitute a large and diverse group of individuals. The Department of the Interior (DOI) reports that 101.6 million US citizens, or 40% of the population, participate in hunting, fishing, and/or wildlife-watching (DOI 2016) Additionally, hunters and anglers have collectively influenced and supported policies in the US such as the Pittman-Robertson Act and the Dingell-Johnson Act which provide conservation funding through taxes on fish- and wildlife-related goods (Duda et al. 2010). Through these taxes and the purchase of hunting and fishing licenses, hunters and anglers contribute substantial funding for conservation and management of fish and wildlife populations (Duda et al. 2010). Besides their direct economic impact on conservation, revenue from the sale of hunting- and angling-related merchandise and tourism contributed $156 billion to the Nation's economy in 2016 (DOI 2016). In Michigan alone, jobs created from hunting- and fishing-related purchases contribute $11.2 billion annually to the state economy (Calantone et al. 2019). Considering the large political and economic impact that hunters and anglers have on the country's fish and wildlife populations, these individuals could provide substantial support for climate change policy and mitigation efforts.

Conservation organizations are groups focused on the conservation of fish and wildlife for the purpose of sustaining hunting and angling opportunities. As such, these organizations represent the interests of hunters and anglers, and they may be in a unique position to engage with their members on issues of climate change. Because hunters and anglers generally trust conservation organizations, these individuals may be more receptive to information about climate change from these groups than they would be if it came from other sources. Increased education on how climate change will affect the fish and wildlife populations that hunters and anglers value may lead to greater support for climate change initiatives.

In light of the role that conservation organizations could play in mobilizing members around climate change initiatives, the goal of this study is to develop strategies to increase organizational engagement with their membership on climate change. Our first objective is to interview individuals in leadership roles in conservation organizations to gather baseline data on how engaged these organizations currently are on climate change issues. The second objective is to identify perceived or real barriers to engagement that currently exist within these organizations and their membership. Finally, the third objective is to make recommendations for strategies that organizations can use to overcome these barriers. This study will provide conservation organizations with information and strategies that will enable them to increase their engagement in climate change, potentially leading to increased hunter and angler support for climate change policy and mitigation.

METHODS

Study Region

Michigan is an ideal location to study conservation organizations because it has an abundance of different ecosystems that support ecologically- and socioeconomically-valuable fish and wildlife populations (Calantone et al. 2019). These include four Great Lakes, more than 11,000 inland lakes, over 36,000 miles of rivers, and 8 million acres of forests, grasslands, and wetlands for public hunting land (MDNR 2018). Additionally, habitats within these ecosystems are very diverse. Due in part to its glacial history and resulting variation in surficial lithology, Michigan's Great Lakes, inland lakes, and rivers have diverse thermal habitats that support a variety of cold, cool, and warmwater fisheries such as Chinook salmon (*Oncorhynchus tshawytscha)*, Walleye (*Sander vitreus)*, and Largemouth Bass (*Micropterus dolomieu*)

(Wuebbles et al. 2019). Michigan also has a variety of forest types including boreal forests dominated by spruce, pine, and aspen trees that support Moose (*Alces americanus)*, Snowshoe Hare (*Lepus americanus)*, and American Marten (*Martes americana)*), as well as temperate deciduous forested primarily composed of oaks, maples, and beech trees that support White Tailed Deer (*Odocoileus virginianus*), Black Bear (*Ursus americanus)*, and Turkey (*Meleagris gallopavo))* (https://www.michigan.gov/dnr/).

Participant Selection

Two criteria were used to select participants for this study. First, we targeted participants from conservation organizations with mission statements focused on conservation of fish and wildlife species and their habitats for the purposes of sustaining hunting and angling opportunities. Groups focused on habitat or species conservation lacking a focus on hunting or angling (e.g., The Nature Conservancy, The Audubon Society, The Sierra Club) were not considered for this study. The second criteria was to select participants in upper-level management positions within the chosen conservation organizations. The rationale for choosing upper management from an organization stemmed from the idea that these individuals typically have a greater ability to affect change at the organizational level than lower level employees or members (Berkout 2011). Additionally, it has been proposed that organizational leadership should reflect individual member views and beliefs (Tsai 2011).

Following this criteria, our sample population was initially identified by conducting a web-based search of national- and state-based conservation organizations operating in Michigan. Upper-level employees of these organizations were contacted by email or phone to schedule interviews. During interviews, we also used the snowball sampling method which entails asking participants to suggest other individuals in the field (Biernacki and Waldorf 1981).

Interview Design and Questions

We chose semi-structured in-depth interviews as the data collection method for this study because we wished to collect detailed information from participants on the current level of organizational engagement in climate change issues and on what barriers existed to increasing this engagement (Young et al. 2018). While there are limitations to this method (e.g., small sample size, lack of generalizable results), it produces insights and substantive information that cannot be collected quantitatively and that enhanced the quantitative outputs of this study (Vining and Tyler 1999, Tindall 2003). Initial interview questions were designed to address the study goal and subsequently refined after pilot testing following the Dillman's Tailored Design Method to ensure that questions were easy to interpret and interview administration was unbiased (Dillman et al 2009). Michigan State University Internal Review Board approval was obtained before the interview process began (IRB #x17-1426e), and each participant signed a consent form (Appendix 1) to ensure that they understood the purpose of the study, their role in it and the precautions taken to guard any identifying information.

The interview consisted of 14 Likert-scale, rank and open-ended questions (Table 1). Question 1-8 were designed to address the first study objective focused on collecting baseline data of current organizational involvement in climate change issues. The first three Likert-scale questions asked participants to report on a scale of 5 (very important) to 1 (unimportant) how important the issue of climate change was to them personally, to their organization's board of directors, and to their organization's membership in order to get a more quantitative assessment. Next, to gain more detailed insights on the degree of organizational involvement in climate change issues, we asked a series of opened-ended questions (Q 4, 7-8) about the participant organizations' policy statements and published materials relating to climate change, as well as any recent successes in mitigating impacts of climate change. Participants were also asked how their organization reacted when climate change was discussed, and what terminology was used most frequently when discussing it (Q 5-6). The remaining questions (Q 9-14) were developed to address the second objective. Participants were asked to describe some of the major barriers they perceived that were hindering their organization from being more engaged in climate change action. Question 9 was open-ended to ensure that a variety of information could be collected, while question 13 asked participants to rank the most important barriers to engagement from a list of common barriers developed from the literature. Participants were then asked two open-ended questions (Q 10-11) about what information they believe their organization should have to be more engaged in climate change, and if they had access to this information. Finally, participants were given the opportunity to expand on anything not explicitly covered in the interview (Q 14).

Data Analysis

Open ended responses to questions 4-12 and 14 were coded using inductive data-driven thematic analysis. Thematic analysis is a process of identifying, analyzing, and reporting patterns (themes) within data, and using these patterns to answer research questions (Braun and Clarke 2006). This process entails carefully reading the interview data and subsequently generating codes that label important features of the data that may help to answer the research questions. The lumping and splitting of text could occur at the sentence or paragraph level as long as the theme remained the same (MacQueen et al. 2008). Once open coding is complete and initial codes are developed, a code book is created. The code book provides a code name, description, and example of a quote that would fall under the code (MacQueen et al 1998, DeCuir-Gunby et al. 2011). The interviews were then coded by other collaborators to ensure inter-coder reliability.

Once all interviews were coded, the researcher examined these codes to identify broader patterns of meaning (themes). Themes were then refined and written up in a narrative to answer the research questions (Ryan and Bernard 2003). Closed-ended responses to questions 1-3 and 13 were analyzed using counts of total responses and relative frequency statistics (the number of responses in each category was divided by the total number of responses).

RESULTS AND DISCUSSION

Overview

Our study identified several characteristics of organizational structure and membership important to determining current and future conservation organization engagement in climate change issues. Results from this study also highlighted common barriers to increasing engagement as well as recommendations from interview participants for overcoming these barriers. Overall, we found that while Michigan conservation organizations vary in their current engagement with climate change issues and in their willingness to increase engagement with their membership depending on perceived barriers, interest in receiving more information on how climate change will affect the state's fish and wildlife populations was unanimous. This interest in climate change research could indicate potential future willingness to support policies and actions that reduce and mitigate the effects of climate change. Based on these findings, we created a tailored list of strategies for organizations to use to overcome barriers and increase their engagement in climate change issues.

Participants Sampled

In total, representatives from twelve conservation organizations participated in the interviews which took place between October 13th 2017 and February 6th 2018 (A.1.2). Each participant worked for a conservation organization, and their position titles included executive director, director, president, vice president, and regional representative (A.1.3). Five interviews were conducted over the phone, and seven were conducted in person, either on Michigan State University's campus or at a locale of the participant's choosing. Interviews lasted between 40-80 minutes, and detailed notes were taken during interviews. Interviews were not recorded at the request of the participants due to the sensitivity of the subject matter.

Current Level of Organizational Engagement in Climate Change Issues

Analysis of questions 1-8 revealed 4 major themes useful in assessing current involvement by organizations in climate change issues (B.1.1, A.1.4). The first included the importance of climate change to members, the board of directors, and the participant (collectively described as "organizational components"). The next theme focused on the level of organizational involvement in politics. The third theme, termed organizational focus, assessed whether or not participants believed their organization's focal species or mission was or would be negatively affected by climate change. The final theme assessed the types of climate change engagement practiced by the organization, including whether or not they did outreach and education with members on climate change, on-the-ground restoration, and/or political advocacy. Collectively, answers to questions under these themes gave us a sense of organizations current baseline engagement in climate change issues.

Importance of Climate Change to Different Organizational Components

Answers to questions 1-3 provide quantitative information on how participants personally prioritize climate change, how they believe the organization's board prioritizes it, and how they believe the organization's members prioritize it. Although these results were based solely on participant perceptions, we hypothesized that because participants all held upper-level management positions, they possessed sufficient knowledge of the organization to provide informed responses about board and member views and priorities. The results revealed two main trends about the importance of climate change to different people in the organization. First, participant rankings of climate change as a priority did not align with the board and member rankings in 75% (n=9) of the interviews (B.1.1). This disagreement could be problematic for conservation organizations because organizational culture, or the shared values and perceptions held by employees within an organization, is not only a significant factor in determining organizational success, but also affects employee productivity and job satisfaction (Tsai 2011). Highlighting this disconnect between how different components of the organization prioritize climate change issues may ultimately lead to a dialogue about priorities of the organization as a whole. Additionally, 66% (n=8) of participants ranked climate change as a higher priority for themselves than they perceived it to be for their organization's board or members, while only one participant (8%) ranked it as a lower priority for themselves than their organization's members (B.1.1). These results may be interpreted based on a study by Berkhout (2011), who found that the first step in affecting organizational adaption to climate change is employee awareness and concern about how climate change may impact the organization's operation.

Political Involvement

Participant responses to question 4 resulted in information about both the degree and type of organizational political involvement in climate change issues (A.1.4). Results showed that only one participant from the study affirmed that their organization had an official policy statement specifically about climate change. However, other participants elaborated on different types of organizational involvement in politics. For instance, several participants spoke about being involved in national politics and advocating for bills and policies that benefited fish and wildlife populations. Additionally, a participant noted their excitement about the organization's new seat on the policy council of the Theodore Roosevelt Conservation Partnership (TRCP) and how their organization helped found the American Wildlife Conservation Partners (AWCP). The TRCP and AWCP are both partnerships that work to give a voice to hunters and anglers in Washington, D.C. by advancing conservation policy, and every national organization involved in our study was a member of at least one of the partnerships (http://www.wildlife-partners.org/, http://www.trcp.org/). Finally, while none of the three state organizations were involved in national-level politics, a state organization participant spoke in depth about their organization's push to inform members about current conservation policy through email alerts and requests to contact political representatives in support of environmental policies.

Many of the strategies suggested by the IPCC and UN to mitigate the effects of climate change involve policy measures at the global, national, and regional levels (Lutsey and Sperling 2008, UN 2015, IPCC 2018). Despite recommendations from these groups, the U.S. government's policy response to climate change has historically been relatively limited in comparison to other countries (Nisbet 2009, Weber and Stern 2011). In light of this, increasing citizen engagement in climate mitigation and adaptation policies is a critical step in motivating government action (Hart and Feldman 2016). To this end, Hart and Feldman (2016) conducted a study to identify what factors influence public support for climate change policy and found that a person's perceived understanding of both climate change science, as well politics and government, were linked with their support for climate change policy. Given that our results show that many of the organizations in this study are currently involved in politics, we believe they may be able to more easily increase their engagement in climate change policy than organizations with no current political involvement.

Organizational Focus

In response to question 5, participants generally attributed their organization's reaction to the discussion of climate change issues to their organization's focal species or mission statement (A.1.4). For example, a participant affiliated with a warm water fish focused organization stated that their members were not very concerned with climate change because they believe that warmwater fish will not be negatively affected by anticipated changes. However, a participant with a cold water fish focused organization stated that, "We have a poster child species that is highly affected by climate change." Both cold water fish focused organizations expressed willingness to be involved in climate change issues because they believe their focal species will be negatively affected by projected changes in air temperature and precipitation patterns. Furthermore, a participant from a wildlife focused organization indicated that climate change issues are rarely discussed, likely because the organization is "mission focused" and climate change "is not part of our specific mission."

Types of Climate Change Engagement

Questions 7 and 8 provided participants the opportunity to expand on the type of climate change engagement their organization could engage in, if any, including outreach and education, on-the-ground restoration, or political advocacy (A.1.4). For example, while one participant said their organization would never explicitly publish articles about anthropogenic climate change, they indicated that they would potentially facilitate a conversation with members about how fish and wildlife populations were changing due to climate change and strategies to mitigate these changes because they felt the organization has "…enough credibility and goodwill with our members that we can manage the conversation in a non-threating way." As another example, one participant felt that their organization could play a bridging role between conservation groups and environmental groups currently engaged in climate change issues, ultimately facilitating partnerships. Furthermore, when asked if they would advocate for select political issues, a participant expressed that if the organization's "voice matters to the outcome, we will be forceful and public about our views on climate change." Finally, although a participant with a wildlife organization didn't believe their organization would increase their engagement in climate change politics or outreach, when asked if they had any recent successes in mitigating the impacts of climate changes they spoke at length about their organization's grassland restoration projects.

Barriers to Organizational Engagement in Climate Change Issues

Analysis of both opened-ended question 9 and multiple choice question 13 lead to the identification of two major themes related to organizational barriers to engagement in climate changes issues. The two barriers that were mentioned most frequently by participants were the political views and conservation priorities of their organizations members and the lack of research and information on climate change (B.1.2). Participants primarily attributed the views and priorities of their members to demographics, political affiliation, and level of education on the topic of climate change (A.1.4). However, the theme of education was often tied to the other major barrier which was the lack of research and information on climate change. Together with the baseline data on current organization engagement, these barriers informed the development of strategies to increase organizational engagement in climate change issues.

Member Demographics

Several participants mentioned that the age of their organization's members played a role in their willingness to support climate change or clean energy initiatives (A.1.4). For example, when asked if their organization attempted to engage multiple perspectives in climate change discourse a participant stated that the membership is mostly white, male, and over the age of 60, and they have never expressed a desire to be involved in climate change issues. However, one of the participants with a cold water fish organization mentioned that their organization was very focused on recruitment and retention of new members. The participant stated that if increasing engagement in climate change would draw new younger members "we would do anything and everything to support those issues." These results support research from Leiserowitz (2005) which found climate "naysayers" who expressed high levels of skepticism about climate change were predominately white, male, Republicans. Additionally, Whitmarsh (2011) found that older respondents without a formal education tended to be highly skeptical about climate change. However, 2008 polls conducted in Europe showed that, compared to older generations, the majority of young people aged 18-34 believe that climate change is a serious yet 'solvable' problem (Corner et al. 2015). These findings could be used as a justification for organizations to increase their support and involvement in climate change policy and actions as a means to attract younger more environmentally-minded members to their organization.

