DESIGNING A DECISION-SUPPORT TOOL FOR HARVEST MANAGEMENT OF GREAT LAKES LAKE WHITEFISH (*COREGONUS CLUPEAFORMIS*) IN A CHANGING CLIMATE

By

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ABSTRACT

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Fisheries are a vitally important renewable resource if managed sustainably (i.e., with harvest at a rate that does not deplete population levels and allows for future use). Climate change is expected to impact fish, fisheries, and the communities dependent upon them by altering fish habitat which will shift the distribution and abundance of fish populations. Changes to fish distribution and abundance will challenge current fisheries management practices and highlight the need for new adaptive approaches to manage the ecological, social, and economic impacts of climate change on fisheries. Decision-support tools can assist fishermen and fisheries managers make more informed management choices related to climate change. Using the Laurentian Great Lakes as a case-study, and specifically the Lake Whitefish (*Coregonus clupeaformis*) fishery in the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior, the objectives of this dissertation were to:

1) Review the physical and biological mechanisms by which cold-, cool-, and warm-water fish species will be affected by climate change in the Great Lakes;

2) Examine the feasibility of decision-support tools for fishery management in the context of climate change;

3) Survey Lake Whitefish fishermen, fishery researchers, and fishery managers to document need and willingness to implement a decision-support tool for harvest management of Lake Whitefish and climate change; and,

4) Develop a model of Lake Whitefish recruitment including climatic relationships and project recruitment with climate change.

By the end of the 21st century, the Great Lakes will be warmer, wetter, winder, with less ice cover. Changes to the Great Lakes climate will change habitat for Great Lakes fishes, including Lake Whitefish. Lake Whitefish recruitment has been linked to climate variables, specifically temperature, wind speed, and ice cover. A mechanistic model confirmed a positive relationship between Lake Whitefish recruitment and temperature and ice cover and a negative relationship between Lake Whitefish recruitment and wind speed using corrected Akaike's Information Criterion for model selection.

Surveying Lake Whitefish fishermen, researchers, and managers showed that those affiliated with the fishery support the use of decision-support tools can assist this fishery integrate science into management. The survey recommendations were used to develop the decision-support tool for the Lake Whitefish climate-recruitment relationship with climate projections. Some management units will expect up to a 50% decline and others up to a 220% increase in Lake Whitefish recruitment because of spatial variability in the climate-recruitment relationships and climate projections.

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While I could never have imagined what was in store for me as I read over the half page position description at a Thai restaurant in Arlington, Virginia, I knew the graduate position at Michigan State University (MSU) was an opportunity to seize. Looking back on my doctoral program at MSU, this document cannot come close to representing all that it entailed. I am so grateful for the amazing perspective-changing experiences and all that I have learned.

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INTRODUCTIORY SUMMARY

Lynch, A. J. 2013. WINNER: One Fish, Two Fish, Where Fish for Whitefish? Fisheries 38(8):356.

The content of the introductory summary contains updated results from the publication cited above but still reflects journal specifications (e.g. formatting).

The publication cited above won the 2013 American Fisheries Society Student Writing Contest. For the contest, students are "asked to submit a 500- to 700-word article explaining their own research or a research project in their lab or school. The article must be written in language understandable to the general public (i.e., journalistic style)."

Designing a climate change decision-support tool for Great Lakes Lake Whitefish

Imagine you are playing a game of *Monopoly* and are investing wisely for the future. You have numerous hotels on “Boardwalk” and are raking in the dough any time another player lands on your valuable property. Then, the rules of the game unexpectedly change. “Baltic Place” is the hot commodity and all of your painstaking investments in “Boardwalk” are for naught. Now, imagine this is not a game and your actual livelihood and family depend on your success.

Currently, the Great Lakes Lake Whitefish fishery is the most economically valuable commercial fishery in the upper Great Lakes. But, like a modified *Monopoly*, this fishery could face new “rules of the game” from climate change. My dissertation research developed a decision-support tool to ensure that the fish, the fishery, and the livelihoods dependent upon them remain sustainable in the face of climate change.

“A better fish cannot be eaten!”

Lake Whitefish, a member of the salmon family, are found in coldwater lakes throughout much of northern North America. Like many salmon species, they are highly valued as food fish: fresh fillets, smoked fillets, frozen fillets, fish cakes, spread, and sausage. Lake Whitefish have been a staple of native communities in the Great Lakes for thousands of years and were a particular favorite of early French explorers—one even wrote that “a better fish cannot be eaten!” They are a favorite still today; over 15 million pounds of Lake Whitefish are consumed each year in the Great Lakes region alone.

Aiming for 20/20 vision of lake whitefish recruitment

To reach someone’s dinner plate, a Lake Whitefish must survive a treacherous journey from an egg to a larvae to a juvenile and, finally, recruit to the fishery. Ultimately, we want to know how many Lake Whitefish enter the fishery so that we can determine how many can be harvested without negatively impacting future populations and harvest. But, it is next to impossible to know how many Lake Whitefish are actually out there. So, we estimate the population size using mathematical modeling.

You can think of mathematical modeling of fish populations like a visit to the eye doctor. For many of us, perfect 20/20 vision is as unobtainable as knowing true population abundance is for fishery managers. But, with corrective lenses and modeling approaches, we can get pretty close to estimating (or seeing) those realities. Like adjusting the lenses in an eye exam, including biologically relevant variables in the model can often improve our ability to predict fish populations.

My dissertation research did just that. I examined climate factors, specifically temperature, wind, and ice cover, which have been shown to influence recruitment of Lake Whitefish to the commercial fishery. Because Lake Whitefish spawn in the fall and hatch as larvae in the spring, these time periods are particularly critical to the survival of Lake Whitefish. I used historical data to model how changes in these climate variables affected recruitment.

Could warmer temperatures be good for a coldwater fish?

Earlier research has observed positive relationship between recruitment and spring temperatures and ice cover and a negative relationship between recruitment and fall temperatures and fall wind speed. My research confirmed these same patterns. Warmer spring temperatures may improve survival of larval Lake Whitefish, if food resources are available, and increase Lake Whitefish production in the Great Lakes. However, warmer fall temperatures, more wind, and less ice cover may inhibit egg survival and, consequently, Lake Whitefish production.

The relationship between climate variables and Lake Whitefish recruitment has significant implications for the fishery in the context of climate change. By the end of this century, the Great Lakes region will be warmer, windier, with less ice cover. Surface temperatures for the Great Lakes, for example, are expected to increase by as much as 7°F. So, is this just another "doom and gloom" climate change story where a species will be ousted by habitat changes? Or, perhaps could warmer temperatures be good for this coldwater fish?

Using the climate-recruitment model, I was able to project anticipated impacts on Lake Whitefish recruitment using my climate-recruitment model and a downscaled climate model developed for the Great Lakes for the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior. The 1836 Treaty Waters currently sustain a highly productive Lake Whitefish fishery, approximately 25% of the whole fishery in the upper Great Lakes. Recruitment projections varied between management units; some had up to a 50% decline and others had as much as a 220% increase. Overall, my research suggests that there is potential for increased Lake Whitefish recruitment in the Great Lakes with climate change and some shift in the distribution of the fishery.

Predicting the* Monopoly *board

These potential changes in Lake Whitefish populations have significant repercussions for fishermen and the communities dependent upon this fishery. Returning to the *Monopoly* analogy, if you could predict changes to the game, you would change your strategy and invest differently. Likewise, my research aims to help the Lake Whitefish fishery adapt to anticipated climate change. I hope my climate-recruitment model and projections will serve as a decision-support tool to assist fishermen and fishery managers. This tool, which is being housed on the Michigan Sea Grant website, will tell fishermen if it's better to give up on the "Boardwalk" fishery locations and focus their investments on "Baltic Place" for a more sustainable and prosperous fishery. Because, ultimately, who doesn't want to win *Monopoly*?

Dissertation format

This dissertation is composed of four central chapters, bounded by this introductory summary and a final synthesis. I studied the potential impacts of climate change on Laurentian Great Lakes fish and fisheries (Chapter 1) and investigated the potential use of decision-support tools in fisheries in the context of climate change (Chapter 2), using Lake Whitefish (*Coregonus clupeaformis*) as a case-study. I surveyed fishermen, managers, and researchers affiliated with the Lake Whitefish fishery to understand their perceptions of Lake Whitefish management and willingness to use decision-support tools (Chapter 3). Using the recommendations from the survey, I developed a decision-support tool for harvest management of Lake Whitefish in a changing climate by modeling the relationship between climate variables, specifically fall and spring temperature, fall wind speed, and winter ice cover, and Lake Whitefish recruitment then projecting that climate-recruitment relationship forward with climate change (Chapter 4).