Member Political Views

Political views were also mentioned by the majority of participants when describing what their organization's members thought about climate change (A.1.4). A participant expressed a common belief when they expressed that "Democrats are happy to be involved [in climate change issues]; Republicans think it's ridiculous. If you look at public opinion research, the thing that shapes your view on climate change is your party." The view that climate change was a deeply partisan issue was expressed frequently by participants and was a concern for organizations with "equal numbers of Republicans and Democrats". This concern was reflected by a participant who thought climate change "had become so weaponized politically, almost to the point where it's a taboo subject, you can't talk about." This same participant also linked several barriers together, stating that political constraints that "inform views of our members who inform the views of our board" lead to a series of barriers to increasing their organizational engagement in climate change.

These results are in line with a study from McCright and Dunlap (2008) who investigated climate change beliefs held by U.S. Republicans and Democrats and found major differences between the parties with respect to the belief that climate was indeed changing, what the risks were, and how willing they were to mitigate these risks through action or policy support. In fact, as recently 2017, poll results showed that while 66% of Democrats were concerned "a great deal" about climate change, only 18% of Republicans reported this level of concern (Gallup poll 2017). In light of this, it has been suggested that to increase public support for climate change policy, it may be effective to identify areas of environmental protection that transcend the political partisan divide. Indeed, many participants from TU, RGS, and NWF spoke about the importance of "finding compromises" and "talking about mutual priorities" that people across the aisle can agree on in an effort to push forward conservation initiatives.

Member Education and Information Needs

The level of member education on the topic of climate change was mentioned by several participants as an influential factor in member support for these issues and tied into the other major barrier that participants identified which was lack of available climate change information (A.1.4). One participant worried that "most of my members aren't aware of the fact that streams are warming, and we may not be able to catch steelhead." This concern over the lack of member education was reflected in several interviews, prompting several participants to highlight the need for more climate change related research that organizations could use for outreach and education. For example, a participant conveyed that it was critical for the organization to gradually increase member education on climate change over the long term. This sentiment was also reflected in a different participant's concern that they didn't want their organization's engagement in climate change issues to appear as an attempt solely to "chase funding." This participant stressed that member outreach and communication on the topic of climate change would have to be on their own terms, and on their own timeline, stating that, "It will take time to build enduring support for an issue, but that's how you create a durable conversation." This same participant also believed that the organization did not have enough information on how climate change will affect the fish and wildlife populations that their organization's members cared about. Additionally, a participant with a wildlife organization drew a connection between membership education and improved habitat management, a focus of their organization, stating, "If the general membership understood climate change more, we could guarantee more proper management." This sentiment was echoed by a participant who believed that there was a need to demonstrate how climate change is directly affecting the organization and its mission in order to increase engagement on around this topic.

As many of the participants in this study recognized, increasing a person's education on the topic of climate change is linked with increased engagement in climate change policy and actions (Weber and Stern 2011). A study by Lorenzoni and others (2007) found that common barriers to public understanding of climate change include a lack of knowledge of the causes and potential solutions to climate change, uncertainty and skepticism over the causes of climate changes, distrust in information sources, and the perception that climate change was a geographically or temporally distant threat. Providing organizational membership with information, not only on the causes of climate change, but also on how climate is impacting the fish and wildlife populations they value in Michigan, could lead to increased engagement in climate change issues.

Participant Needs and Recommendations

Analysis of questions 10 and 11 revealed four major themes that captured participants' needs and recommendations for overcoming the barriers to engagement they described in the previous section (A.1.5). The first and most prevalent theme was the call for more research on how climate change was affecting Michigan's fish and wildlife populations and the habitats that support them. Next, the theme of financial issues related to climate change and clean energy was identified in several different capacities including, the loss of money from the fossil fuels industry, the need for more funding for research and projects to further engage in climate change issues, and the request for potential monetary incentives from clean energy and climate change initiatives to support natural resource conservation (i.e., taxes on renewable energy that benefits natural resource management). A third theme identified by a variety of participants was the desire to form new partnerships with groups that were currently engaged in climate change mitigation. Finally, many participants expressed the importance in selecting who presented climate change information and the terminology they used to do so. The identification of these novel suggestions by participants formed the basis for our recommended strategies to increase organizational engagement in climate change policy and action.

Research on Direct Effects of Climate Change in Michigan

The theme of direct effects was the most emphasized theme identified in this study and was mentioned by every participant. Participants expressed their desire and the perceived desires of their organizations' board and members to have local, regional, and statewide examples of how climate change was directly affecting resources they care about and what actions they could take to address it. A participant stated that, "For our folks to connect and care, it's gotta be something they can see from their deer blind or their fishing boat." Several participants stated that they knew some of this research already existed, however, they did not have the time or resources to spend compiling existing data to distribute to their members. This finding suggests that conservation organization may be open to communicating with climate change researchers about their findings and could present an opportunity for scientists to effect climate change policy and mitigation actions through the process of sharing their work with the public. For example, extension professionals specialize in serving as the inter-face between scientists and the public and frequently disseminate information to the public.

Funding and Monetary Incentives

One participant articulated that although their organization is getting better at characterizing climate change mitigation activities in economic terms, a better economic argument to disengage with fossil fuel is needed. This perceived need to decrease reliance on fossil fuels in order to more fully engage in climate change and clean energy may pose a challenge for participants who work for organizations with board members and general membership directly involved in the fossil fuel industry or receiving funding from them. A participant with a wildlife focused organization mentioned that because many of their members are involved in the fossil fuel industry and more regulations can decrease profits of that industry, they are predisposed to not be involved in climate change and clean energy. Additionally, several participants requested more funding for staff who could focus on conducting research on the direct effects of climate change to fish and wildlife populations in Michigan or gathering existing information and publishing it for members. Two participants from different organizations also suggested that if more funding was made available for climate change related projects that align with their organizations' missions, they would be more willing to engage.

The issue of monetary incentives was also brought up in relation to clean energy in several interviews. Participants mentioned that they would be more open to clean energy initiatives such as wind or solar farms if some part of the revenue was used for natural resource conservation. For example, a participant questioned how conservation efforts could financially benefit from clean energy initiatives asking, "Is there going to be money in it for habitat and wildlife?" One statement by a participant is echoed in numerous other interviews, "I don't have a problem with our organization supporting clean energy. But because it's not strongly advocated by our membership and board, I can't push for it if it's to the detriment of our mission. If there is an initiative that could put money into conservation projects, for example if we had lease payments from clean energy go to conservation. Those are opportunities we could support."

Partnerships

Many participants talked about the potential for partnering with other organizations if their goals and objectives lined up, even if they did not necessarily agree on issues relating to climate change. One participant voiced that their organization was very eager to engage in coalition building through finding common ground with other organizations, an idea also supported by another participant who expressed the opinion that "partnerships are our future" This participant even mentioned a partnership they had formed with the Audubon Society, a group once dismissed by the organization for their vastly different focus and mission statement. One participant with a wildlife focused organization said that although "members aren't going to rally around climate change" because the organizations focus was primarily on improving deer habitat through protection of woodlands and replanting native vegetation, "there is no downside in partnering with groups who are doing these activities for the purpose of carbon sequestration"

Information Sources and Terminology

It was clear from the interviews that the source of climate change information and how it was communicated played a big role in the organizations' receptiveness to this information. A participant stated that for their organization's membership to even look at climate change research, it needed to be published in a neutral source that is not "automatically seen as a liberal mouth piece." Another participant expressed that if the right person presented this type of information it might "peak the interest" of members. A different participant echoed this belief with their opinion that for members to listen to information on climate change "the message has to come from people they trust." Many of the people interviewed shared thoughts on the source that was best-suited to address their organization. These suggestions were divided along focal species for the most part with fisheries-focused groups advocating for Michigan Sea Grant (MSG) to present climate change research. Michigan Sea Grant is part of a network of over 30 university-based programs throughout the country run through the National Oceanic and Atmospheric Administration (NOAA). The mission of Michigan Sea Grant is to promote better understanding of Michigan's coastal resources and foster science-driven conservation of these resources. However, wildlife-focused groups advocated for the Wildlife Management Institute (WMI) to present climate changes research. The Wildlife Management Institute is a professional conservation organization that works to improve the professional foundation of wildlife management. WMI is involved in a range of issues from policy, to research to educational efforts, all with the goal of supporting the wise use of wildlife. Finally, Michigan State University was also explicitly recommended by several participants as a trusted information provider.

Because terminology is a crucial consideration when communicating about divisive issues like climate change, we asked participants about the terminology they use to discuss climate change and clean energy (CRED, 2009). A participant said their organization was focused on "increasing people's vocabulary gradually" and "being very careful to make sure anything we do to communicate about [climate change] doesn't put people off. If people stop reading our material we can't change their minds." This participant also thought it may be easier to talk about clean energy than climate change because clean energy is a more solution-based discussion whereas "it's hard to play a tangible role in global issues like climate change." When asked what terminology a participant with a wildlife focused organization used when discussing climate change they stated that it depended on the audience and could include "extreme weather, sea level rise, or clean energy, but we generally don't lead with the term climate change."

Recommendations

The purpose of these in-depth interviews was to develop a richer understanding of where conservation organizations stand on the issues of climate change. Using this format, participants had a chance to express how engaged their organizations were currently in climate change issues, highlight barriers to engagement, and describe novel opportunities for increased engagement. Based on the barriers and needs that emerged from these interviews, we have complied a list of recommendations for conservation organizations. This list is not exhaustive but it addresses some of the most common requests.

1. Support research that characterizes effects of climate change on Michigan's fish and wildlife populations.

A request we heard from every participant was for research conducted at the local, regional and state level on how climate change is currently impacting Michigan's fish and wildlife populations and how it will affect them in the future. In some cases, participants understood that this information may already exist, but expressed that they did not have the time or money to find it and deliver it to their members. In other cases, participants believed the research they wanted had not yet been conducted and requested it.

2. Provide funding or monetary incentives for increased support of climate change and clean energy.

Funding was mentioned by several organizations as a barrier to engagement. Numerous participants suggested that resources should be provided for regularly collecting and disseminating climate change information specific to Michigan. Additionally, several participants expressed a willingness to engage in climate change mitigation if funding was available for on-the-ground projects that aligned with their organization's mission. In terms of clean energy, a variety of participants conveyed a desire to see monetary incentives for natural resource conservation coming from clean energy projects.

3. Increase opportunities for organizations to partner with groups currently engaged in climate change mitigation.

The formation of partnerships with the goal of increasing capacity to carry out organizational missions through pooled resources and people-power was a major focus of the interviews. Several participants indicated that they would be willing to partner with organizations who were currently engaged in climate change initiatives if the outcomes benefited their organization, even if motivations differed. Other participants were eager to discuss current and future collaborations with other organizations.

4. Choose the right terminology and messenger to deliver information on climate change

Our findings illustrate the importance of choosing the right language and messenger or organization to convey climate change information to conservation groups in the state. Given that these topics can be politically divisive, choosing a neutral or trusted source to relay this information may have a positive effect on the receptivity of the audience. Several participants explicitly named organizations they felt would be the best conduits of information to their members. Fishing organizations pointed to Sea Grant, an organization focused on promoting better understanding of Michigan's freshwater resources, while wildlife organizations pointed to the Wildlife Management Institute, an organization focused on improving wildlife management. Additionally, several conservation organizations said they trust Michigan State University as a neutral conveyer of scientific information on climate change.

5. Hold a symposium for conservation organizations about climate change in Michigan

Our final recommendation is to hold a symposium. The goal of this symposium would be to encourage prominent conservations organizations throughout Michigan to increase their engagement in the issues of climate change by presenting Michigan-focused research on the direct effects of climate change on natural resources, presenting funding opportunities to increase participation in climate change mitigation projects, and bringing organizations together to form new collaborations. Based on our findings we recommend this symposium be hosted by Sea Grant, the Wildlife Management Institute and Michigan State University. The symposium would address many of the needs participants expressed and potentially reduce some of the barriers to engagement in these critical issues.

CONCLUSION

Collectively, we found that while Michigan conservation organizations vary in their current engagement with climate change issues and in their willingness to increase engagement with their membership depending on perceived barriers, interest in receiving more information on how climate change will affect the state's fish and wildlife populations was unanimous. This interest in climate change research could indicate potential future willingness to support climate-friendly policies and actions. To increase membership engagement in climate change issues we recommend that organizations not only provide up to date information about the effects of climate change on Michigan fish and wildlife species to their members, but also that they select the right mechanism and messenger to deliver this information, in addition to increasing funding or monetary incentives for these issues as well as partnering with groups that are currently involved in these issues. Overall this study was an important initial first step in understanding how conservation organizations engage in the issue of climate change and will ultimately be useful for their work protecting, managing, and restoring fish and wildlife populations under a changing climate.

APPENDICES

APPENDIX A.1

TABLES

Table A.1.1 Interview questions.

Question	Possible answer
1. Where does climate change rank in importance to you personally? 2. Where does it rank for your board of directors? 3. Where does it rank for your members?	Very important (5), Somewhat important (4), Neutral (3), Somewhat unimportant (2), Unimportant (1)
4. Does your organization have an official policy statement about climate change?	Open ended
5. How does your organization react when climate change issues are discussed?	Open ended
6. Do you use the terminology climate change. If not what terminology do you use to discuss these issues? For example is it easier to talk about clean energy?	Open ended
7. Do you publish any articles or distribute any information about the impacts of climate change to your members or the public? If so where do you publish?	Open ended
8. Are there any recent successes your organization has had in mitigating the impacts of climate change? This can include policy initiatives, on the ground restoration, or educational outreach.	Open ended
9. What do you believe are the barriers preventing your organization from being more actively engaging in public conservations and policy debates around climate change?	Open ended
10. What information do you feel your organization needs to be more engaged in climate change action? Such as scientific studies or models predicting the effects of climate change, current policies, laws and regulations regarding climate change, member views on climate change.	Open ended
11. Do you have access to this information?	Open ended
12. Does your organization attempt to engage multiple perspectives in climate change discourse?	Open ended
13. Please rank the following from most important barrier to least important barrier for your organization to engage in climate change activities.	**1.** The mission or values of your organization. **2.** The views and priorities of your members. **3.**The views and priorities of your board. **4.** Lack of research and information on climate change. **5.** Political constraints. **6.** Funding sources. **7.** Other.
14. Is there anything we didn't cover that we should know?	Open ended

Table A.1.2. Organizations represented in the study, the acronym of the organization, and organization affiliation with either the Theodore Roosevelt Conservation Partnership (TRCP) or the American Wildlife Conservation Partners (AWCP).

	Organization	Acronym	Partnership
National			
	Bass Angler Sportsmen's Society	BASS	TRCP
	Ducks Unlimited	DU	TRCP/AWCP
	National Wild Turkey Federation	NWTF	TRCP/AWCP
	National Wildlife Federation	NWF	TRCP/AWCP
	Ruffed Grouse Society	RGS	TRCP
	Safari Club International	SCI	AWCP
	Trout Unlimited	TU	TRCP
	Pheasants Forever	PF	TRCP/AWCP
	Quality Deer Management Association	QDMA	TRCP/AWCP
State			
	Michigan Charter Boat Association	MCBA	
	Michigan Steelhead and Salmon Fishers Association	MSSFA	
	Michigan United Conservation Clubs	MUCC	

Table A.1.3. Number of participants with different job titles from conservation organizations represented in the study.

Title	Number of participants
Executive Director	3
Director	3
President	4
Vice President	1
Regional Representative	1

Table A.1.4. List of themes developed from interview analysis including how the theme is defined and examples of positive and negative responses of participants.