Climate change will influence recruitment of Lake Whitefish in the Great Lakes. Some management units will increase in productivity and others will decrease, as a result of the climate influences on recruitment and the projections for climate change in each of the management units. The objective of the tool developed in this dissertation is to communicate the potential impacts of climate change on the Lake Whitefish fishery with fishermen, fishery managers, researchers, students, and the public to help them anticipate changes to the fishery (synthesis). Ultimately, the goal of this tool is to support an ecologically sustainable, prosperous fishery and promote the well-being of associated communities.

CHAPTER 1: THE INFLUENCE OF CHANGING CLIMATE ON THE ECOLOGY AND MANAGEMENT OF SELECTED LAURENTIAN GREAT LAKES FISHERIES

Lynch, A. J., W. W. Taylor, and K. D. Smith. 2010. The Influence of Changing Climate on the Ecology and Management of Selected Great Lakes Fisheries. Journal of Fish Biology 77: 1964-1982.

The content of this chapter is intended to be identical to the publication cited above and reflects journal specifications (e.g. formatting, British spelling). Any differences should be minor and are unintended.

Abstract

The Laurentian Great Lakes Basin provides an ecological system to evaluate the potential effect of climate change on dynamics of fish populations and the management of their fisheries. This review describes the physical and biological mechanisms by which fish populations will be affected by changes in timing and duration of ice cover, precipitation events and temperature regimes associated with projected climate change in the Great Lakes Basin with a principal focus on the fish communities in shallower regions of the basin. Lake whitefish *Coregonus clupeaformis,* walleye *Sander vitreus* and smallmouth bass *Micropterus dolomieu* were examined to assess the potential effects of climate change on guilds of Great Lakes cold, cool and warm-water fishes, respectively. Overall, the projections for these fishes are for the increased thermally suitable habitat within the lakes, though in different regions than they currently inhabit. Colder-water fishes will seek refuge further north and deeper in the water column and warmer-water fishes will fill the vacated habitat space in the warmer regions of the lakes. While these projections can be modified by a number of other habitat elements (*e.g.* anoxia, ice cover, dispersal ability and trophic productivity), it is clear that climate-change drivers will challenge the nature, flexibility and public perception of current fisheries management programmes. Fisheries agencies should develop decision support tools to provide a systematic method for incorporating ecological responses to climate change and moderating public interests to ensure a sustainable future for Great Lakes fishes and fisheries.

KEYWORDS: adaptive management; climate change; decision support; fisheries conservation.

A changing global climate

Scientific evidence suggests global air and ocean temperatures are rising at a relatively rapid pace with increased melting of snow and ice and rising sea levels (IPCC 2007). While some climatic variability is expected and cooler years have occurred, temperature increases over the last 50 years (1955 to 2005) have been nearly twice what they were in the 100 years preceding and are anthropogenically induced (IPCC 2007).

The effects of climatic warming are predicted to be significant on the distribution and abundance of freshwater fishes as water temperature, quantity and quality are all factors influenced by the atmosphere with direct implications for the structure of fish communities (Regier and Meisner, 1990). In particular, measures of sustained fish yields in North America have been empirically related to water temperature with increased yields at lower latitudes and warmer water systems (Schlesinger and Regier, 1982; Meisner *et al.*, 1987). In the Laurentian Great Lakes region, climate change is estimated to alter the hydrographic and geographic distributions of freshwater fishes (Regier and Meisner, 1990), their year-class strength (Casselman, 2002), growth and bioenergetics (Brandt *et al.*, 2002) and trophic dynamics (Jackson and Mandrak, 2002). For example, Regier & Meisner (1990) suggest that cold-water habitat for lake trout *Salvelinus namaycush* (Walbaum) and lake whitefish *Coregonus clupeaformis* (Mitchill) will be shifted deeper within each lake, particularly during the warmer summer months.

Climate change will challenge the current practices and tenets of fisheries management within the basin. It is important for fisheries managers to understand the implications for fish communities and their productivity within these lakes in order to implement strategies that accommodate climate change (*i.e.* focus conservation efforts on populations capable of persisting in a changing climate). This paper reviews the climate change literature pertinent to Great Lakes fisheries, with focused assessments on three key species from different thermal guilds, cold: *C. clupeaformis*, cool: walleye *Sander vitreus* (Mitchill), and warm: smallmouth bass *Micropterus dolomieu* (Lacépède). In addition, this paper suggests models for managing Great Lakes fisheries in a dynamic, adaptive manner based on lessons learned via aquatic invasive species management to ameliorate the impact of climate change on Great Lakes fishes.

Climate projections for the Great Lakes Basin

The regional climate of the Laurentian Great Lakes Basin is predicted to be warmer with increased precipitation and less ice cover by the end of the 21st century (Table 1.1). Air temperatures in the Great Lakes region are projected to increase by 0-11^{o}C in the summer and 0.5-9.1^{o}C in the winter (Mortsch and Quinn, 1996; Sousounis and Albercook, 2000; Sousounis and Grover, 2002; Kling *et al.*, 2003; Wuebbles and Hayhoe, 2004).

Concurrent with temperature increases, Sousounis & Albercook (2000) estimate a 15-25% increase in summer precipitation across much of the region. This increase in precipitation, however, will not necessarily result in higher lake levels because higher temperature and evaporation rates will occur with less ice cover during the winter months (Smith, 1991a); Angel & Kunkel (2010) modelled a range of −3 to +1.5 m changes in lake level, depending on emission conditions. These changes will contribute to an increase in water temperature and changes in Great Lake morphometry, which will influence resident fish distribution and production.

Effects on Great Lakes fish habitat

As one of the largest bodies of surface fresh water in the world, representing *c.* 20% of the world's supply (Lehman *et al.*, 2000), the Great Lakes provide a diverse set of fish habitats: wetlands, embayments, nearshore, and open water. Climate change will alter the structure and dynamics of these habitats and affect the distributions of resident fishes. This will principally

TABLE 1.1. Selected climate change projections grouped by feature class (air temperature, precipitation and lake level, ice cover, wind speed, water temperature, stratification and dissolved oxygen, thermal habitat and bioenergetics) for the Laurentian Great Lakes region with ecological relevance to fisheries. GCMs = General Circulation Models; 2×CO_2 = 2×present CO_2 concentration; IPCC = Intergovernmental Panel on Climate Change.

Air temperature	
Declines from -3 m to increases of +1.5 m in lake level for all lakes using 23 GCMs and three IPCC emission scenarios	(Angel and Kunkel, 2010)
4-11^{o}C increase using three GCMs with 2×CO_2.	(Croley, 1990)
3-8^{o}C increase (winter); 3-9^{o}C increase (summer) by the end of the 21st century using two GCMs and three IPCC emission scenarios.	(Kling *et al.*, 2003)
3.4-9.1^{o}C increase (winter); 2.7-8.6^{o}C increase (summer) with 2×CO_2.	(Mortsch and Quinn, 1996)
Minimum summer temperature increase by 1-2^{o}C and maximum temperature increase by 0-1^{o}C; minimum winter temperature increase by 0.5-6^{o}C and maximum temperature increase by 0.5-3^{o}C using two GCMs and steady CO_2 increase for the period 2025-2034.	(Sousounis and Albercook, 2000)
3-7^{o}C increase (winter); 4-11^{o}C increase (summer) by the end of the 21st century using two GCMs and four IPCC emission scenarios.	(Wuebbles and Hayhoe, 2004)

Precipitation and lake level	
Reduction between 23 and 51% of water supply to the Great Lakes using three GCMs with 2×CO_2.	(Croley, 1990)
10-20% increase in precipitation by the end of the 21st century using two GCMs and three IPCC emission scenarios.	(Kling *et al.*, 2003)

TABLE 1.1 (cont'd).

Precipitation and lake level, *continued*	
Declines by 0.06 m – 0.94 m in lake level for all lakes with a 3.2-4.8^{o}C increase in average annual air temperatures for the Great Lakes Basin.	(Meisner *et al.*, 1987)
Declines from -0.23 to -2.48 m in lake level for all lakes with most scenarios using four GCMs and 2×CO_2.	(Mortsch and Quinn, 1996)
Precipitation increases throughout large portions of the basin but declines in southwestern portion of the basin (Ohio, Indiana) using four GCMs and 2×CO_2.	(Mortsch and Quinn, 1996)
Water supply decreases due to warmer air temperatures, higher evapotranspiration and evaporation, and decreased runoff using four GCMs and 2×CO_2.	(Mortsch and Quinn, 1996)
Summer precipitation increases by 15-25% using two GCMs and steady CO_2 increase for the period 2025-2034.	(Sousounis and Albercook, 2000)

Ice cover	
Ice cover virtually absent in Lake Erie's central and eastern basins and reduced from 4 months to 1-1.5 months in Lake Superior using three GCMs with 2×CO_2.	(Assel, 1991)
All but Lake Erie ice-free year round; Lake Erie with a 50% decline in ice cover using one GCM with 2×CO_2.	(Howe *et al.*, 1986)
Substantially reduced ice cover duration in Lake Erie and Whitefish Bay, Lake Superior by the end of the 21st century using two GCMs with 2×CO_2.	(Lofgren *et al.*, 2002)
Ice-free winters between 0 and 17% of simulated years for Lake Erie and between 7 and 43% of simulated years for Lake Superior using four GCMs and multiple emission scenarios.	(Magnuson *et al.*, 1997)

TABLE 1.1 (cont'd).