Theme	Definition	Positive response example	Negative response examples
Political involvement	If the organization is currently involved in climate change politics or is willing to increase involvement	"Our lead organization policy statement calls for federal legislation to address carbon pollution on a national, state, and regional level."	"Our organization tends not to have a lot of broad policy issue statements….we are focused more on habitat creation."
Organizational focus	How the participant believes the organization's mission or focal species will be effected by climate change	"We work with cold water fish, we have a poster child species to worry about that is highly affected by climate change"	"Because it's not strongly advocated with our membership and board I can't push for [climate change engagement] if its to the determinate of our mission."
Type of organizational engagement	Organizational involvement in outreach and education, ecological restoration or political advocacy	"For years we have supplied our affiliates with climate change information."	"…we have not tried to facilitate any common perspective of the hunting and fishing community on climate change."
Member diversity	Age, gender and ethnic diversity of organization members	"If increasing engagement in climate change would draw new, younger members we would do anything and everything to support those issues."	"Our membership is mostly white and older male and have never expressed a desire to be involved in climate change issues."
Member political views	Membership political affiliations	"…we have a broad agenda and work closely with both sides of the [political] aisle." "I believe we have an equal number of Republicans and Democrats."	"We found that engagement broke down along party lines. Democrats are happy to be involved, Republicans thinks it's ridiculous. If you look at public opinion research the thing that shapes climate change views is your party."
Member education	The amount of education members have about climate change	"We have very discerning member, they need to dig into [the research] of these issues. Building the knowledge base over the long term is critical."	"Most of our members aren't aware of the fact that streams are warming and we may not be able to catch steelhead."

Table A.1.5. List of participants responses detailing needs to increase organizational engagement in climate change.

Organization	Needs
National Wildlife Federation (NWF)	
	- There are research gaps including local and regional forecasting of climate change effects. "We want to know how climate change is specifically effecting the Great Lakes" The modeling and forecasting has not been reliable enough or on a local enough scale.
	- We need funding for staff that are dedicated to tracking Michigan specific research and reporting on it.
Trout Unlimited (TU)	
	- We need to integrate more climate change predictions including temperature change (air-water) into restoration planning to build climate change adaptability.
	- We want more tangible, local examples of the direct effects of climate change on Michigan streams.
	- Member education is a priority for our organization. We want to be able to communicate information about climate change in a way members will understand and support. We could update publications like seasons end.
	- Funding and resources are limited, therefore we have to prioritize our activities.
Michigan United Conservation Clubs (MUCC)	
	- We need Michigan focused research on focal species such as deer, turkeys and grouse.
	- We want to trend lines that represents change in weather and climate patterns over time correlated with 5 major wildlife diseases. Maybe also with invasive species, plants or insects.
Quality Deer Management Association (QDMA)	
	- We need information that shows a direct relationship between climate change and impacts on wildlife habitat.
	- Research on EHD is available, we want more information on CWD.
Michigan Charter Boat Association (MCBA)	
	- Gather information on climate change impacts on Michigan Great Lakes like water levels and invasive species
	- Blow days research (how many days weather conditions allowed for boats to be out on the Lakes fishing)
Michigan Steelhead and Salmon Fishers Association (MSSFA)	
	- We are interested in building coalitions through common interests, our voices are stronger together.
	- We want someone to package information with direct links between water level, temperature, thermocline and climate change. How these result in local impact (such as adjusted fishing methods)
	- We want information on how MI is involved in water use, allocation, Great Lakes regional summit and aquaculture.

Table A.1.5. (cont'd).

Ducks Unlimited (DU)	
	- We want more Mallard research. We have some data related to peak migration dates and nesting times and how warmer temperatures result in earlier nests and people respond well to this local data.
	- We want more local Michigan research and funding for staff that can provide this. We don't invest in doing this ourselves but if this kind of information is provided we would use it.
Bass Angler Sportsmen's Society (BASS)	
	- We need climate change information to come from a neutral source, not something perceived as liberal or it will be ignored (e.g., Fishingwire).
Safari Club International (SCI)	
	- We trust WMI (Wildlife Management Institute) and want them to deliver climate change information
	- We want information on the how clean energy business and policy can benefit fisheries and wildlife.
Ruffed Grouse Society (RGS)	
	- We already have some information on woodcock routes and stop over sights.
	- We need data that would help us decide if we should change hunting seasons based on shifts in migration timing
	- We could also use data on how climate change affects Aspen cover and snow cover.
National Wild Turkey Federation (NWTF)	
	- We need someone to gather and distribute climate change information.
	- We would be open to seminars because we try to keep membership engaged through different avenues.
	- Partnerships are a priority for us so we can pool resource for higher impact projects.
Pheasants Forever (PF)	
	- We want information that will demonstrate how climate change is going to impact grassland habitat and pheasants. Is there data that show climate change current and future impacts to ground nesting birds?
	- Water issues are of great importance to the organization, if clean energy is linked to water issues that could be impactful to members.

APPENDIX B.1

FIGURES

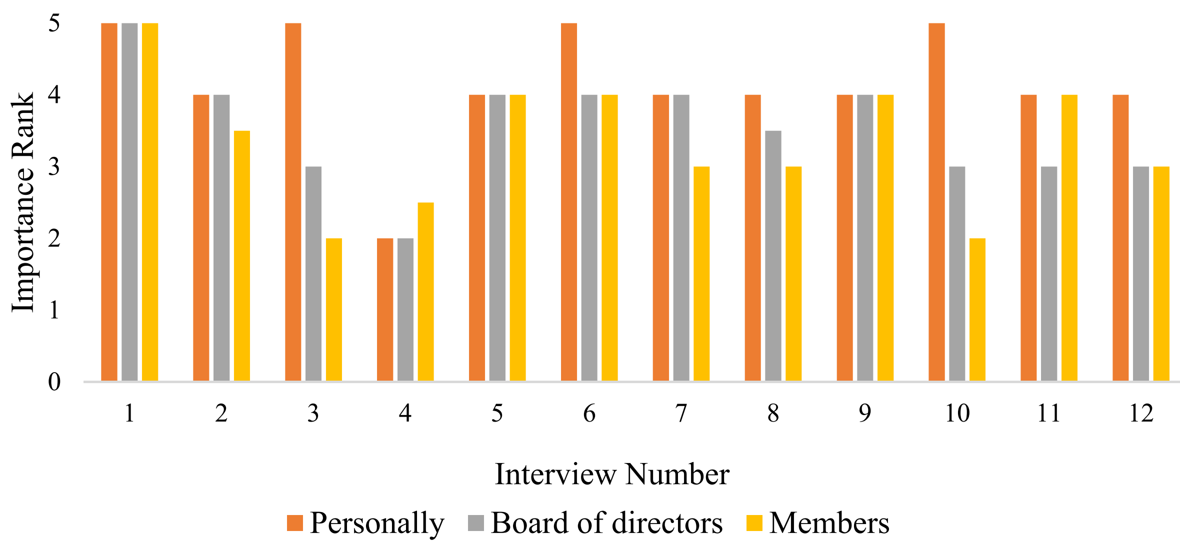

Figure B.1.1 Participants rankings on the importance of climate change to them personally (orange), to their organization's board of directors (gray), and to their organization's members (yellow). Rank are as followed: Very important (5) Somewhat important (4) Somewhat important-neutral (3.5) Neutral (3) Neutral-Somewhat unimportant (2.5) Somewhat unimportant (2) Very unimportant (1). N=12.

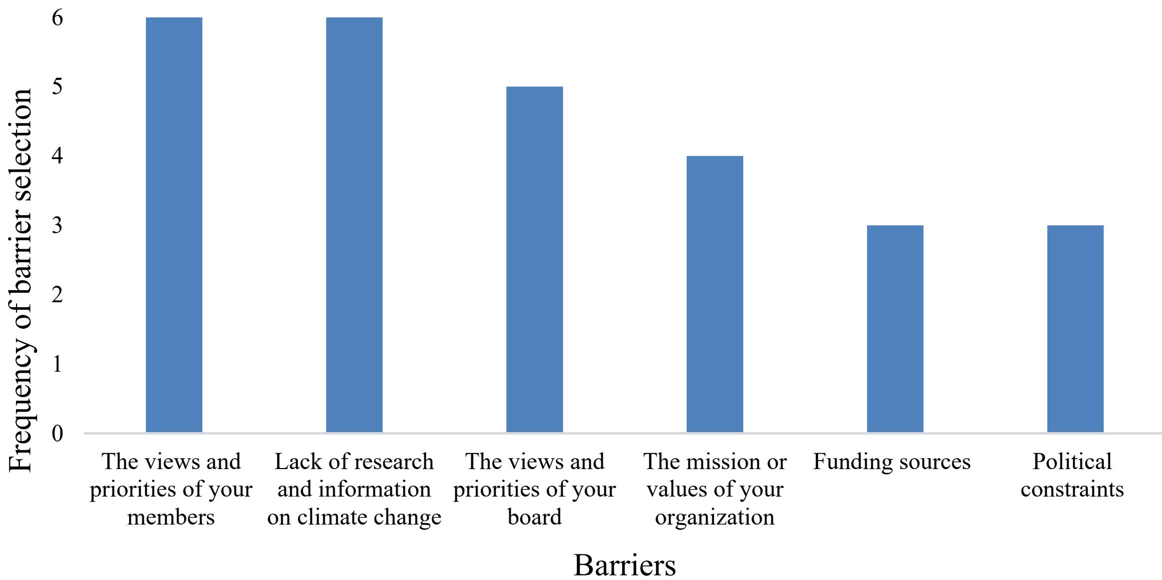

Figure B.1.2. Barriers that participants felt posed the biggest challenge to their organization increasing its involvement in climate change. Participants could mention more than one barrier.

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CHAPTER 2: CHARACTERIZING RESILIENCE OF STREAMS UNDER A CHANGING CLIMATE: IMPROVED INFORMATION FOR CONSERVATION OF FISH HABITAT

ABSTRACT

Michigan stream habitats and fishes they support are ecologically, economically, and culturally important, yet they are increasingly threatened by changing climate. To effectively prioritize actions to conserve streams into the future, natural resource managers need information on how resilient stream habitats and the fish they support may be to changes in climate. To address this need, the goal of this study was to estimate the resilience of fish habitat in Michigan streams to changing climate. Ecosystem resilience is a multi-faceted property affected by a variety of physical and biological habitat features, and because of this, our first objective was to identify a set of landscape-scale and habitat variables that may promote resilience. We then created four sub-indices to characterize different aspects of resilience including natural landscape factors and anthropogenic stressors within stream catchments and length of connected habitat and habitat heterogeneity within patches. These sub-indices were calculated separately to allow for the identification of specific factors that may be driving down the resilience of a stream and that may be addressed by natural resource managers, including fragmentation of habitats by dams or anthropogenic land uses in catchments. Finally, we integrated individual sub-indices into one cumulative resilience score to show a composite estimate of stream resilience. Results from our study show that while stream resilience based on natural factors varies across the state, resilience as influenced by anthropogenic stressors decreases from north to south. Additionally, both length of connected stream habitat within patches and heterogeneity of habitat within patches varies across the state. Lastly, our results show that while cumulative resilience is generally higher in the UP and NLP, resilient streams

are also found in the SLP suggesting that managers have opportunities in every part of the state for protecting or improving stream resiliency to changing climate. Collectively, these findings are the first state-wide assessment of the resilience of Michigan streams to changing climate, providing natural resource managers with novel information that can aid them in implementing actions that mitigate effects of changing climate on stream habitats and the fishes they support.

INTRODUCTION

Michigan stream habitats and the fishes they support are ecologically, economically, and culturally important, yet they are increasingly threatened by climate change. Over the last century, the Great Lakes region, including the state of Michigan, has experienced a 0.9°C increase in mean annual temperature and an almost 10% increase in precipitation (USGCRP 2018, Wuebbles et al. 2019). Furthermore, a recent study by the IPCC predicts that annual temperature will continue to increase 0.2°C with each subsequent decade through the current century (IPCC 2018). These changes in climate will change stream habitat factors including flow and thermal regimes, water chemistry, channel morphology, and substrate, ultimately affecting stream biota and the region's valuable fluvial fishes (Ciruna and Braun 2004, Allan 2004). Considering that recreational angling contributes over two billion dollars annually to Michigan's economy (Calantone et al. 2019), conserving stream habitats and fish supported by those habitats with changing climate are high priorities for the state's natural resource management organizations.

Currently, natural resource managers in Michigan have implemented multiple practices to protect fishes from on-going threats including human land uses and overfishing, with examples of actions including restricting urban and agricultural development in select locations and limiting fishing in priority watersheds (Zorn 2018). However, much less has been done to protect fishes from the threat of climate change. To do so would require information on how stream habitats and their fish communities may change with changes in climate, as well as information on how habitats may be resilient to anticipated changes. To date, observational studies that document responses of fishes to changing climate (e.g., Hari et al. 2006, Isaak et al. 2010, Ward et al. 2015) and predictive studies that model anticipated impacts of climate change on freshwater habitats (e.g., Herb et al. 2016, Van Zuiden et al. 2016) are two types of information that mangers can use to better understand how streams may change with changing climate. However, such efforts do not specifically address a stream's ability to resist those changes in habitat that may occur with changes in climate.

Ecological resilience can be defined as an ecosystem's ability to either resist changes or reorganize after disturbance while still maintaining current structures and functions (Holling 1973, Walker et al. 2004). The ability of an ecosystem to continue to support various ecosystem services after disturbance could be of particular interest to natural resource managers who could use such information to identify locations to protect and/or restore to prepare for a changing climate. However, quantifying resilience is a complex task given the fact that varied biological and physical features and processes of an ecosystem can contribute to its resilience (Davidson et al. 2013, Hilderbrand and Utz 2015). In this way, resilience is similar to the concept of biotic integrity, which is a measure of ecosystem condition relative to its condition in the absence of human disturbance. One way in which biological integrity is assessed is by considering various biological attributes of ecosystems that may contribute to overall ecosystem health (Karr et al. 1986). To measure biological integrity of a specific system, Karr and others proposed considering multiple characteristics of a system's biological assemblages as a way to determine overall integrity. Metrics could include estimates of species richness, taxonomic composition, tolerance to stressors, and/or prevalence of disease, with overall system condition based on existing, regionally-specific knowledge of how key metrics respond to disturbances (Karr et al. 1999). Ecosystem resilience could be assessed in a similar manner by using a range of biological and physical metrics that describe major components of resilience and combining those metrics into a single resilience score.

To assess resilience of stream habitats, using landscape-scale data (along with stream habitat data) may be an effective framework to identify the important and diverse factors that contribute to resilience. First, because streams are hierarchical systems, with stream reaches affected by the catchments they drain, landscape factors can be used to estimate in-stream habitat conditions as well as fish assemblage characteristics (Frissell et al. 1986, Wiens 2002, Allan 2004). Additionally, specific variables characterizing different features of the landscape can be grouped in a variety of ways such as by scale or type to assess different components of stream resilience, depending on the focus of managers. Finally, recent advances in geographic information systems (GIS) technology coupled with increases in availability of landscape-scale datasets across large regions can contribute to development of regional resilience maps (Wang et al. 2006). Such a large-scale assessment of resilience conducted in a consistent and comprehensive manner would allow managers to identify patterns in sources of vulnerability in streams, providing information that would be helpful in prioritizing management actions.