Wind speed	
Average wind speed decline; more frequent easterly wind events using two GCMs and a gradual increase in CO_2 concentrations.	(Sousounis and Grover, 2002)

Water temperature	
As much as 5^{o}C increase (bottom temperature) by the end of the 21st century using two GCMs with 2×CO_2.	(Lehman, 2002)
As much as 6^{o}C increase (summer surface temperature) by the end of the 21st century using one GCM and two emission scenarios.	(Trumpickas *et al.*, 2009)

Stratification and dissolved oxygen	
Declines of 1 mgl^{-1} dissolved oxygen in upper layers and 1-2 mgl^{-1} in deeper layers of Lake Erie using three GCMs with 2×CO_2.	(Blumberg and Di Toro, 1990)
Longer length of thermal stratification, stronger stability of stratification, and deeper depth of daily mixing during peak thermal stratification using two GCMs with 2×CO_2.	(Lehman, 2002)
Increased intensity and duration of summer stratification in Lake Michigan (by up to two months) using three GCMs with 2×CO_2.	(McCormick, 1990)
No thorough winter turnover in Lake Michigan using three GCMs with 2×CO_2.	(McCormick, 1990)

TABLE 1.1 (cont'd).

Thermal habitat	
Habitat increases for all three thermal guilds in southern Lake Michigan and for cool and warm water fishes in central Lake Erie with three GCMs and $2\times CO_2$.	(Magnuson *et al.*, 1990)
Increases in thermal habitat for all three thermal guilds in the deep, stratified lakes; decreases in thermal habitat for cold water species in Lake Erie using four GCMs and multiple emission scenarios.	(Magnuson *et al.*, 1997)
Twenty-seven of 58 fish species with high potential for expanding their range to the Great Lakes found to be likely invaders as a result of climatic warming using discriminate function and principal component analyses comparing ecological characteristics of potential invaders with recently established species.	(Mandrak, 1989)

Bioenergetics	
Year-class strength of *M. dolomieu* increase by 2-5 times with a $1^{o}C$ increase in temperature and six times with a $2^{o}C$ increase in temperature at the northern extent of the species current distribution.	(Casselman, 2002)
Increased growth of fishes if factors currently limiting growth also increase using three GCMs with $2\times CO_2$.	(Hill and Magnuson, 1990)
Increases in growth for species currently below their thermal optimum; decreases in growth for species at or above their thermal optimum using four GCMs and multiple emission scenarios.	(Magnuson *et al.*, 1997)
Faster development and time to maturity with climate change.	(Regier *et al.*, 1990)

entail a northward shift of colder-water species in the longitudinally-oriented lakes (Michigan and Huron) and changing dominance in many assemblages towards warmer-water fishes in the southern and nearshore regions. For some species, the altered state will provide opportunities to expand their range, increase growth and reproductive rates and reduce over-winter mortality. For others, however, it will contract their niches. Because the shallower regions of these lakes will be the first to experience impact from climatic warming, this review focuses principally on the effects within shallower areas of the basin. In long-term scenarios, though, these factors are also predicted to have significant influence on the deep, open water regions of the lakes (Kling *et al.*, 2003).

Temperature

Temperature is an important abiotic factor governing the distribution (Shuter and Post, 1990), growth and survival of fishes in the Great Lakes and is directly linked to climate change (Christie and Regier, 1988; Brandt *et al.*, 2002). Because the northern and southern edges of the range for many species are largely influenced by temperature (Shuter and Post, 1990), there is greater variability in abundance and growth rates at the edges of their range than in the middle (Shuter *et al.*, 2002). Populations at these margins, consequently, show the most pronounced correlations with global climate signals (King *et al.*, 1999). For example, as climate warming shifts the southern limit of a species' range northward in the Great Lakes and deeper in the water column, previously stable populations may become more variable because they will no longer be in their optimal thermal habitat, which provides ideal conditions for maximal survival, growth and reproduction.

In the Great Lakes, fishes have been grouped into three broad thermal guilds according to their recorded approximate optimal temperatures (cold water: 15 degrees C; cool water: 24

degrees C; and warm water: 28 degrees C; Hokanson, 1977). Though it may appear counterintuitive, in a warmer climate, optimal thermal habitat is expected to expand volumetrically for all three thermal guilds in the Great Lakes. The reason for this is that fish will have the opportunity to move both northward (in the longitudinally oriented lakes) or deeper (in the deep lakes) to maintain their preferred temperature (Magnuson *et al.*, 1997). It is important to note, however, that while this analysis considered the deeper depth strata fairly depauperate of fish fauna (*i.e.* currently free habitat space), recent deep water surveys have revealed higher than expected abundances of siscowet, the deepwater morphoptype of *S. namaycush*, among other species, in depths exceeding 200 m (Sitar *et al.*, 2008).

Nonetheless, overall projections of warmer temperatures in the Great Lakes are predicted to increase growth and survival for most cold, cool and warm-water species (Shuter and Post, 1990). Additionally, fishes in the Great Lakes are often transition species, living at the edge of their thermal range. As such, they generally live in temperatures where their metabolic rate is not optimal; thus exhibiting lower growth and reproduction rates. Increased temperature, and consequently metabolic rates, will allow for greater growth, higher fecundity and generally better survival rates. This is particularly true for Great Lakes cool and warm-water species. Assuming prey abundance is non-limiting, productivity of fishes increases with time spent at optimal temperature with optimal metabolic rates (Christie and Regier, 1988).

Increased optimal temperature alone, however, does not necessarily equate to increased optimal habitat space for all fishes. Lake morphomentry also has a significant influence on the suitability of habitat available to fish (Regier and Meisner, 1990). *Micropterus dolomieu*, for example, require sheltered environments to build nests. Though a habitat may have temperatures in their optimal range, if it is turbulent, it will not be suitable for high *M. dolomieu* nest success (Goff, 1986).

Dissolved oxygen

While temperature is generally predicted to expand the amount of optimal thermal fish habitat space in the Great Lakes with climatic warming, dissolved oxygen may well be a limiting factor to fish productivity, particularly in Lake Erie and warm nearshore bays such as Saginaw Bay (Lake Huron) and Green Bay (Lake Michigan) (Stefan *et al.*, 1996). With warmer water temperatures, the thermocline is expected to sharpen, the duration of stratification is predicted to increase and the timing, extent and duration of winter mixing is expected to decrease (Lehman, 2002). When light levels are too low in the hypolimnion to allow dissolved oxygen levels to be replenished *via* photosynthesis, oxygen consumed in respiratory activities of the biotic community, including fishes, zooplankton, phytoplankton and bacteria, cannot be readily replaced (Lehman *et al.*, 2000). This generally leads to hypoxic (*e.g.* 2 mgl^{-1} dissolved oxygen or less) or even anoxic conditions. Some species and age classes of fish can avoid these harmful areas by being mobile and can relocate to suitable living conditions elsewhere. But as temperatures warm and fish move deeper in the water column to maintain their optimal thermal habitat, loss of dissolved oxygen could become another factor reducing optimal habitat. Lower dissolved oxygen could also increase competition for food and space within the remaining livable habitat, further reducing overall fish production of the current assemblage of fishes.

Current summer oxygen levels in Lake Erie's central basin, for example, range between 8 and 9.5 mgl^{-1} in the epilimnon and between 2 and 6 mgl^{-1} in the hypolimnion (Rao *et al.*, 2008). Climate warming simulations for this location predict central basin summer oxygen declines by 1 mgl^{-1} in the epilimnon and 1-2 mgl^{-1} in the hypolimnion (Blumberg and Ditoro, 1990). These declines are expected to lead to increases in anoxic dead zones, or areas that do not contain sufficient oxygen levels to sustain aquatic organisms. Similarly, McCormick (1990) modelled an increase in summer stratification by up to two months and a permanent deep zone of isolated water below the thermocline because of minimal winter mixing in Lake Michigan. These studies suggest that climate-related reductions in dissolved oxygen will significantly limit the availability of suitable habitat for some cold-water fishes, including *C. clupeaformis* and *S. namaycush* (Magnuson *et al.*, 1990; Stefan *et al.*, 1996).

Food web dynamics

Plankton biomass is the foundation of the Great Lakes food chain. Phytoplankton supports the productivity of higher trophic levels, including zooplankton and fishes (Lehman *et al.*, 2000). Though increasing temperatures are unlikely to increase the standing biomass of phytoplankton, annual productivity and diversity are likely to increase with a longer ice-free season (Magnuson *et al.*, 1997). This is expected to occur because phytoplankton production depends principally upon water temperature, sunlight, oxygen and nutrients (*i.e.* nitrogen and phosphorus). Nutrients, rather than temperature, however, are the principal limiting factor for phytoplankton abundance in the Great Lakes (Hecky and Kilham, 1988). A shallower epilimnion is expected to affect the nutritional value of phytoplankton because of a reduced residence time of nutrients in the mixed layer where they can be incorporated into the phytoplankton and be transferred to higher trophic levels (Magnuson *et al.*, 1997).

Zooplankton species are also expected to be impacted by climatic warming. Because temperature provides important cues for maturity stages of zooplankton, particularly overwintering stages (Magnuson *et al.*, 1997), some species of zooplankton may be physiologically more sensitive to warmer summer temperatures or lower oxygen levels (Stemberger *et al.*, 1996). However, the overall projection is for zooplankton biomass to increase in the Great Lakes with warming (Regier *et al.*, 1990).

Climate change is projected to increase primary production and has the potential to translate through the intermediate zooplankton trophic levels to increase fish production in the Great Lakes overall. Rainbow smelt *Osmerus mordax* (Mitchill), as one example, are an important prey species for salmonids in the Great Lakes. With warmer spring water temperatures and greater plankton production, juvenile *O. mordax* abundances should increase (Bronte *et al.*, 2005), providing a larger forage base that could translate into increased salmonid production.

Potential Consequences of Climate Change on Fish Populations

Overall, climate change projections for the Great Lakes fishes should result in an increase in optimal thermal habitat for cold, cool and warm-water species (Magnuson *et al.*, 1990). However, habitat increases will be largest for warmer-water species moving in to occupy the more southern and shallower habitat space vacated by the cool and cold-water species. Because the cool and cold-water fishes are expected to move to more northern and deeper, offshore regions and not gain habitat, there should be a predominant shift of species types from the current cold-water dominated community towards a warmer-water assemblage (Mandrak, 1989). Further exacerbating this trend is the probable ecological consideration that cold-water species, such as *S. namaycush* and *C. clupeaformis*, may have difficulty competing with cooler-water adapted species at the warmer, southern edges of their current distributions.

Translation of this potential for greater optimal thermal habitat may not, however, directly transfer into greater overall fish production. A number of limiting habitat elements, namely anoxia, ice cover, dispersal ability and food-web dynamics need to be considered. For instance, while McLain *et al.*(1994) predicted that deep-water refuges over large latitudinal ranges for the Great Lakes would be maintained in the face of climate warming, they did not factor in effects from increases in anoxia that would be expected with warmer temperatures and higher phytoplankton production. These latter two factors will likely reduce suitable habitat. In open water, however, phytoplankton productivity is not expected to increase as much as in shallow areas and embayments because primary production in the open water is still heavily influenced by the establishment of the thermocline and nutrient availability (Lehman, 2002).

Climate warming may also directly impact fish production through physiological means, particularly for fish species adapted to cold water. Some species, including yellow perch *Perca flavescens* Mitchill, require cold temperatures for full gonadal development (Jones *et al.*, 1972). Others, like *C. clupeaformis*, need ice cover to protect over-wintering eggs in marginal nursery habitat to increase year-class strength (Taylor *et al.*, 1987a). While suitable habitat may exist in a theoretical context, realised habitat is only possible if a species can travel there, namely if eggs or larvae can physically reach suitable habitat (Sharma *et al.*, 2007). *S. vitreus* larvae, for example, are passively transported large distances with surface currents. Their survival is dictated in part by drift into productive habitats that provide them with appropriate temperature and food for growth and survival (Roseman, 1997). Fish growth is also strongly dependent on biological factors, particularly production at lower trophic levels. Annual fish growth may decrease if prey availability is insufficient for the increased metabolic costs associated with living at higher temperatures (Hill and Magnuson, 1990).

Influx of new species is another extensive threat to current fish communities in the Great Lakes. Mandrak (1989) predicted that 19 warm-water fish species from Atlantic coastal basins and the Mississippi may extend their range to Lakes Ontario, Erie, and Michigan and that 8 warm water species currently in these three lakes could expand to Lakes Huron and Superior. These 27 new species could additionally introduce up to 83 parasites that currently do not exist in the Great Lakes (Marcogliese, 2001).

To examine the potential effects of climate change on a smaller scale, three species were evaluated in this study as representatives of the three thermal guilds in the Great Lakes: *C. clupeaformis* (cold), *S. vitreus* (cool), and *M. dolomieu* (warm):

Cold water: Coregonus clupeaformis

Since 1980, populations of *C. clupeaformis* have supported the most economically valuable commercial fishery in the upper Great Lakes (Madenjian *et al.*, 2006). Commercial landings have fluctuated over the last half century with variation in population abundance caused by overfishing, habitat degradation, sea lamprey *Petromyzon marinus* L. parasitism and competition with exotic species (Taylor *et al.*, 1987a). *Coregonus clupeaformis* populations have rebounded since the 1960s, with a 10-fold increase in Great Lakes commercial harvest between 1959 and 1995 (Ebener, 1997).

The *C. clupeaformis* recovery has been principally attributed to control of *P. marinus* (Ebener, 1997), but the species' recruitment variability has been linked with climatic influences, including water temperature, wind speed and ice cover (Miller, 1952; Christie, 1963; Lawler, 1965; Taylor *et al.*, 1987a; Freeberg *et al.*, 1990). As a result, *C. clupeaformis* production varies with the amount of thermally suitable habitat (Christie and Regier, 1988), which is likely to be modified significantly by climate change. In particular, *C. clupeaformis* year-class strength has been found to be directly related to the timing and duration of ice cover (*i.e.* egg survival) and temperature of spring plankton blooms (*i.e.* larval growth and survival) (Taylor *et al.*, 1987a; Freeberg *et al.*, 1990).

While climate warming should increase suitable thermal habitat volume for *C. clupeaformis* (Magnuson *et al.*, 1997) in most of the Great Lakes, predictions for realised habitat space are not entirely positive. There are projections for significant reductions in ice cover

(Marchand *et al.*, 1988) and higher mortalities at the southern boundary of the range (Meisner *et al.*, 1987) because of reduced egg and larval survival (Taylor *et al.*, 1987a). In Lake Erie, for example, cold water habitat will shrink between the thermocline and either the bottom of the lake or the anoxic “dead zone” (Magnuson *et al.*, 1990). However, in the deeper lakes, such as Lake Michigan, *C. clupeaformis* will not experience the same loss in potential habitat space because they can shift with the thermocline to deeper regions which have livable temperatures and oxygen levels (Regier and Meisner, 1990).

Additionally, the survival of eggs is largely contingent upon substrate size and the amount of ice cover during the winter (Taylor *et al.*, 1987a). When winter ice cover is extensive, *C. clupeaformis* eggs are protected from wave and current damage and their survival is greater for all depths and substrates up to 6 m (Hayes *et al.*, 1996). With predictions for substantial reductions in annual lake ice cover (surface area and duration) (Lofgren *et al.*, 2002; Assel *et al.*, 2003), protection, and hence survival, for over-wintering *C. clupeaformis* eggs will decline. This will particularly be the case in sub-optimal spawning habitat, which is essential for strong year classes.

On a basin-wide scale, abundance and distribution of *C. clupeaformis* adults are expected to shift northward and deeper in the water column (Regier and Meisner, 1990). Though they may experience some decreases in habitat space at the southern edge of their range (Meisner *et al.*, 1987), mortality and reduced scope for growth will not be significant as the available deep habitat for these fish should increase. While distribution changes are likely, overall *C. clupeaformis* production in the Great Lakes is expected to remain stable, if not increase.