To ensure that natural resource managers have the information they need to effectively manage streams and the fish they support under a changing climate, the goal of our study was to estimate the resilience of fish habitat in Michigan streams to changing climate. Our first objective was to identify a set of landscape-scale and habitat variables that may promote resilience of stream fish habitats; because we were working to create a statewide assessment, variables had to be available for all streams in Michigan. Building from the first objective, our second objective was to use resilience variables to create sub-indices that characterize different factors that contribute to system resilience. These sub-indices highlighted specific characteristics of systems that may promote system resilience and aid in understanding how habitats may be most strongly affected by changes in climate. Our final objective was to combine sub-indices into a cumulative index to broadly represent resilience of Michigan streams and describe patterns in resilience across the state. Outcomes from this effort offer natural resource managers critical information about stream resiliency that could ultimately assist them in prioritizing actions to take to mitigate effects of changing climate on stream habitats and the fishes they support.

METHODS

Study Region

This study was conducted in the state of Michigan which covers a total area of 250,493 km^2 and includes over 58,000 kilometers of streams (Zorn 2017) (A.2.1). Across this large region, landscape features that influence physical and biological characteristics of streams vary. For example, while the Northern Lower Peninsula (NLP) and Upper Peninsula (UP) are sparsely populated and dominated primarily by forests, the Southern Lower Peninsula (SLP) is more densely populated and includes comparatively more urban and agricultural land use (NLCD 2001, Wang et al. 2008). Additionally, streams in Michigan have been heavily influenced by historical glacial activity. Glaciation and lacustrine deposition have resulted in a unique distribution of coarse and fine surficial geology contributing to many cold, groundwater-fed streams in parts of the UP and NLP in addition to cool and warm water streams throughout the state (Farrand and Bell 1982, Zorn et al. 2008). Finally, while elevation does not vary substantially in Michigan compared to other regions (173 m – 603 m above sea level; NED

2005), variation in stream gradient leads to differences in stream power, sediment transport, and deposition, affecting channel morphology, substrate and grain size statewide (Rosgen 1994). Overall, these natural and anthropogenic landscape features have contributed to a variety of different stream habitats which support diverse fish assemblages throughout Michigan.

Spatial Framework

The 1:100,000 National Hydrography Dataset Plus Version 1 (NHDPlusV1) was used to characterize the streams assessed in this project (NHDPlus 2008). Stream reaches are the basic unit of our spatial framework and are defined as stream sections extending from stream origins to stream confluences, stream confluences to stream confluences, or stream confluences to terminal outlets (e.g. lakes, Wang et al. 2011). All stream reaches have defined local catchments (i.e., land areas that drain directly to reaches) and local buffers (i.e., 90 m area of land on either side of stream reaches). Additionally, information can be summarized within the network catchment or network buffer (i.e., cumulative land area draining into a given local catchment or local buffer, respectively) through aggregation coding developed by Tsang and others (2014). An additional unit in our spatial framework was defined by Cooper et al. (2017) who used dam locations to split stream reaches where dam locations did not already coincide with a reach confluence in the NHDPlusV1. This work resulted in the identification of discrete sets of stream reaches bound by large dams, small dams, and waterfalls, termed "patches." Collectively, patches represent unfragmented subdivisions of the stream network and terrestrial landscape draining to the network occurring throughout Michigan (Cooper et al. 2017; B.2.1).

Index Creation

We created four sub-indices to describe the resilience of Michigan stream fish habitats to changing climate (B.2.2). Two were specific to stream reaches and characterized effects of natural landscape factors and anthropogenic stressors on resilience of stream habitats (A.2.1). The remaining two indices were specific to patches (A.2.2). The connectivity index described the total length of connected stream reaches in a patch, while the heterogeneity index assessed diversity of various stream habitat characteristics within the patch including reach gradient, water temperature of individual reaches, and network catchment area drained by reaches. Our final cumulative resilience index was developed by summing all sub-index scores into one cumulative score for each stream reach in Michigan (B.2.2).

Natural and Anthropogenic Stressor Variables

We initially selected 27 ecologically relevant landscape variables (i.e., 14 natural and 13 anthropogenic variables) to consider for creation of sub-indices (A.2.1). Variables were obtained or developed from a variety of data sources over multiple spatial extents. Local catchment area included the land draining directly to a given stream reach, and network catchment area was calculated by aggregating the area of all local catchments occurring above a given reach (Tsang et al. 2014). Surficial geology data were obtained from Farrand and Bell (1982, https://ngmdb.usgs.gov/Prodesc/proddesc_71889.htm) and used to create summaries of both coarse and fine geology in catchments. Coarse geology, summarized in both local and network catchments, includes the sum of all geologic types with a hydraulic conductivity greater than 5.0 m/day including ice contact, coarse end-moraines, coarse outwash, dune sand, lacustrine deposits, and alluvium. Fine geology, also summarized in both local and network catchments, includes the sum of all geologic types with a hydraulic conductivity less than 5.0 m/day including exposed bedrock, fine end-moraine, lacustrine clay and silt, fine glacial till and water. The base-flow index was developed by the United States Geological Survey (USGS) and is defined for each stream reach as the ratio of base flow (defined as the component of streamflow that can be attributed to groundwater) to total flow *100 (http://water.usgs.gov/GIS/metadata/usgswrd/XML/bfi48grd.xml). Elevation data were obtained from the NHDPlusV1 and National Elevation Dataset (NED) 2005 (http://nationalmap.gov/elevation.html). Mean elevation of network catchments was calculated by averaging all elevation data in local catchments draining to a given reach. Natural land cover data are from the National Land Cover Dataset (NLCD) 2006 (https://www.mrlc.gov) and were used to create the forest cover composite variables. Forest cover, summarized in the local and network catchments and local and network buffers, include the sum of all land cover types with greater than 20% deciduous, evergreen, and mixed forest and woody wetlands. Land use data were also obtained from the NLCD and used to create both the agricultural land use and urban land use composite variables as well as the impervious surface variables (NLCD 2006). Agricultural land use, summarized in local and network catchments and buffers, includes pasture/hay and cultivated crop land cover. Urban land use, summarized in local and network catchments and buffers, includes developed open space and low intensity, medium intensity, and high intensity developed land cover. Impervious surface, also summarized in local and network catchments and buffers, includes the total amount of impervious surface. Water use data assembled by the Environmental Protection Agency (EPA) and the USGS were used to create the composite variable total water withdrawal (http://water.usgs.gov/watuse/data/2005/index.html). Total water withdrawal was summarized only in network catchments and includes agricultural, domestic, industrial, and thermoelectric water withdrawals.

We followed multiple steps to reduce the initial set of 27 variables to identify a parsimonious set for characterizing stream resilience. First, we calculated average, maximum, and minimum values for all variables, and we chose to exclude elevation due to its comparatively small range across the study region. Next, variables were tested for linearity, and non-linear variables were transformed using natural log for continuous variables and arcsine square root for proportional variables. Pearson correlations were performed on natural and anthropogenic stressor variables separately, and when highly correlated variables were identified (Pearsons r >0.6), one was retained based on ecological interpretability. Through this step, we eliminated base-flow index and fine geology in favor of coarse geology, and impervious surface was eliminated in favor of urban land use. As a final step, when a single factor was summarized over multiple spatial extents, we chose its summary within the network catchment. The exception to this was our choice of forest cover summarized in the network buffer; we chose this variable because forest cover in the network catchments was strongly correlated with agricultural and urban land use in network catchments. After variable reduction was complete, 3 natural landscape variables and 3 anthropogenic stressor variables were used to create the natural and anthropogenic sub-indices, respectively (A.2.1).

Natural Factor and Anthropogenic Stressor Index Development – Reach Scale

We integrated 3 natural landscape variables and 3 anthropogenic stressor variables into two discrete indices to characterize different contributors to resilience. We began by using the transformed version of the variables (described above). Next, to ensure that high values of both indices represented relatively more resilient habitat, we calculated the inverse of the anthropogenic stressor variables by subtracting each value from the maximum. Next, all variables were rescaled from 0 (minimum resilience) to 1 (maximum resilience) using a max-min linear rescaling method $[x_i - x_{min}]/[x_{max} - x_{min}]$) following Allan et al. (2013). The resulting continuous, unitless scale allowed for direct comparison of all variables whose original units vary widely. This approach follows previous studies which use simple linear rescaling of all variables to retain quantitative spatial information (Allan et al. 2013, Cooper et al. in press). Finally, all 3 natural variables were summed to create the natural factor sub-index; and all 3 anthropogenic stressor variables were summed to form the stressor sub-index. Both indices were grouped into quartiles to visualize results.

Connectivity Index – Patch Scale

Barriers including large dams, small dams, and waterfalls may limit access of stream fishes to spawning and feeding grounds (Pringle 2001). Because of this, we considered the length of connected stream miles between barriers as a measure of connected habitat, with more habitat suggestive of high resilience. This measure was obtained from Tingley et al. (In Prep) following Cooper et al. (2017). The connectivity index was created using a similar approach as the natural and anthropogenic stressor indices. First we calculated average, maximum, and minimum values to evaluate the range in stream length within patches across the state. Next, we natural log transformed values, and then rescaled them from 0-1 following the max-min linear rescaling approach described above. Finally, we grouped the values into four classes (based on quartiles) to create the connectivity index reflecting low, medium-low, medium- high, and high resilience based on available habitat within patches.

Heterogeneity Index – Patch Scale

We quantified the variation in gradient, size, and thermal classes of stream reaches within patches to assess habitat heterogeneity of patches (Nichols et al. 1998, Massicotte et al. 2014). These variables were selected because of their influence on stream habitats and fish assemblages (e.g., Vannote et al. 1980, Rosgen 1994, Zorn et al. 2008). Reach gradient, summarized at the stream reach scale, was calculated as the m of drop in elevation per m of stream reach length (m/m)*100 using information from the NHDPlusV1 and National Elevation Dataset (NED) (http://www.horizon-systems.com/NHDPlus). We then assigned reaches to classes based on gradient following Olivero and Anderson (2008) who presented a classification of gradient based on relationships between gradient and distributions of rare stream biota in the northeastern U.S. We chose to use this classification because natural landscape conditions are similar between the northeast and our study region (Crawford et al. 2016). Gradient of stream reaches less than 0.02% are classified as very low gradient, 0.02 to 0.1% are low gradient, 0.1 to 0.5% are moderate to low gradient, 0.5 to 2% are moderate to high gradient, 2 to 5% are high gradient, and greater than 5% are very high gradient. Temperature class data were obtained from Zorn et al. (2008) who assign reaches to classes based on modeled July mean water temperatures and general thermal preferences of cold, cool, and warm water fish species in Michigan (https://www.researchgate.net/publication/249008702). Following this approach, streams are classified into cold (July mean water temp ≤ 63.5 F (17.5°C)), cold-transitional (July mean water temp >63.5°F (17.5°C) and ≤67°F (19.5°C)), warm-transitional (July mean water temp >67°F (19.5°C) and ≤70°F (21.0°C)), and warm (July mean water temp >70°F (21.0°C)) categories. Finally, network catchment area of reaches comprising patches (calculations described previously) was chosen because large stream systems are more likely to have more diverse habitats leading to greater habitat heterogeneity and species diversity (e.g., Wang et al. 2006, Cumming et al. 2011.) We followed Wang et al. (2011) to assign streams into size categories. Streams less than 10 km^2 are classified as headwaters, 10 to 100 km^2 as creeks, 100–1,000 km^2 as small streams, 1,000–10,000 km^2 as medium streams, and 10,000–25,000 km^2 as large streams.

After each variable was assigned to categories, the number of different categories per patch were tallied to produce a measure of heterogeneity for each factor. To capture gradient heterogeneity, patches with only one category of gradient scored a 0, patches with two categories scored a 0.2, patches with three categories scored a 0.4, patches with four categories scored a 0.6, patches with five categories scored a 0.8, and a patch with all six different gradient classes was scored a 1 (A.2.3). To capture temperature heterogeneity, patches with only one temperature class scored a 0, patches with two types of temperature classes scored a 0.33, patches with three types of temperature classes scored a 0.67, and patches with all four types of temperature classes scored a 1 (A.2.4). To capture stream size heterogeneity we scored patches with only one stream size a 0, patches with both headwaters and creeks scored a 0.2 given their ecological similarity, patches with any other combination of headwaters or creeks and a larger stream size class a 0.4, patches with three size classes scored a 0.6, patches with four size classes scored a 0.8 and patches with all five stream size classes present scored a 1 (A.2.5). Finally, all 3 variables were summed together to form the heterogeneity index for the patch. Once the patch score was calculated that score was applied to each stream reach in the patch to calculate the cumulative score.

Cumulative Resilience Index Development /Mapping

Our final cumulative resilience index was developed by summing all sub-index scores (natural, anthropogenic stressors, connectivity, heterogeneity) into one cumulative score for each of the 40,201 stream reaches in Michigan (B.2.2). In this way, the variables comprising individual sub-indices each contributed equally to the overall score. These scores range from a theoretical minimum of 0 to a maximum of 10, with high scores representing high stream resilience and low scores representing low stream resilience. We then categorized each score into quartiles including high (100-75%), medium-high (75-50%), medium-low (50-25%) and low (25-0%).

Analysis

After indices were created, results were mapped in ArcGIS to visualize spatial patterns. We also created summaries of the sub-index scores and cumulative resilience score in the UP, NLP, and SLP to further investigate regional trends. Finally, to gain additional insights that could prove useful for identifying specific management actions to protect or improve resiliency under changing climate, we identified the top 25% of streams based on cumulative resilience scores. Of those streams we then identified those that fell in the bottom 50% for the connectivity score and the bottom 50% for the anthropogenic stressor score. This gave us insights into where managers could address habitat fragmentation and anthropogenic stress in the catchment as strategies for increasing overall system resilience to changing climate.

RESULTS

Natural Factor Sub-Index

The natural factor sub-index is comprised of 3 landscape-scale variables that vary widely across the state. Catchment areas of stream reaches are right-skewed (B.2.3), indicating that the majority of streams drain small areas of the landscape. Larger catchment areas are less common, aligning with locations of mainstems of major streams. Coarse geology is less skewed than catchment area but reflects extremes in conditions; many streams have catchments lacking any coarse geology while others have catchments comprised entirely of coarse geology (B.2.3). Values vary throughout the state, with high percentages of coarse geology in both the eastern and western UP, NLP, and the southeastern portion of the SLP (B.2.4). Finally, forested land cover in the network buffer is dominated by low values indicating that very few streams have fully forested buffers in Michigan (B.2.4). Values are lowest in the SLP and generally highest in the UP, which is primarily dominated by a mixture of deciduous and evergreen forest as well as woody herbaceous wetland (B.2.4). The resulting natural factor sub-index scores vary greatly throughout the state. The UP, northeastern NLP and southeastern SLP have relatively higher natural factor scores, while the southwestern portion of the SLP has lower natural factor scores, suggesting lower resilience to climate change in this part of Michigan (B.2.4).

Anthropogenic Stressor Sub-Index

The anthropogenic stressor sub-index is made up of 3 landscape variables that generally increase from north to south in Michigan. Agricultural land use is slightly left skewed, indicating that many areas of the state have little to no agriculture (B.2.3). Agriculture has strong regional patterns in Michigan; it is much more common in the SLP, with decreasing prevalence in the NLP and UP (B.2.5). While the urban land use variable is highly right-skewed (suggesting few locations dominated by urban land use) (B.2.3), it follows a similar pattern to agriculture in that it is more prevalent in the southern part of the state (B.2.5). Finally, total water withdrawals occur in moderate levels in many watersheds in Michigan (B.2.3). This variable also follows a north-south gradient and tends to be more common in the southern portion of Michigan, corresponding to locations of agricultural and urban land use (B.2.5). The resulting anthropogenic stressor score follows gradients of individual variables; high scores are more common in the UP and NLP and low scores are more common throughout the SLP (B.2.5).