Cool water: Sander vitreus

Sander vitreus is a very popular nearshore, shallower water recreational species throughout the Great Lakes and is also a commercially captured species in Canada (Knight, 1997). Commercial landings increased precipitously until catches collapsed around the basin in the first half of the 20th century due to over exploitation, pollution and degraded habitat (Roseman, 1997) but have since made significant recoveries. Though *S. vitreus* can disperse to open water in the summers, it is primarily restricted to the shallow waters and embayments of the Great Lakes and is prolific in Lake Erie and connecting waterways (*i.e.* Lake St. Clair, Detroit River), Saginaw Bay (Lake Huron), and Green Bay (Lake Michigan). As mentioned earlier, these shallower areas of the lakes will be the first to experience significant impacts from climate change. A number of key abiotic factors that influence *S. vitreus* recruitment will certainly be affected by climatic warming. The rate of spring warming and variability of May water temperature, for instance, both play important roles in structuring year-class strength during early life-history stages (Nate *et al.*, 2001). These abiotic factors serve principally as proxies for the presence and abundance of quality food sources for larval *S. vitreus* (Roseman, 1997). Additionally, adult *S. vitreus* need an extended period where temperatures are below 10^{o}C for initiation and successful completion of their gonadal maturation cycle (Hokanson, 1977). Given the forecast for warmer (*i.e.* when temperatures do not stay below 10^{o}C for extended periods of time) and shorter winters (Trumpickas *et al.*, 2009), *S. vitreus* reproductive success, and hence abundance, may be inhibited in the extreme southern edge of their range.

Nonetheless, populations of *S. vitreus* are expected to expand to more northern regions (Shuter *et al.*, 2002) and deeper depths throughout much of their present range (Chu *et al.*, 2005). The resulting increase in fish production and change in distribution of *S. vitreus* will have major implications for fisheries management because recreational and commercial fisheries come principally from different jurisdictions (*i.e.* recreational from U.S.A. states and commercial from Ontario) (Roseman *et al.*, 2008). With climate warming, management authorities could be faced with potentially contentious policy issues because of a shift northward in the abundance of *S. vitreus* populations, thus favoring stakeholders from some jurisdictions (*i.e.* Ontario) over others (*i.e.* U.S.A. states) (Roseman *et al.*, 2008).

Warm water: Micropterus dolomieu

Micropterus dolomieu is currently found in the southern regions of the Great Lakes Basin and inhabit warm water habitats. Like *S. vitreus*, it is a particularly popular recreational species but, unlike *S. vitreus*, its commercial harvest is not permitted. As a result, there have been no large scale surveys to monitor population distributions and abundances of this species within the Great Lakes. *Micropterus dolomieu* colonised the Great Lakes via multiple sequential dispersal events following Pleistocene glaciation (Borden and Krebs, 2009) and is expected to increase its range within the basin as a result of climate warming (Casselman, 2002).

Micropterus dolomieu is particularly sensitive to climatic events, particularly with respect to growth rates and nesting behaviour. Changes in growth rates, for example, are known to be associated with other global climate events, such as El Niño warming periods (King *et al.*, 1999) and changes in nesting behaviour are related to storm events (Steinhart *et al.*, 2005). Warming periods are conducive to recruitment while high intensity storms can hinder recruitment success. With climate change, warmer water temperatures and a longer growing season are predicted to lead to higher production of *M. dolomieu* because of a greater scope for growth (Shuter and Post, 1990). Casselman (2002) predicted that climatic warming would strongly favor *M. dolomieu* over northern pike *Esox lucius* L. by relating abundance indices to temperature variables for

Lake Ontario populations of both species. However, Steinhart et al. (2005) found that storms reduce *M. dolomieu* reproductive (*i.e.* nest) success. With greater numbers of extreme storm events predicted with climate change (Kling *et al.*, 2003), there is the potential for decreased *M. dolomieu* production due to this interference with successful nest recruitment.

The ability of this species to increase its range northward will thus be limited by its ability to build and protect nests in a more turbulent, high wave environment (Goff, 1986). If this does not become a major recruitment bottleneck, *M. dolomieu* is expected to extend its distribution substantially northwards to inhabit shallow water embayments and riverine systems. As its abundance increases in these areas, there is also potential for the species to exhibit competitive and predatory pressure on the current fish communities in the nearshore zones of the Great Lakes (Vander Zanden *et al.*, 2004); which may be severe enough to further change the current fish community in these regions.

Future of Fisheries Management

Climate change compounds the uncertainty of Great Lakes fisheries management, making the already difficult task more complex. With climate change, fisheries managers must consider potentially greater abundances of some fish populations, possible collapses of others and likely expanded warm-water habitat in their decision making process. These changes will, ultimately, affect opportunities for commercial and recreational fisheries in these lakes and impact the value they have in the public mindset. Management in a changing environment must be adaptive and decisive in the face of uncertainty. While improving data sets, ecological modelling, and predictions will surely aid decision makers with more precise planning (Smith, 1991a), management initiatives often need to be implemented before such improvements to the predictions can be fully achieved. The question for managers is how to implement measures that effectively sustain Great Lakes fisheries using the available science.

Site-based management is, ultimately, ineffective and inappropriate, given the scale at which the threats from climate change act upon Great Lakes fisheries and their ecosystems. The application for this type of management paradigm, which has been used as the standard in addressing many 20th century concerns in fisheries management (*e.g.* overfishing in specific areas, point source pollution), is clearly not adequate for broad-scale threats such as climate change. Stabilising a segment of shoreline on Lake Erie will not, for example, ensure that the habitat is suitable for *S. vitreus* if the winter temperature exceeds 10^{o}C. To address issues, such as climate change, at a broad scale, management must shift from site-based to regional-based; higher levels of governance are needed to prioritise landscape-level actions for rehabilitation efforts (see Liu and Taylor, 2002 for examples). By considering Great Lakes fisheries management from a basin-wide scale, managers can act strategically, comprehensively, and in a coordinated fashion so as to better address key elements. This approach will increase the resiliency of the fisheries for the entire basin.

The second issue that needs to be recognised for effective Great Lakes fisheries management in the face of a changing climate is that there are few realistic opportunities for mitigating its effects. If there is no change in greenhouse gas emissions, it is estimated that up to one-third of plant and animal species worldwide will be “committed to extinction” by 2050 (IPCC 2007). It is important to take responsibility for the consequences of anthropogenic changes to biodiversity; but, even if some remediating changes are implemented, chances are it will not be enough to protect all Great Lakes species. Thus fisheries managers must gauge their ability to rehabilitate, maintain, or enhance these ecosystems and the expense of such action in relation to its benefits and likelihood of success. As optimistic as fisheries managers might like to remain, pragmatic management strategies will serve the resources, and the public better. As management ethics have the goal of conserving natural resources for future generations, fisheries managers must focus their efforts on populations and species of fish that are capable of being conserved in the face of changing climate *in lieu* of those, such as the cold water *C. clupeaformis* in Lake Erie, that are not likely not to persist.

Learning from Aquatic Invasive Species Management

The spread of aquatic species beyond their native ranges, be it intentionally or unintentionally, is considered one of the most ubiquitous and detrimental processes to natural ecosystems (Ricciardi and Rasmussen, 1998). It can also serve as a model, of what should and should not be done, for designing management methods to address climate change. Despite the often devastating consequences of invasions, forecasting aquatic species invasions and taking precautionary measures are almost always difficult to implement because of tracking the potential paths of invasion (Cooney, 2005). Management of invasive species is often reactionary; a response to successfully established threats. This approach to management is inherently inefficient, expensive, (OTA, 1993) and almost always unsuccessful (*i.e.* does not eradicate the threat).

Because of its large-scale causes and implications, the effects of climate change may be orders of magnitude greater than the effects of aquatic invasive species observed to date. Reactionary management measures may have less potential to ‘restore’ fish populations to pre-climate change conditions than is even possible when dealing strictly with aquatic invasive species. The Great Lakes will probably never return to a prior state, but the term ‘restore’ brings exactly that connotation to the public. Fisheries and ecosystems may be rehabilitated to some level of former state and function, such as a given spawning stock biomass or specific water quality variables; but ecosystems evolve and the managers and the public must be prepared to cope with that change.

Natural resource managers are increasingly aware of the importance of human values in the process of achieving management goals (Decker *et al.*, 1996). Jacobson & McDuff (1998) state that people must be considered 'the beginning, middle, and end of all management issues. Recognition of this central role will improve our ability to conserve.' The public can inform and improve sustainable strategies for managing effects on natural resources related to climate change in comparison with what has been used to manage effects of invasive species. Coping with change is difficult for the general public. Managers and researchers often struggle to prepare the public for inevitable changes that are bound to occur.

A prime example of this is the introduction of predatory Chinook salmon *Oncorhynchus tshawytscha* (Walbaum) in Lake Huron to control invasive alewife *Alosa pseudoharengus* (Wilson). A manufactured byproduct of this fishery management strategy has been the creation of a highly valued recreational fishery for *O. tshawytscha* (Whelan, 2004). Subsequent decreases in biomass of *A. pseudoharengus*, a function of *O. tshawytscha* predation, climatic conditions and other invasive species (*i.e. Dreissena* spp. mussels), have caused the *O. tshawytscha* population and the recreational industry dependent upon it to crash in recent years (Johnson *et al.*, 2007).

Concurrently, populations of recreationally viable native species of fish including *S. vitreus, S. namaycush, M. dolomieu* and *E. lucius* have rebounded (Johnson *et al.*, 2007). These species, however, are not perceived by the public to have the same value as *O. tshawytscha*. This is somewhat ironic as residents on Lake Huron three-quarters of a century ago did not have the productivity of native species that is present today and they would likely have found the recreational and commercial opportunities provided by the current fish communities in Lake Huron to be outstanding and highly valuable. This highlights the importance of perception of value in fisheries management. The recreational fishery for *O. tshawytscha* was nonexistent mere decades ago. But, as the salmonid fishing industry grew and boomed, people came to rely upon its economic outputs and set expectations that were unrealistic for the Lake Huron fishery ecosystem.

Managers preparing strategies for climate change have an advantage over those dealing with aquatic invasive species in that effects from climate change will likely be gradual. While people are resistant to change and the change associated with aquatic invasive species is generally rapid and drastic, climate change will occur over a much longer period of biological time. As such, managers will have time to educate the public on predictions for ecosystems changes, mitigating the negative perceptions by giving the public time to adjust and accept the changes.

Climate Change Decision Support

Forecasting the effects of climate change on Great Lakes fisheries, as with aquatic invasive species, will be a difficult task because the projections have high uncertainty and also because fisheries management needs to effectively integrate differing perspectives and competing objectives (Clemen and Reilly, 2001). Good decisions require good information, but in the absence of perfect knowledge about a fishery and its ecosystem, managers can use adaptive management practices in the decision making process (Enck and Decker, 1997). In the context of Great Lakes fisheries management, climate change poses to have a significant, long-term impact, affecting the biological, economic and social functioning of this system. By integrating these analyses into the management process, decision support tools can facilitate the communication of the most current scientific, economic and social data and management outcomes. An understanding of the interactions between these factors will improve the prospect for implementing appropriate conservation action that is feasible, cost-efficient and sustainable.

Jones *et al*. (2006) argued that mechanistic modelling of habitat changes, which incorporates the interactions of multiple climate-induced changes to thermal habitat with fish population dynamics, is a useful, though by no means perfect, approach to fisheries management. As a working example of this approach to decision support, Jones *et al*. (2006) developed a series of models linking habitat parameters with population dynamics for *S. vitreus* in Lake Erie and applying five climate change scenarios. This study found that warmer temperatures led to increased habitat space for *S. vitreus*, primarily in the central and eastern basins of Lake Erie, but that lower lake levels counteracted that increase to produce a net decline in habitat space in the western and central basins. While high uncertainty limits the predictive powers of this and other modelling exercises, Jones *et al*. (2006) revealed potentially important interactions between *S. vitreus* habitat (*i.e.* basin hydrology and lake levels) and population dynamics (*i.e.* larval recruitment) which can help inform management decisions.

For these large-scale impacts, decision support tools can be particularly useful because ecosystem and regional-level issues are dynamic and operate at large spatial scales (Gavaris, 2009). Fisheries management also includes multiple considerations (*e.g.* biological, economic, social and political) involving many participants (Lane and Stephenson, 1998). In the context of the three thermal guild case studies, decision support tools can assist in defining policies that increase the resiliency of fish populations in the Great Lakes to the impacts of climate change. Building from the Jones *et al*. (2006) example, when setting harvest allocations for Lake Erie *S. vitreus*, managers could potentially take climate change into consideration by lowering catch quotas in the western and central basins while maintaining quotas in the eastern basin. In the case of *M. dolomieu*, a biological understanding of future habitat usage could allow for the management of extended seasons for recreational fisheries. With regards to *C. clupeaformis*, because it has a particularly important commercial fishery, managers could use predicted habitat and population changes to allocate quotas appropriately among the multiple jurisdictional interests (*i.e.* state, provincial and tribal). With the integration of interdisciplinary considerations, decision support tools can assess multiple decision alternatives (Lane and Stephenson, 1998) and can help objectively compare potential policies and their outcomes for the fish, their ecosystems and society (Azadivar *et al.*, 2009).

As helpful as it sounds to have a decision support tool simplify these complexities, it is important to note that these decision support tools are just that, *i.e.* decision support. They will not 'fix' the Great Lakes and their limitations must be taken into account (Shim *et al.*, 2002). Models of natural systems, for example, are rarely very precise or reliable; but, they can examine proposed management actions and suggest which options are the most feasible to carry forward through the policy process (Riley *et al.*, 2003). When carefully applied, they can assist with making better decisions (Azadivar *et al.*, 2009) but may not necessarily give a manager the 'correct' answer in an unpredictable environment. The managers and decision-makers cannot shirk the responsibility for the management of the resources to a support tool (Taylor and Dobson, 2008).

Climate change will surely challenge the flexibility of current Great Lakes fisheries management programs and require enlisting public support to set realistic expectations. Learning from past experience and the public's perception of invasive species management, a precautionary, adaptive approach to managing Great Lakes fisheries is essential. Decision support tools provide a platform for integrating the best and most current science with management needs to craft appropriate fisheries conservation action in the face of a changing climate.

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CHAPTER 2: THE NEED FOR DECISION-SUPPORT TOOLS FOR A CHANGING CLIMATE: APPLICATION TO INLAND FISHERIES MANAGEMENT

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Abstract

Large-scale environmental impacts, such as those of climate change on fisheries, require policy and management action not only at the local level, but at regional, national and international levels. Fisheries biology and ecology, along with social, political and economic considerations, can influence policy design and implementation. Decision-support tools can integrate these sciences to distil often complex, mechanistic and synergistic processes into a format that the public, policy makers and managers can use when designing strategies to ensure fisheries sustainability in the face of large-scale environmental perturbations, such as climate change. Harvest management of lake whitefish, *Coregonus clupeaformis* (Mitchill), in the Laurentian Great Lakes provides an excellent case study to examine the value and utility of a decision-support tool for inland fisheries management when considering the effects of climate change because this fishery is expected to be impacted by future changes in water temperature, ice cover and wind speed.

KEYWORDS: climate change, decision support, inland fisheries management

Introduction

Fisheries policy makers, in concert with managers, set fishing regulations, ideally to balance the ecological productivity of fish populations with the current and future needs of fisheries resource users. A primary goal of fisheries management decisions is sustainable use of the resource (i.e. continued use with minimal ecological impact). Fisheries research, historically external to this decision-making process, can provide information to assist policy makers in forming decisions if reliable and clearly articulated information is available. It is common for researchers to complete a study or develop a new approach and then feel frustrated when it is not implemented into management (Roux *et al.*, 2006). Rather than reflect on this fact, it is more productive to question why the research was not implemented into management. In this article, discussions within human dimensions are drawn upon to explore factors that influence fisheries management decisions with the purpose of providing context for the utility of decision-support tools, particularly for inland fisheries management impacted by a changing climate. Incorporating policy implications into research is a valuable exercise that will result in more relevant research and management strategies that lead to sustainability given a changing climate, as demonstrated in the concluding case study on Laurentian Great Lakes lake whitefish, *Coregonus clupeaformis* (Mitchill).

Factors that influence fisheries management decisions

Often, researchers fail to acknowledge that other factors besides fisheries biology and ecology are involved in guiding management decisions (Fig. 1). Today, there are multiple ways to approach problems and decisions are revisable (Beck *et al.*, 2003). While science is acknowledged as an important consideration for fisheries policy makers, it is not the only influence on decisions (Lahsen, 2005). Policansky (1998) observed that in many controversial topics studied by the United States (US) National Research Council, such as wetlands delineation, anadromous salmon declines and the US Endangered Species Act, science was generally not even relevant to the issues in dispute (Policansky, 1998). Ultimately, effective decisions are made by a shared commitment to a particular line of action (Sarewitz, 2004). This commitment comes from an integration of factors related to society, economics, politics and scientific uncertainty (Figure 2.1).