Connectivity Sub-Index

The connectivity sub-index was developed from one variable that indicates the length of connected stream miles between barriers as a measure of connected habitat. Connected habitat scores vary throughout the state of Michigan (B.2.3). Connectivity values are slightly rightskewed with the majority of values falling below 0.5. (B.2.3). Small, medium, and large patches occur throughout the UP, NLP, and SLP, however, small patches are somewhat common along the coasts, reflecting locations of smaller watersheds (B.2.6).

Heterogeneity Sub-Index

The heterogeneity sub-index is comprised of 3 landscape-scale variables that vary widely across the state. The majority of catchment area scores fall between 0 and 0.25 indicating that most patches only have 1 or 2 different categories of stream catchment sizes (B.2.3). Similarly, temperature class scores fall primarily between 0 and 0.50 indicating that most patches only have 1 or 2 different temperature classes represented (B.2.3). Finally, gradient is slightly right-skewed but has a more even distribution than the other two heterogeneity variables indicating that patches have a mix of 1, 2, 3, 4 or 5 different gradient classes (B.2.3). While the composite heterogeneity score varies across Michigan, lower scores tend to be concentrated along the costs, reflecting smaller watersheds that are less likely to include heterogeneous habitats (B.2.7).

Cumulative Resilience Score

The cumulative resilience score is comprised of scores from all 4 sub-indices, and scores vary regionally (B.2.8). The UP includes many high and medium-high resilience streams, with few medium-low to low resilience streams. The NLP also includes many high and medium-high resilience streams, with a group of low resilience streams near the east coast which extend southward throughout the thumb in the SLP. While the SLP has a greater occurrence of medium-low and low resilience streams in general, there are high and medium-high resilience streams also occurring throughout the region (B.2.9).

Identifying Areas for Specific Management Actions

Nearly 30 percent of stream reaches with a high or medium high score for the natural landscape index were found in the UP and NLP, while 36.5% of stream reaches with a low or medium-low score were found in the SLP (A.2.6). Additionally, 46.4% of all reaches with a medium-low or low anthropogenic stressor score were found in the SLP, while 41.9% of reaches scoring high or medium-high were found in the UP and NLP, with only 4% of all streams with a medium-low or low score found in the UP or NLP. Connectivity scores were more evenly distributed across all regions, with the SLP containing the highest number of reaches that were part of networks with high connectivity (13.4%). Heterogeneity scores were also somewhat evenly distributed across all regions, but 36.4% of reaches in the state with medium-low or low heterogeneity scores were found in the SLP (A.2.6). Finally, 18.5% of reaches with high or medium-high cumulative resilience were in the UP, 14.7% were in the NLP, and 16.9% were in the SLP, suggesting that resilience river reaches occur throughout Michigan (A.2.6).

The complement the regional analysis, we investigated the top 25% most resilient stream reaches in the state based on the composite score. Within this subset, we then identified river reaches that may be limited by connectivity and anthropogenic stressors because managers could choose to improve resilience by taking specific actions to address these factors. Figure 2.10 shows the subset of stream reaches with high cumulative resilience that are in the bottom 50% of scores based on the anthropogenic stressor index (n=1187). These stream reaches are predominately located in the southeastern portion of the SLP. If managers prioritize reducing effects of stressors through actions such as restoring forested buffers or reducing agricultural and urban runoff, these streams could become highly resilient to changes in climate. We also identified stream reaches with cumulative resilience scores in the top 25% and connectivity scores in the bottom 50% and found 2673 streams reach that met these criteria (B.2.10). These stream reaches are found throughout the UP, NLP, and SLP. Collectively, if managers prioritized removal of dams or implementation of fish passage structures, these streams could be more resilient to climate change.

DISCUSSION

Overview

The ability of stream fish habitat to resist changing with changes in climate is affected by multiple catchment landscape and stream habitat factors which collectively contribute to overall system resilience. To assess resilience of all stream reaches in Michigan, we first created multiple sub-indices comprised of these factors to characterize different aspects of resilience including indices characterizing natural landscape factors and anthropogenic stressors within catchments as well as length of connected habitat and habitat heterogeneity within connected patches. Development of these specific sub-indices allows for the identification of specific factors that may be driving down the resilience of streams and that may be addressed by natural resource managers, including fragmentation of habitats by dams or anthropogenic land uses in catchments. Results from our study show that while stream resilience based on natural factors varies across the state, resilience as influenced by anthropogenic stressors decreases generally from north to south. Additionally, both length of connected stream habitat within patches and heterogeneity of habitat within patches varies across the state. By combining individual subindices into one cumulative resilience score, we create a composite estimate of stream resilience. While cumulative resilience is generally higher in the UP and NLP, resilient streams are also found in the SLP suggesting that managers have opportunities in every part of the state for protecting or improving stream resiliency to changing climate. Collectively, these findings are the first state-wide assessment of the resilience of Michigan streams to changing climate, providing natural resource managers with novel information that can aid them in implementing actions to mitigate effects of changing climate on stream habitats and the fishes they support.

Resilience Based On Natural Landscape Factors

Natural landscape factors contributing to resilience of stream habitat to changing climate include network catchment area, coarse geology in network catchments, and forest in network buffers. Catchment area was chosen as a surrogate for stream size because large streams are more likely to have more diverse stream habitats than smaller streams (Allan and Castillo 2007). Diverse habitats support more diverse fish assemblages than are typically found in comparatively more homogeneous habitats (Infante and Allan 2010), and diverse assemblages should be more resilient to changes in climate because more species and individuals comprising an assemblage increase the likelihood that species can persist or can functionally compensate for one another following disturbances (Weins 2002, Chapin et al. 2009). The second variable that we selected was coarse geology in network catchments. Streams with more coarse geology have more stable flows and thermal regimes that aid in buffering against extreme flow events or warming water temperatures expected with climate change in the region (Sear et al. 1999, Snyder et al. 2015). Finally, the third variable chosen was forest cover in the buffer. Forested buffers contribute to more stable stream flows; cooler water temperatures; and reduced runoff, erosion, and sedimentation to stream channels (e.g., Roth et al. 1996, Wang et al. 2003). Given these attributes, streams with forested buffers may be more resilient to extreme flows or warming air temperatures than streams with unforested buffers. By combining these variables into a single sub-index, we can broadly assess how these natural landscape factors collectively contribute to stream resilience to changing climate in Michigan.

Anthropogenic Stressor Sub-Index

Studies show that streams currently experiencing human landscape stressors in their catchments, including agricultural and urban development, commonly have modified habitats and/or biological assemblages compared to similar systems with less disturbance. Because of this, currently-stressed streams may be less resilient to future stress (Hilderbrand and Utz 2015). To explicitly account for the influence of anthropogenic stressors on resilience of stream habitats, we developed a sub-index of anthropogenic stressor factors. The first variable selected was agricultural land use in the network catchment. High amounts of catchment agriculture can lead to increased water temperature; modified stream flows; and greater inputs of sediment, nutrients, and pesticides, all resulting in changes to stream fish habitat (Roth et al. 1996, Kaushal et al. 2010). Urban land use was also considered for this study because, like agricultural land use, urbanization can increase stream water temperatures, destabilize flow regimes by increasing surface runoff, and increase inputs of sediments and toxics to stream channels, leading to altered stream habitat and biological assemblages (Allan 2004). Total water withdrawals in the network catchment was the third variable incorporated into the anthropogenic stressor sub-index. Increased water withdrawals for agricultural, urban, and industrial uses can decrease groundwater input to streams and negatively impact a stream's ability to buffer against rising air temperatures and altered precipitation (Palmer et al. 2008). Together, these stressors collectively reduce stream resilience through habitat degradation and alteration of biological assemblages. However, actions can be taken that reduce effects of anthropogenic landscape stressors on stream habitats. Examples of these actions include implementing forested buffers, enhancing stream habitat, and mitigating surface runoff.

Connectivity Sub-Index

Longer streams networks contain more diverse habitat types than shorter networks. More habitat supports diverse assemblages of species requiring different habitats for feeding, reproduction, refuge, and migration, and assemblages with many species tend to be associated with a more diverse set of functional traits. Following loss of a species, diverse assemblages may have greater likelihood than less diverse assemblages that another species could fill a niche emptied by the lost species, ensuring that ecosystem functions remains similar following disturbances (e.g., Naeem and Li 1997). Additionally, longer stream networks allow for the movement of species to refugia during extreme events contributing the recolonization of habitats after disturbance, ultimately increasing stream resilience to climate change (Pringle 2001, Timpane-Padgham et al. 2017). Based on these principles, we chose total connected stream length in patches to represent connectivity in this study. This is an important factor for managers to consider, because dam removal or implementation of fish passage structures is one strategy that can improve connectivity.

Heterogeneity Sub-Index

Streams with more heterogeneous habitats are more likely to support diverse fish assemblages than streams with more homogenous habitats, ultimately promoting resilience by buffering against habitat degradation and species loss caused by climate change (Forbes and Chase 2002, Mellin et al. 2012). To characterize habitat heterogeneity, we quantified diversity in stream reach gradient, July mean temperature of reaches, and catchment size of reaches comprising patches (Nichols et al. 1998, Massicotte et al. 2014). Gradient is a key factor in determining stream channel morphology, water velocity, sediment transport, and substrate size (Rosgen 1994). Patches with a diversity of different gradient classes will be more resilient to climate change because they offer a range of different habitat types. The second variable, water temperature, exerts fundament control over fish metabolic rate, is a key determinate for fish growth and reproduction, and influences habitat dynamics and habitat ranges (Zorn et al. 2008). Streams with a diversity of temperature classes may be more likely to support a variety of cold, cool, and warm water fish species. Finally, stream size plays a major role in determining aquatic biological assemblages (Vannote et al. 1980). Streams with a diversity of different stream size classes will be more resilient to climate change because they will offer a range of different habitat types. Prioritizing the protection of streams with high habitat heterogeneity may be a strategy managers can employ to promote system resilience to climate change (e.g., Anderson et al. 2013).

Estimating Cumulative Resilience

To effectively manage stream fish habitat in a changing climate, natural resource managers need information on how stream habitat may change with changes in climate as well as information on how habitats may be resilient to anticipated changes. To date, observational studies that document responses of fishes to changing climate and predictive studies that model anticipated impacts of climate change on freshwater habitats are two types of information that mangers can use to better understand how streams may change with changing climate. While we are aware of no observational studies conducted in Michigan documenting effects of changing climate on stream fishes, studies on some of the fish species found in Michigan have been conducted in other regions. For example, Isaak et al. (2010) found that average mean stream temperatures in Idaho increased over a 13 year period, resulting in a loss of Bull Trout *Salvelinus confluentus* habitat in central Idaho. Similarly, Hari et al. (2006) showed that increases in air temperature were associated with reductions in habitat availability for Brown Trout *Salmo trutta* in Switzerland. Finally, a more recent study in the Pacific Northwest by Ward et al. (2015) linked increases in winter stream flow variability with declines in Chinook salmon *Oncorhynchus tshawytscha* reproduction. While observational studies are useful for understanding specific influences of a changing climate on stream fishes and, in some cases, mechanisms by which those changes occur, observational studies describe changes that have already occurred, limiting the ability to pro-actively manage river habitat as climate changes (Lynch et al. 2016). However, predictive models and tools that utilize such models have been developed in the Great Lakes region to assist managers in anticipating future conditions to proactively manage natural resources under changing climate conditions. For example, FishVis (https://ccviewer.wim.usgs.gov/FishVis/) is web-based mapper developed for the Great Lakes region that displays how suitability of stream habitats for 13 priority fish species may change with changes in air temperature and precipitation anticipated to occur under future climate scenarios (Stewart et al. 2016). Fishtail (https://ccviewer.wim.usgs.gov/fishtail/#) is another useful tool that integrates information on current condition of stream fish habitat with predictions of which stream reaches may change in their ability to support their current stream fish assemblages with projected changes in climate. Finally, the Stream Prioritization Tool (SPT) synthesizes current and future stream temperature, relative abundance of trout, and groundwater input information to aid fisheries managers when prioritizing limited conservation funding (Carlson et al. 2019). While such tools account for changes in air temperature and precipitation that may lead to changes in fish and fish habitat, they don't fully account for a streams ability to resist those changes and retain their current structures and functions.

Previous works attempt to describe resilience of streams to changing climate by integrating theoretical principles of stream ecology with those of resilience theory and describing possible outcomes (McCluney et al. 2014, Hilderbrand and Utz et al. 2015). However, we are aware of only one effort that implements a method for comparatively assessing resilience of actual stream habitats. The Nature Conservancy estimated resilience of streams in the Northeast and Mid-Atlantic U.S. (Anderson et al. 2013) as well as in the state of North Carolina (Benner et al. 2014) using similar metrics to our study including amount of connected habitats within a unit comparable to our patches as well as heterogeneity of habitats within those units based on stream catchment size, temperature class, and gradient. They also incorporated amount of impervious surface in catchments of stream reaches (similar to our urban land use variable), as well as metrics that we did not consider including risk of hydrologic alteration to reaches and amount of natural land cover in floodplains of reaches. While TNC showed the utility of their resilience assessment in informing freshwater conservation actions, limitations mentioned in their efforts include the lack of a comparable estimate of groundwater input to stream reaches throughout their study region, lack of waterfalls in their barrier dataset, and lack of water withdrawal data for stream reaches in their study region (Anderson et al. 2013). Our study was able to address these limitation within Michigan by using waterfalls as one type of barrier used to define patches, incorporating groundwater inputs into our natural sub-index, and incorporating water withdrawals into our anthropogenic stressor index. By combining sub-indices into a cumulative resilience score, we provide novel information to managers who can use results to account for a streams capacity to resist change with changes in climate.

Management Recommendations and Next Steps

Regional analysis of sub-index scores identified important patterns that managers can consider when prioritizing conservation actions. Natural factor scores were highest in the NLP, indicating that streams in this area have highly-resilient natural landscape characteristics and may be good candidates for protection. Similarly, anthropogenic scores were lowest in the SLP and highest in the UP indicating that restoration and protection may be the most effective use of conservation efforts in these regions. Connectivity had similar trends in all 3 regions, indicating that there are similar levels of opportunities across the state related to barrier removal or implementation of fish passage. Additionally, heterogeneity scores also had similar trends across the state, indicating that there are options for protection of highly heterogeneous habitats statewide. Finally, although cumulative resilience scores were highest in the UP and NLP, streams with high and medium-high resilience were present in the SLP, suggesting that managers have opportunities in every part of the state for protecting or improving stream resiliency to changing climate.

Future directions for research may include combining results of our resilience assessment with results of predictive models in order to provide managers with a more complete picture of stream habitat and fish assemblage response' to climate change. Additionally, a study that estimates both aquatic and terrestrial habitat resilience could better account for these integrated systems' influences on each other and may illuminate where restoration or protection would lead to improved resilience for both types of systems. Finally, this research could potentially be used to justify additional funding for proactive management of valuable stream ecosystems and fishes, as well increased political support for policies that mitigate climate change.

APPENDICES

APPENDIX A.2

TABLES

Table A 2.1. The 27 variables initially considered for stream resilience analysis. Variables were summarized at five spatial scale: local catchment (LC), network catchment (NC), local buffer (LB), and network buffer (NB). Asterisks (*) indicate the 6 variables selected for creation of sub-indices.