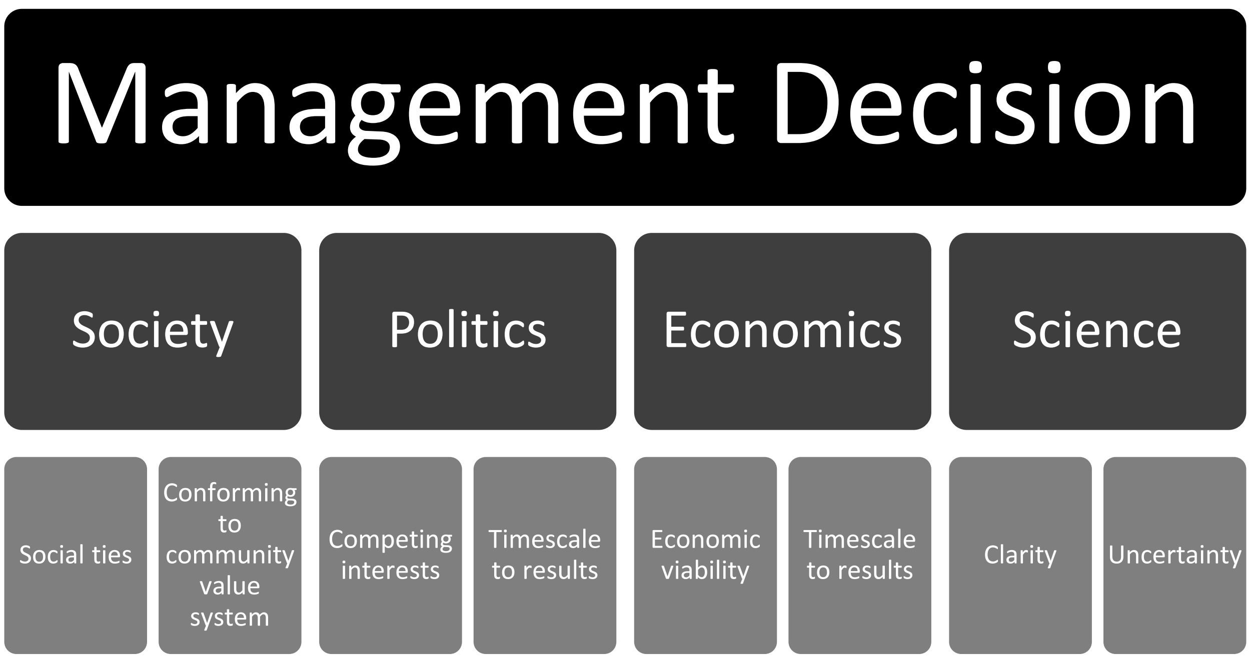

FIGURE 2.1. Factors that contribute to fisheries management decisions.

Society

Societies exert a tangible influence on and are influenced by their environment, be it through industries, voluntary associations or governing bodies (Dunlap and Catton, 1979). Fisheries systems, from subsistence fishing communities to international governing institutions, are no exception; strong social ties are important at all scales of management. In self-managed fishing communities, for example, social networks often maintain social norms and behaviours of fishers (Frank *et al.*, 2011). If a fisher does not conform to the value system of the community, he or she may be excluded from benefits of local fishing knowledge and may have lower yields. Conversely, if a fisher is well-integrated into the social network, he or she will have access to expert knowledge, high social capital and likely higher yields. For example, Leonard et al. (2011) found that a well-integrated social network supported the effectiveness of a Joint Strategic Plan for Management of Great Lakes Fisheries. Participants in the Joint Strategic Plan formed strong social ties, benefitted from an easy exchange of information and their ability to share resources facilitated the implementation of the Plan. Understanding the role of people in these fisheries systems is, therefore, important to understanding how social forces drive management decisions. Translating these factors into policy action requires consideration not only of how people have acted in the past, but also their future outlook (Peterson, 2000). Values, attitudes, beliefs, intentions and behaviours are personal motivators which, when scaled up to a societal level, influence fisheries management decisions. Fishing families and fishing communities, with strong social bonds, can be a powerful force in support of, or opposition to, the management process (Arlinghaus *et al.*, 2002). For example, US walleye, *Sander vitreus* (Mitchill), anglers on Lake Erie were integral in converting the US fishery, once dominated by commercial harvest, to solely recreational harvest (Koonce *et al.*, 1999).

Politics

Political dynamics can be a major motivation for human action and decision making, and both are heavily influenced by the political framework in which they exist (Peterson, 2000; Beck *et al.*, 2003). Because fisheries management is prescribed at a governmental level, managers are often tasked with producing results on the timescale of political appointments, which often are not biologically meaningful. As a result, political actors may prioritise short-term interests over long-term sustainability at regional, national and local levels. For example, Axelrod (2011) examined the conditions under which regional fisheries management organisations adopted climate actions (i.e. included climate change in their research and management plans). He found that member countries were more apt to favour climate action not when it aligned with scientific recommendations, but rather when it coincided with avoiding catch regulations (Axelrod, 2011). Also to circumvent catch regulations, O'Leary et al. (2011) found that European Union Fisheries Ministers engage in competitive bargaining driven by immediate national interest when setting total allowable catch (TAC) regulations. Competitive bargaining for Atlantic bluefin tuna, *Thunnus thynnus* (L.) quotas is an oft-cited cautionary tale of the impacts of quota overinflation (Safina and Klinger, 2008), but it is far from the only case. In 68% of the TAC decisions analysed by O'Leary et al. (2011), for example, quotas were set higher than the scientific recommendation for catch limits. Tan-Mullins (2007) evaluated fisheries management enforcement on a smaller governance scale, in Pattani Province, Thailand, but found similar motives (e.g. personal interests and gains) that led to unsustainable behaviours. Weak enforcement of regulations at any level of governance allows local enforcement officers to act in personal interest (e.g. accept bribes for non-compliance with ordinances) rather than enforce regulations (Tan-Mullins, 2007).

Economics

Economic influence often drives political motivations of fisheries management decisions (Beck *et al.*, 2003). Fishing, at all scales, is a livelihood and contributor to quality of life and, hence, is economically driven (Valdimarsson and Metzner, 2011). Fishers attempt to maximise profit and minimise inter-annual variation in effort, catch and market value (Christensen, 1997).

Market dynamics can be very powerful; maximizing profits and value while reducing the cost of 'doing business' is often a high priority in how decisions are rationalised (Mohai *et al.*, 2009; Valdimarsson and Metzner, 2011). Differing economic and political objectives, as a result of different governing structures, frequently weaken fisheries legislation, particularly with respect to inter-jurisdictional fisheries (Collares-Pereira and Cowx, 2004). For example, the commercial fishers who sit on the Chilean National Fisheries Council ultimately represent the interests of their industries. Appealing to potential impacts of fish processing plant closures and losses of jobs, these council members vote in favour of TAC regulations that generate higher levels of employment and perceived greater, at least on the short term, economic value, potentially at the expense of population-level sustainability (Leal *et al.*, 2010).

In effect, policy makers must often consider trade-offs between political, economic (i.e. market value) and ecological (i.e. biodiversity) services, in selecting cost-effective management options that are conscious of needs for predictability (Farber *et al.*, 2006), although one need may not be exclusive of the other. Often, conservation action is beyond the economic scope of a region (Collares-Pereira and Cowx, 2004). However, there are other institutional processes, such as subsidies and incentives, which may decouple the economic viability and ecological sustainability of fishing. If fisheries management is realigned with resource and market realities, for example through rights-based systems, the sector can become attractive to fishers, investors and consumers (Valdimarsson and Metzner, 2011).

Scientific uncertainty

Often it is appropriate for fisheries managers to weigh other factors as much as fisheries biology and ecology. But, it is not appropriate for them to claim scientific rationale for decisions when there is none (Policansky, 1998) or defer decision making until a given level of scientific certainty is achieved (McCright and Dunlap, 2010). For example, casting doubt on complex stock assessment methods has been used as a shield for many fisheries, including Inter-American Tropical Tunas (Oh, 2011), European fish stocks under the Common Fisheries Policy (O'Leary *et al.*, 2011) and Chilean fisheries (Leal *et al.*, 2010). As in these cases, scientific uncertainty can aggravate management controversy (Policansky, 1998) and is often used as a justification for not adhering to scientific advice (O'Leary *et al.*, 2011).

While reduction of uncertainty may be the central goal of scientific research conducted for management purposes (Sarewitz, 2004), predictive sciences cannot capture all stochasticity in both human and natural systems. The greater the uncertainty in a system, the less managers are able to predict the consequences of their conservation action. Decision making under these conditions must be flexible and adaptive and able to incorporate new information and circumstances into its processes so that management and policy are implemented most effectively and efficiently (Grafton, 2010). Reducing uncertainty narrows the range of potential strategies and likely increases certainty of resultant policy outcomes.

Decision support

While improved data sets, modelling and predictions will surely aid decision makers with more precise planning (Smith, 1991b), many fisheries management decisions must be implemented before such improvements to the predictions can be achieved (de Bruin and Hunter, 2003). For example, the International Commission for the Conservation of Atlantic Tunas is responsible for maintaining stock levels of highly migratory species at sustainable levels in the Atlantic Ocean. While in many cases, incidental catch of non-target species also under their purview is largely unknown, the Commission has to determine the harvest limits on both the target fisheries and associated bycatch species (Lynch *et al.*, 2011). Often such decisions lack scientific input because the science is not available or highly uncertain to the decision makers at the time of need (Klein *et al.*, 2008; Lynch *et al.*, 2010).