Type	Variable name (unit)	Scale	Definition	Data source
Natural Factors				
	Catchment area (km2)	LC, NC*	Total area draining to stream reach	NHDPlus V1, 2010
	Coarse geology (%)	LC, NC*	Sum of all geologic types with a hydraulic conductivity > 5.0 m/d in catchments	Farrand and Bell, 1982
	Fine geology (%)	LC, NC	Sum of all geologic types with a hydraulic conductivity < 5.0 m/d in catchments	Farrand and Bell, 1982
	Base-flow index	LC, NC	Ratio of baseflow to total flow *100	USGS, 2003
	Mean elevation (m)	LC, NC	Mean elevations in catchments	NED, 2005
	Forest cover (%)	LC, NC, LB, NB*	Sum of all deciduous, evergreen, mixed forest, and woody wetlands land cover	NLCD 2006
Anthropogenic Stressors				
	Agricultural land use (%)	LC, NC*, LB, NB	Sum of pasture/hay and cultivated crop land use	NLCD, 2006
	Urban land use (%)	LC, NC*, LB, NB	Sum of developed open space, low, medium, and high intensity development	NLCD, 2006
	Impervious surface (%)	LC, NC, LB, NB	Sum of impervious surface	NLCD, 2006
	Total water withdrawal (MGY)	NC*	Sum of all water withdrawal (million gallons/year) in the network catchment	EPA, USGS, 2005

Table A.2.2. Patch scale variables that comprise the connectivity and heterogeneity scores and the methods followed to categorize them. All variables were first summarized at the patch scale and then scores were applied at the stream reach scale.

Type	Variable name	Scale	Description	Categories	Data source
Heterogeneity					
	Gradient class	stream reach	Drop in m per m of stream reach	Very low gradient: < 0.02%	NHDPlus V1, 2010, Olivero and Anderson 2008
				Low gradient: >= 0.02 < 0.1%	
				Moderate-low gradient >= 0.1 < 0.5%	
				Moderate-high gradient >= 0.5 < 2%	
				High gradient: >= 2 < 5%	
				Very high gradient: > 5%	
	Temperature class	stream reach	Habitat suitability (catchment size, base flow yield, July mean water temperature) for Michigan's discrete cold, cool, and warm water fishes	Cold: ≤ 63.5 F (17.5°C)	Zorn et al. 2008
				Cold-transitional: >63.5°F (17.5°C) and ≤67°F (19.5°C)	
				Warm-transitional: >67°F (19.5°C) and ≤70°F (21.0°C)	
				Warm: >70°F (21.0°C)	
	Size class	network catchment	Total area draining to stream reach	Head-waters: < 10 km2	NHDPlus V1, 2010, Wang et al. 2011
				Creeks: 10 - 100 km2	
				Small streams: 100 - 1,000 km2	
				Medium streams: 1,000 - 10,000 km2	
				Large streams: 10,000 - 25,000 km2	
Connectivity					
	Connectivity	patch	Length of connected stream reach		USGS, 2013-2017, Cooper et al. 2017

Table A.2.3. Scores applied to patches based on numbers of different gradient classes of stream reaches comprising patches.

Number of classes within patches	Patch score
1	0
2	0.2
3	0.4
4	0.6
5	0.8
6	1

Table A.2.4. Scores applied to patches based on numbers of different thermal classes of stream reaches comprising patches.

Number of classes within patches	Patch score
1	0
2	0.33
3	0.67
4	1

Table A.2.5. Scores applied to patches based on numbers of different size classes of stream reaches comprising patches.

Number of classes within patches	Score
1	0
2 (headwaters and creeks)	0.2
2 (any other combination)	0.4
3	0.6
4	0.8
5	1

Table A.2.6. Percent of stream reaches of all 4 categories of sub-indices and cumulative resilience scores and by region including the Upper Peninsula (UP), Northern Lower Peninsula (NLP), and Southern Lower Peninsula (SLP).

Score Type	UP	NLP	SLP
Natural Score	%	%	%
High	7.6	7.6	5.2
Medium-high	6.9	7.4	12.3
Medium-low	6.4	3.1	12.9
Low	4.8	2.4	23.6
Stressor Score			
High	19.1	4.8	0.5
Medium-high	6	12	7.1
Medium-low	0.4	2.9	22.9
Low	0.1	0.6	23.5
Connectivity Score			
High	3.9	4.9	13.4
Medium-high	5.3	5.4	15.6
Medium-low	7.8	5.1	12.2
Low	8.7	5	12.8
Heterogeneity			
High	7.6	7.4	8.7
Medium-high	6.3	6.3	8.9
Medium-low	3.9	2	18.1
Low	7.8	4.7	18.3
Cumulative Resilience Score			
High	11.9	9	6.1
Medium-high	6.6	5.7	10.8
Medium-low	4.4	3.5	17.2
Low	2.9	2.2	19.9

APPENDIX B.2

FIGURES

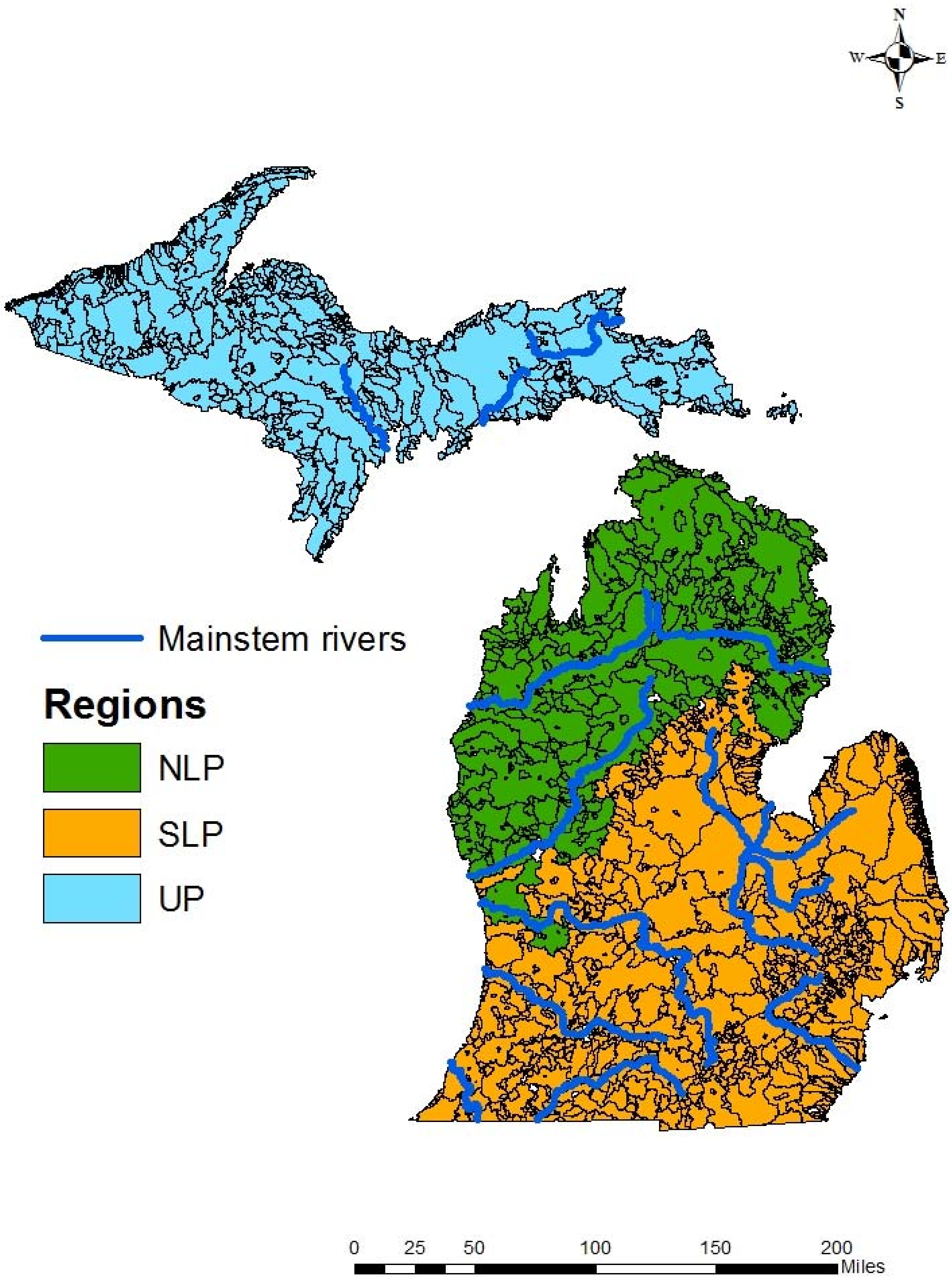

Figure B.2.1. Map of study region including major main stem streams and patch spatial units. The UP, NLP, and SLP are also identified.

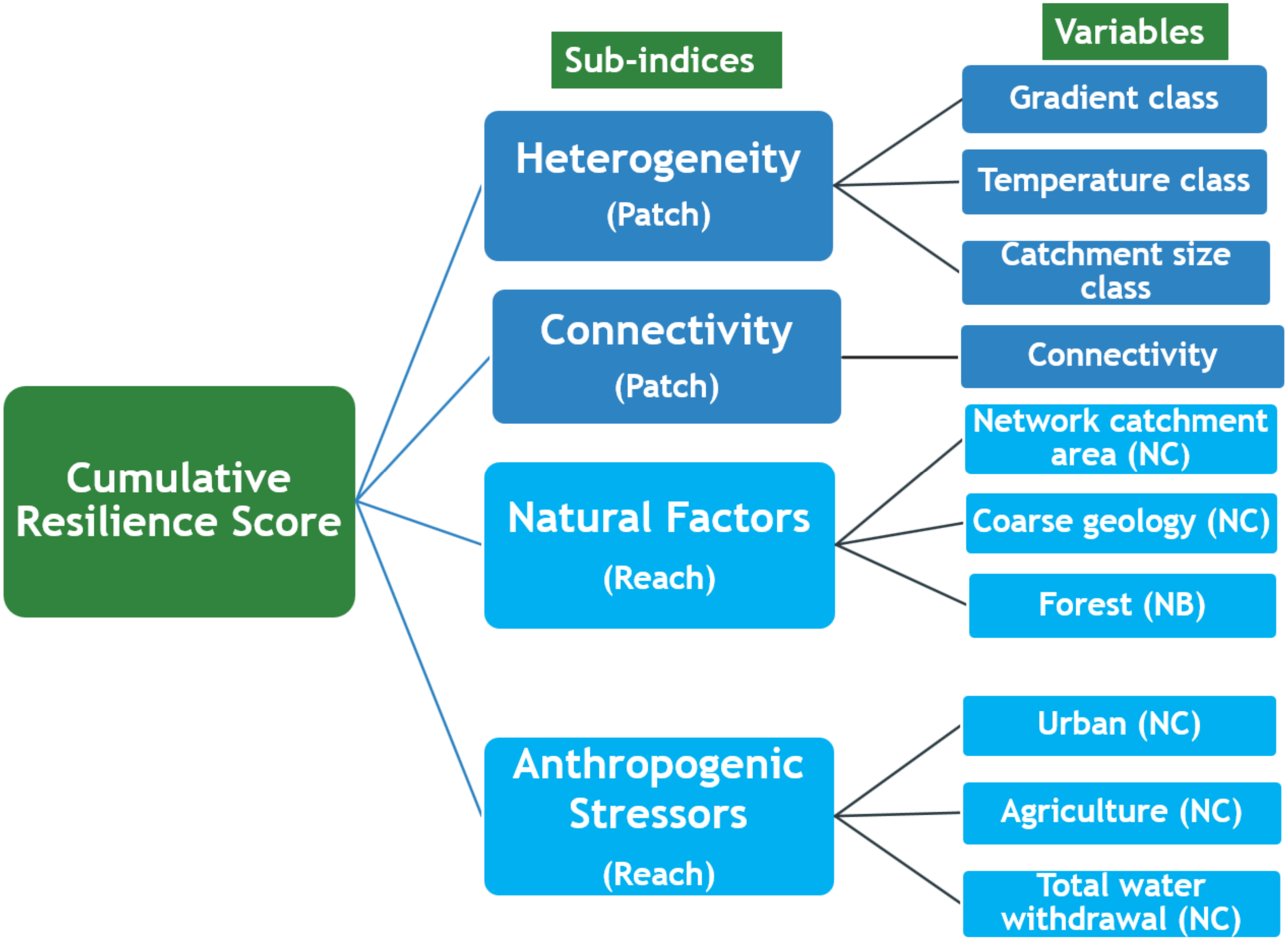

Figure B.2.2. Conceptual diagram showing variables used to create sub-indices and sub-index integration into the cumulative resilience score for each stream reach.

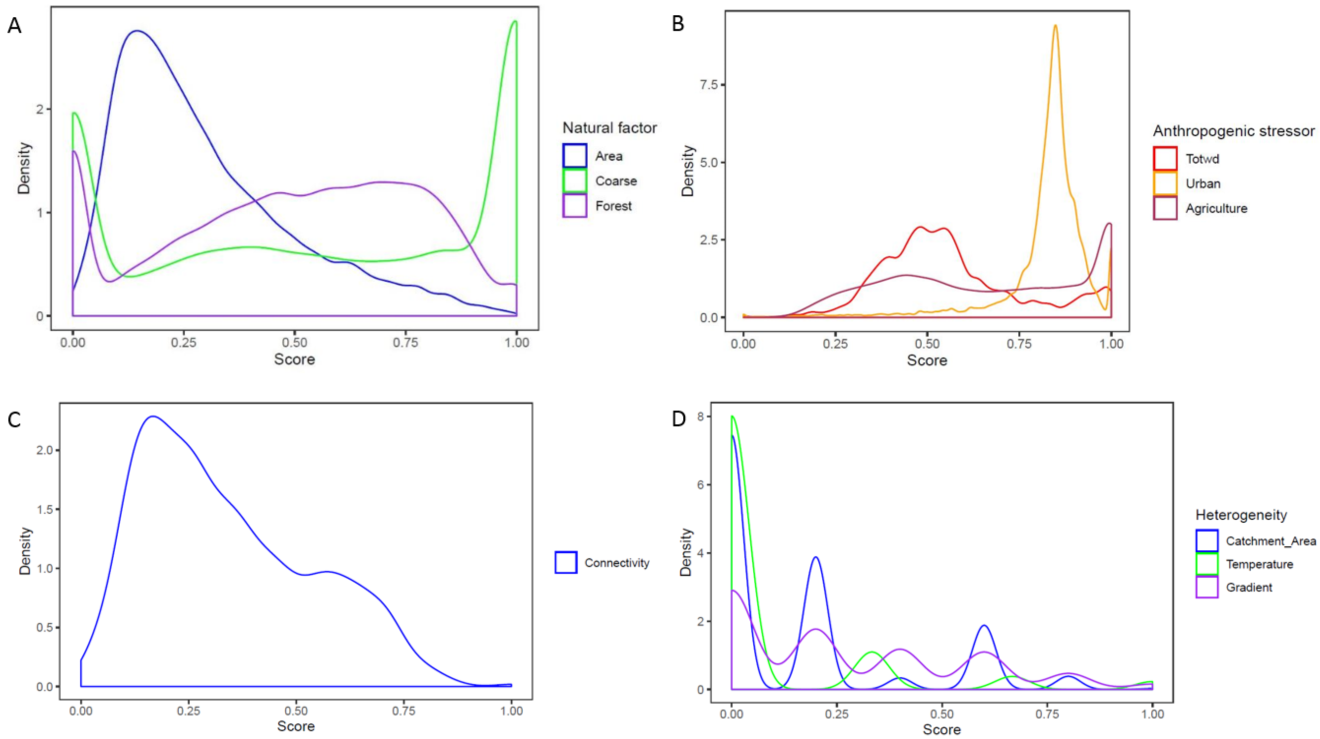

Figure B.2.3. Kernel density estimations for each variable in each sub-indices: A. natural factor variables. B. anthropogenic stressor variables, C. connectivity variable, and D. heterogeneity variable.

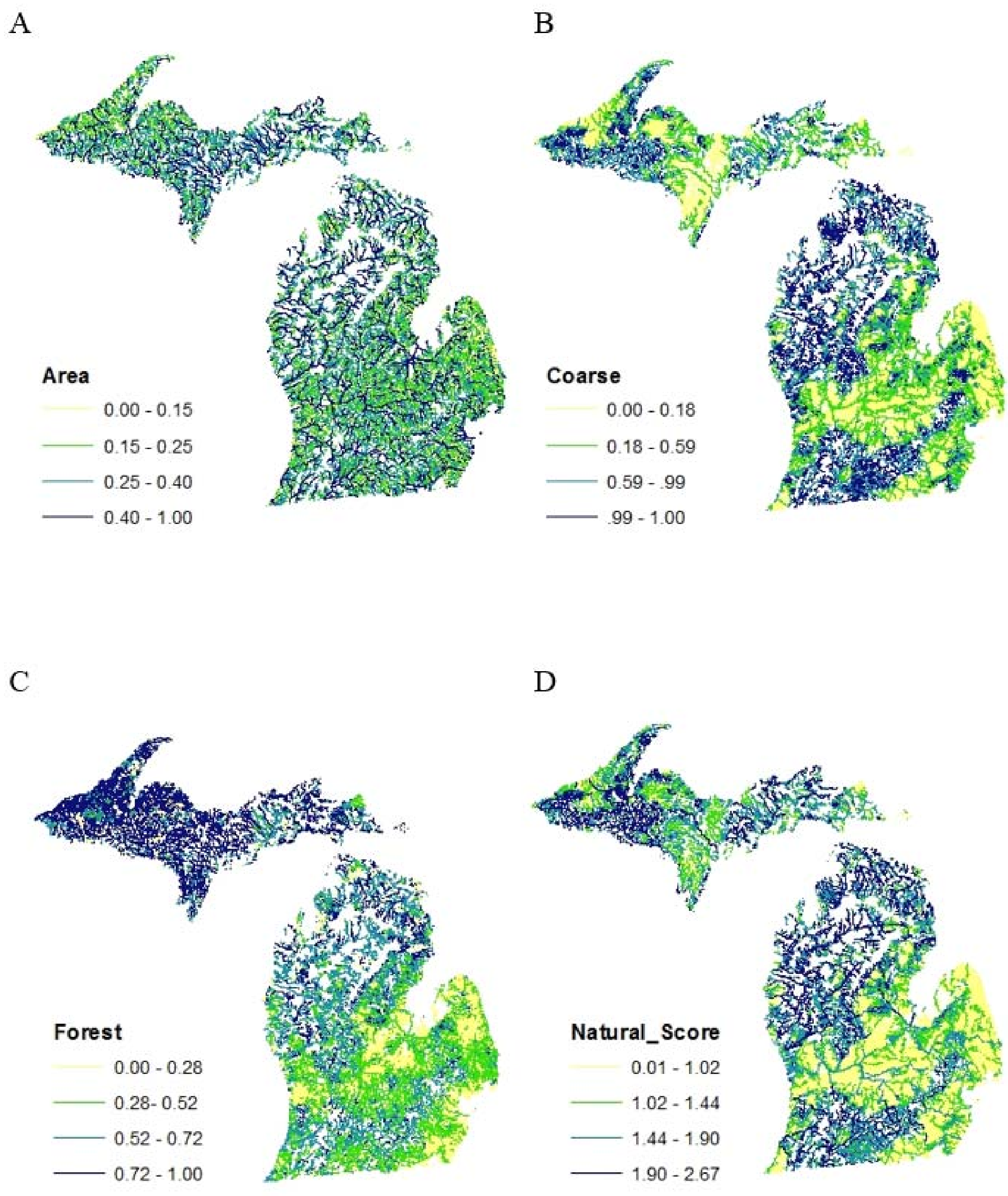

Figure B.2.4. Range in catchment area of stream reaches (A), coarse geology in network catchments of stream reaches (B), and forest cover in network buffers (C). Panel D shows the natural factor subindex score.

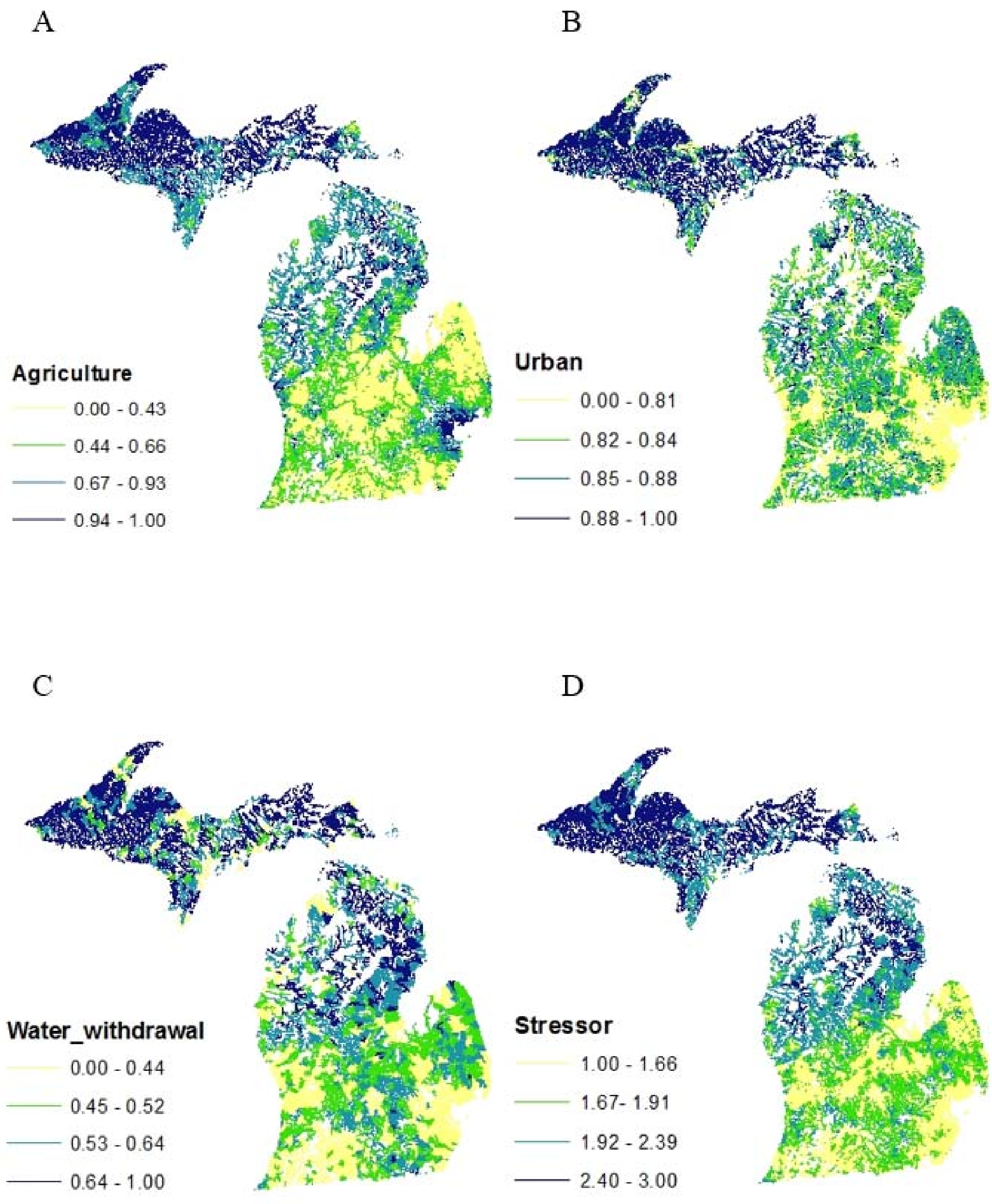

Figure B.2.5. Range in agricultural land use in network catchment (A), urban land use in network catchment (B), and total water withdrawal in network catchment (C). Panel D shows the anthropogenic stressor sub-index score.

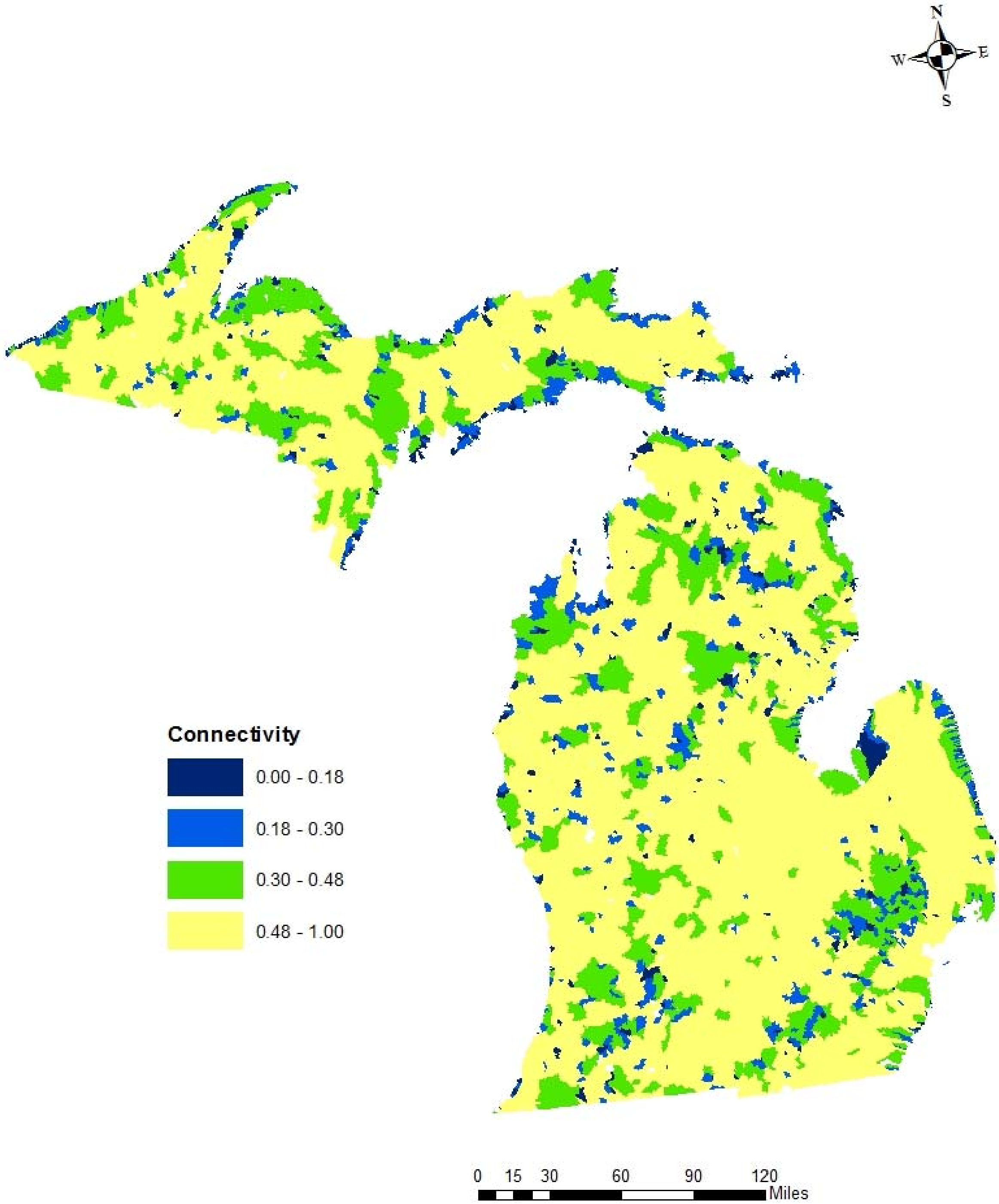

Figure B.2.6. Map of connectivity score by patch divided into 4 equal categories based on quartiles: low, medium-low, medium-high, and high.

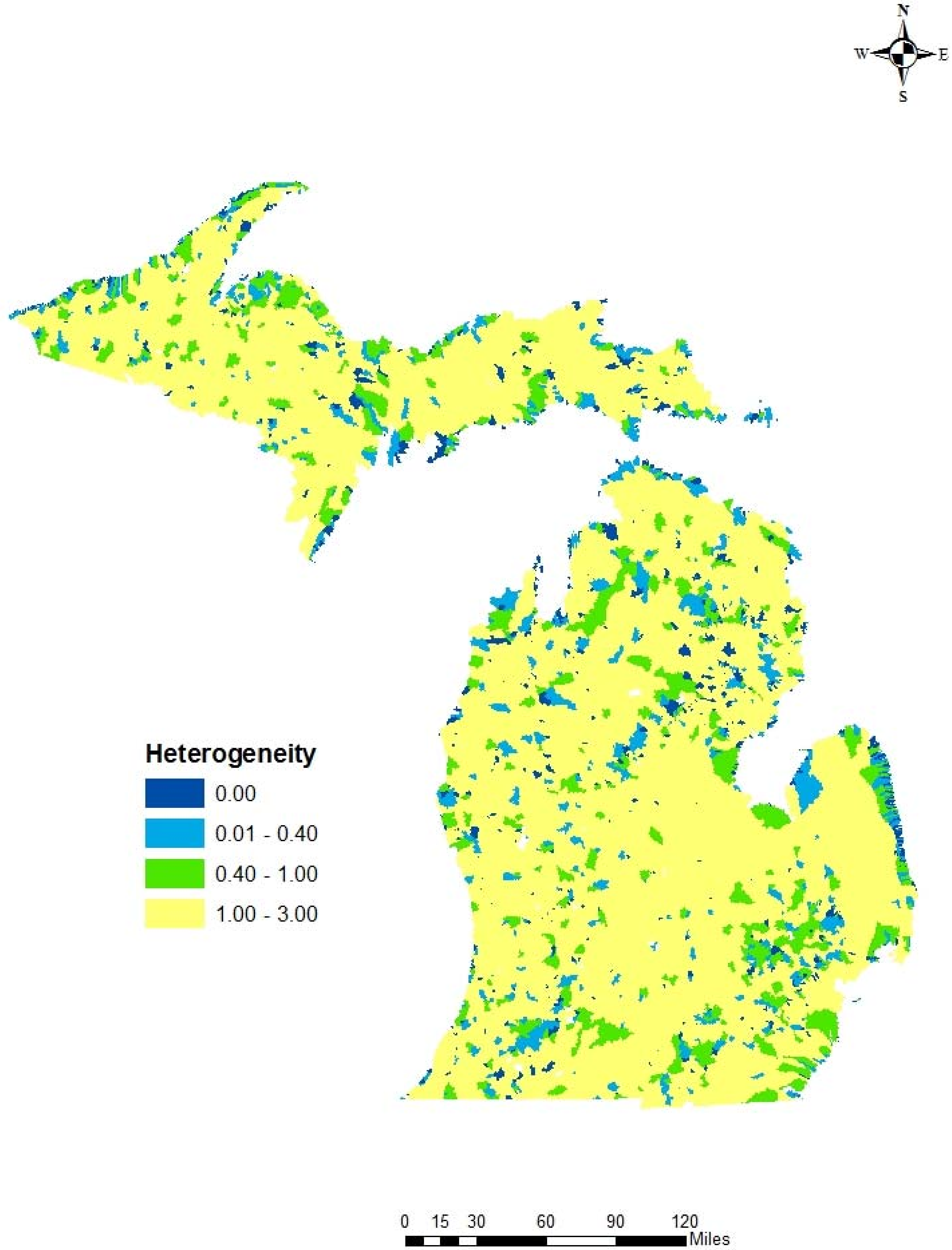

Figure B.2.7. Map of heterogeneity score by patch divided into 4 equal categories based on quartiles: low, medium-low, medium-high, and high.

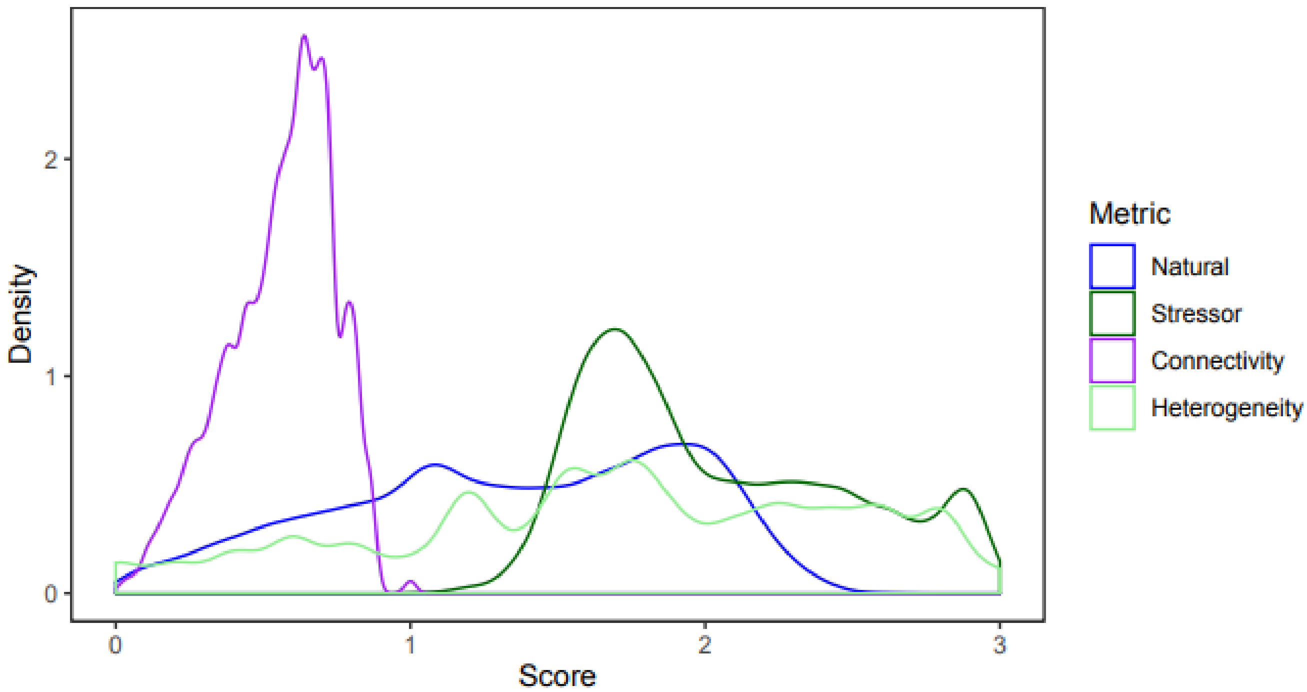

Figure B.2.8. Kernel density function of all variables that comprise the cumulative resilience score.

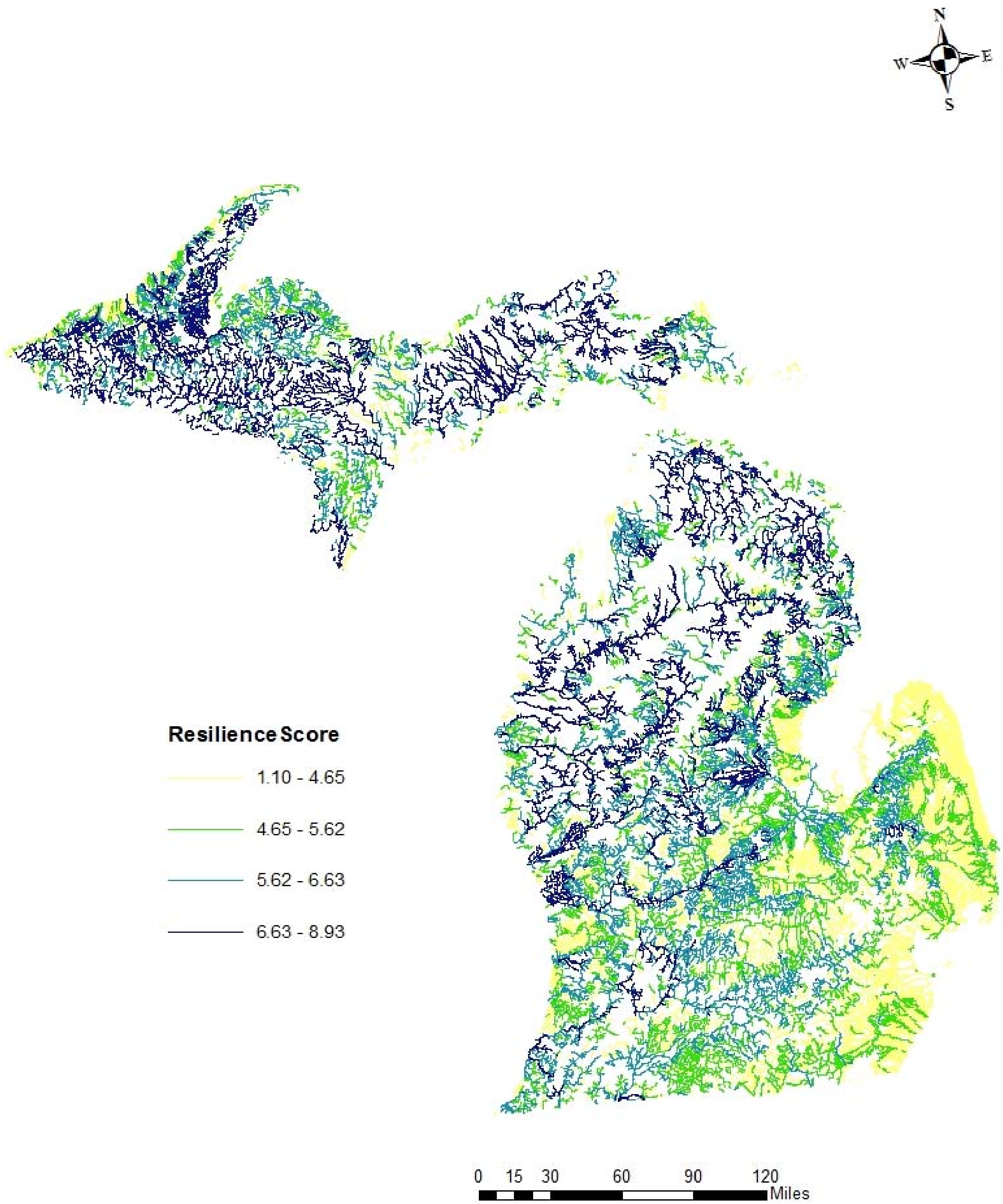

Figure B.2.9. Cumulative resilience score in 4 quartiles: low, medium-low, medium-high, high.

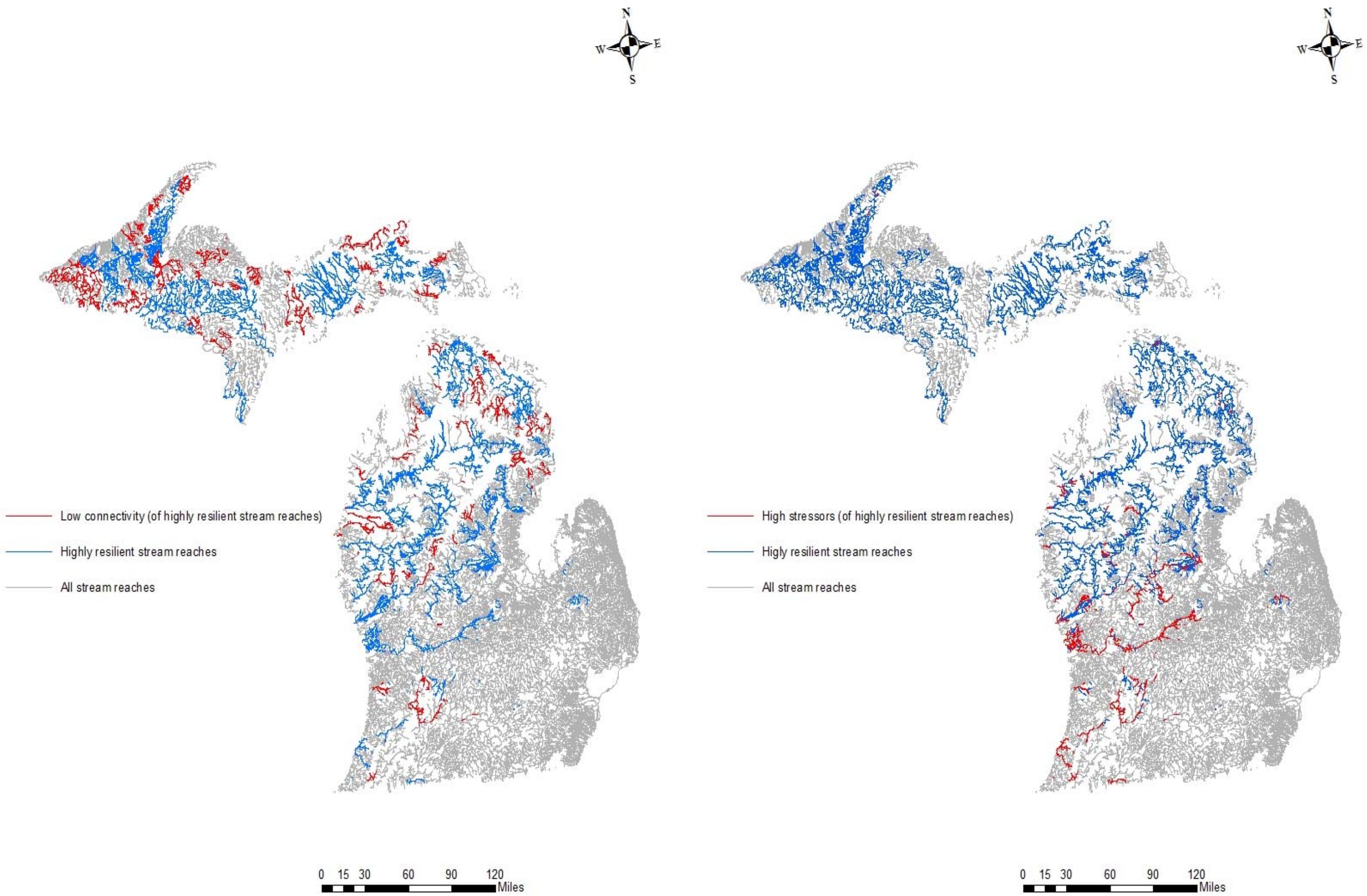

Figure B.2.10. Panel A. Stream reaches with a resilience score in the top 25% and an anthropogenic stressor score in the bottom 50% (n=1187). Panel B. Stream reaches with a resilience score in the top 25% and a connectivity score in the bottom 50% (n=2673).

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MANAGEMENT IMPLICATIONS

Rising air temperatures and changes in precipitation will ultimately impact the distributions and abundance of ecologically and economically valuable fish and wildlife populations found throughout the Great Lakes region as well as the people who rely on them (Kunkel et al. 2013, Wuebbles et al. 2019). To effectively address the impacts of climate change within the region (and globally) will require managers to mitigate the causes of climate change as well as to adapt to current threats and to future changes in both social and ecological systems (Liu et al. 2007, Ostrom 2009). In light of this need, the goal of this thesis is to provide natural resource managers with novel information related to climate change mitigation and adaption. In this section, we synthesize the main findings of Chapter 1 and 2 and present suggestions for how findings can inform management of natural resources under a changing climate.

CHAPTER 1

In Chapter 1 we developed strategies for increasing conservation organization engagement with membership on climate change. To meet this need, we conducted interviews with individuals in leadership roles at 13 conservation organizations with chapters in Michigan. Through these in-depth interviews, participants had a chance to express how engaged their organizations were currently in climate change issues, highlight barriers to engagement, and describe opportunities for increased engagement. Based on the barriers and needs that emerged from these interviews, we developed recommendations for conservation organizations.

Collectively, we found that while Michigan conservation organizations vary in their current engagement with climate change issues and in their willingness to increase engagement with their membership depending on perceived barriers, interest in receiving more information on how climate change will affect the state's fish and wildlife populations was unanimous. This interest in climate change research could indicate potential future willingness to support climate-friendly policies and actions. In light of this finding, our first recommendation to conservation organizations is to support research that characterizes the effects of climate change on Michigan's fish and wildlife populations. Additionally, our findings indicate that selecting the right messenger (e.g. SeaGrant, Wildlife Management Institute, Michigan State University) and mechanism (symposium) to deliver this climate change information is essential when engaging members. Finally, increasing funding or monetary incentives for climate change mitigation policies and actions as well as partnering with groups that are currently involved in mitigation may enable conservation organizations to more effectively engage with their membership. Ultimately, this study provides conservation organizations with information and strategies that will enable them to increase their engagement in climate change, potentially leading to increased hunter and angler support for climate change mitigation policies and actions.

CHAPTER 2

In Chapter 2, we developed an estimate of the resilience of fish habitat in Michigan streams to changing climate. This work was conducted in partial response to interest in more information on climate change expressed in Chapter 1. Because resilience is a multi-faceted property, we began by identifying a set of variables that may promote resilience. We then created four sub-indices to characterize different aspects of resilience including natural landscape factors and anthropogenic stressors within stream catchments and length of connected habitat and habitat heterogeneity within patches (e.g. sections of stream networks located between dams). These sub-indices were calculated separately to allow for the identification of specific factors that may be reducing the resilience of a stream and that may be addressed by natural resource managers, including fragmentation of habitats by dams or anthropogenic land uses in catchments. Finally, we integrated individual sub-indices into one cumulative resilience score to show a composite estimate of stream resilience.

Results from our study show that while stream resilience based on natural factors varies across the state, resilience as influenced by anthropogenic stressors generally decreases from north to south. Additionally, both length of connected stream habitat within patches and heterogeneity of habitat within patches varies across the state. Lastly, our results show that while cumulative resilience is generally higher in the Upper Peninsula and Northern Lower Peninsula, resilient streams are also found in the Southern Lower Peninsula suggesting that managers have opportunities in every part of the state for protecting or improving stream resiliency to changing climate. Collectively, these findings represent the first state-wide assessment of the resilience of Michigan streams to changing climate, providing natural resource managers with novel information that can aid them in adapting their management strategies to ensure proactive management of stream habitats and the fishes they support under a changing climate.

CONCLUSION

The Great Lakes region has an abundance of natural resources that are ecologically and socioeconomically valuable to residents and visitors, and to preserve their value these resources should be protected under a changing climate. Responding to the effects of climate change locally, nationally, and globally requires both mitigating the causes of climate change (e.g. decreasing carbon emissions) and adapting to actual or expected future changes in climate (e.g. habitat restoration) (Wuebbles et al. 2019). Outcomes of this research offer natural resource managers with novel information and strategies for both mitigating the effects of and adapting to a changing climate, ultimately facilitating the sustainable management of natural resources in the future.

While the information presented in these chapters can aid natural resource managers in specific mitigation and adaptation actions, more research is needed to provide a holistic picture of social and ecological system change under a changing climate. In particular, while hunters and anglers in the U.S. are an important group to engage in climate change issues, the need for public support of climate change mitigation necessitates more research into how best to engage other sectors of the public. Additionally, while we now have an estimate of Michigan stream resilience, more information on ecosystems resilience is needed for other states and parts of the world to ensure effective management of natural resources. Finally, more information is needed on how other aspects of social and ecological systems may change with changing climate. For example, human components, such as economics and politics, as well as natural factors, such as disease and invasive species, may be affected by and interact with a changing climate. Ultimately, to ensure the sustainable management of social and ecological systems we must prioritize climate change mitigation and adaptation.

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