Decision-support tools

The question policy makers and managers often grapple with is how to determine regulations that ensure sustainability using currently available science. It is the role of fisheries scientists to ensure that fisheries biology and ecology are understood and not misrepresented in the decision-making arena (Policansky, 1998). One way to do this is to use decision-support tools, which can come in many forms including economic models, integrated assessment models, policy simulations and mechanistic models of ecosystem processes. Each approach has strengths, weakness and limits when applied to fisheries management (see Table 2.1). The overall goal of any decision- support tool is to identify policy options within the range of a desired outcome in the face of uncertainty. The different types of tools deal with uncertainty in different ways; uncertainty can be considered resolved prior to decision making (i.e. deterministic), random and in need of an iterative approach to management (i.e. stochastic) or as a likelihood where policy recommendations are determined through optimisation procedures (i.e. integrated assessment models). Understanding how uncertainty is accounted for is important to increase the transparency, objectivity and inclusiveness of management decisions (Jones and Bence, 2009), and the likelihood of voluntary compliance with those decisions.

Integrated assessment models typically link a climate model with models of the economic system, land use, agriculture or ecosystems, depending on which is applicable to the question being addressed (NCR 2010). These models can examine proposed management actions and suggest which options are likely to reach the most desired policy outcomes as defined by the managers or stakeholders involved (Riley *et al.*, 2003). Particularly for large-scale impacts, such

TABLE 2.1. Select decision-support tools, their approaches, strengths, and weaknesses with relation to fisheries and climate change. Modified from NRC (2010) Table 4.1.

Tool	Modelling approach	Strengths	Weaknesses
Economic models	-Cost-effectiveness/cost-benefit analysis -Agent based models	-Estimates the costs and benefits of policies	-Difficult to measure beyond economic value
Integrated assessment models	-links relevant sub-models: climate, economic system, land use, agriculture, and/or ecosystems	-Examines proposed management actions in the context of pre-defined desired policy outcomes	-Complex -Difficult to validate -Do not account for tradeoffs
Policy simulations	-Heuristic methods	-Compares alternative policies -Accounts for tradeoffs	-Simple; may not capture full implications
Mechanistic models	-Ecosystem processes	-Analyzes the impact of changes in climate on the environment and human activity -Capable of capturing synergistic effects	-Complex -Difficult to validate -Do not account for tradeoffs

TABLE 2.2. Examples of potential effects of climate change and impacts on inland fish production.

Direct effects	Indirect effects	Inland fisheries impacts
↑ water temperatures	↑ eutrophication Δ in location of optimal thermal habitat	↓ dissolved oxygen Δ in species abundance and distribution possible ↑ in invasive species
↑ evaporation	↓ river discharge ↑ groundwater extraction	↓ habitat space
↑ extreme storm events	↑ runoff ↑ flash flooding	↑ habitat contamination

as climate change, which are experienced at local and regional scales, management decisions need a method to evaluate management options for wide geographic ranges. This requires governance at a regional or higher level and a thorough understanding of landscape-level impacts on a system (for examples, see (Liu and Taylor, 2002). While they are helpful for examining the synergies of these dynamic systems, integrated assessment models are difficult to validate and do not allow for value trade-offs (i.e. different stakeholder values of what should be conserved, enhanced or sacrificed).

Mechanistic models are often the ecosystem component (e.g. risk analysis of ecosystem indicators) of integrated assessment models. They are ecological (i.e. involve population or food web dynamics) and consequently tend to be complex (i.e. parameter rich) and difficult to validate. When modelling fish movement, for example, spatial processes can be inferred from recreating spatial patterns rather than from actual observed movement behaviour (Humston *et al.*, 2004). By examining and integrating these ecological responses, these models can be informative tools for decision support to fisheries management. However, decision makers must understand that most models are specific and do not address all ramifications of actions (e.g. while a fish population may rebound under a certain harvest regime, that regime may have other negative impacts to the ecosystem). The strength in these models is that they allow scientists and decision makers to recognise possibilities that may not be inferred from more empirical, but less integrated, approaches (Jones *et al.*, 2006). For example, Jones et al. (2006) found that the projected impact of climate change on walleye population dynamics was quite different using multiple factors (temperature, river hydrology, lake levels and light penetration) than just considering temperature alone.

It is important to note, however, that decision-support tools are just that – decision support. They will not fix problems, and their limitations must be taken into account (Shim *et al.*, 2002). Fisheries science is an important process that provides predictable information and answers questions but does not make decisions (Sarewitz, 2004). These tools aid decision making by systematically incorporating information, accounting for uncertainties and facilitating evaluation of trade-offs between different choices (NRC, 2010). By formalizing the complexities of a system into a modelling framework, decision-support tools can provide managers with a quantitative comparison of potential policy outcomes (Azadivar *et al.*, 2009). Decision-support tools cannot make policy choices, but rather assess the implementation of those choices (Sarewitz, 2004). The onus of the decision still resides with the decision maker (Taylor and Dobson, 2008), not a support tool.

Application of science-based decision support to inland fisheries management

Decision-support tools may help inform successful inland fisheries management strategies as they can be designed to assist management at a range of geographic scales. Arlinghaus et al. (2002) suggested that decision-support tools can improve decision making for the management of inland fisheries resources by providing options that maximise societal welfare without compromising the integrity of aquatic ecosystems. By capturing synergies of multiple types of information (e.g. economic, social, biological), decision-support tools can ensure a more transparent, objective and inclusive management process (Azadivar *et al.*, 2009; Jones and Bence, 2009). To be effective, decision-support systems should involve individuals, organisations and institutions with decision-relevant information and be readily communicable to decision makers and stakeholders (NRC, 2010). Citizen involvement needs to be a key component in the design of a decision-support tool because more ownership generally equates to higher implementation success (Irvin and Stansbury, 2004) and voluntary compliance.

Effective and efficient river management, for example, must connect monitoring and assessment of the water cycle to ensure that the approach produces the desired outcome (Goethals and De Pauw, 2001). Restoration projects whose objectives are narrowly focused may be incomplete, and consequently, they likely will not accomplish their goals because they do not consider the impact of the key factors driving system processes (Verdonschot and Nijboer, 2002). For example, Lynch and Taylor (2010) found that small-scale restoration projects for brook charr, *Salvelinus fontinalis* (Mitchill), could not always fulfill their proposed objectives, likely because of larger-scale perturbations. To incorporate these important components into a model requires considering large-scale before small-scale influences. Addressing large-scale problems, like upstream agricultural run off, through which moving water may spread waste and disease over a wide distance, will strengthen the success of localised efforts (Verdonschot and Nijboer, 2002), such as restoration of habitat structure for brook charr further downstream.

Climate change and inland fisheries

Managing inland fisheries is a complex task, with or without the added potential effects of climate change. Addressing climate-related risks proactively, whether the impacts are mild or severe, will be beneficial to fisheries because these actions may buffer against other ecological changes (Hay and Mimura, 2006; Grafton, 2010). For example, climate change will manifest itself in more ways than just temperature increases in aquatic habitats (e.g. precipitation patterns, evapotranspiration, wind patterns, ground water and surface water inputs and dissolved oxygen content). As a result, models regarding fish production that account only for thermal habitats may not be sufficient to predict the full suite of consequences of climate change to these populations and their fisheries (Jones *et al.*, 2006).

Potential impacts of climate change on inland fisheries

Fish stocks continually face stress associated with human transformation of the land, air and waterscapes, including fishing, loss of habitat, pollution, invasive species and pathogens (Brander, 2007). These factors lead to changes in the production dynamics of affected waterways and their biotic communities, impeding resiliency of these communities to environmental changes (Planque *et al.*, 2010). For instance, global air temperature increases over the past 50 years (1955–2005) have been nearly twice what they were in the preceding 100 years (IPCC 2007). As water temperature, quantity and quality are all influenced by climate, the effects of this warming have been predicted to affect the distribution, production and abundance of freshwater fishes (Regier and Meisner, 1990).

Although surface fresh water accounts for only 0.01% of global water supplies and 0.8% of the earth's surface, it provides habitat for approximately 40% of global fish diversity, 25% of global vertebrate diversity (Dudgeon *et al.*, 2006) and 23% of global aquatic production (in 2004; (Brander, 2007), as well as being an essential component to human life and well-being. Inland waters are particularly sensitive to landscape-level changes because they have a direct tie to terrestrial inputs and experience the compounded effects from perturbations further upstream in a watershed. Freshwater ecosystems are highly vulnerable to land use alterations, invasive species and climate change because of the proximity to and impacts from people (see Table 2.2). Additionally, these effects impact both the quantity and quality of ground water and surface water delivered to these environments that influence fish distribution and production. Terrestrial runoff of nutrients and sediments from human use have the potential to impact freshwater ecosystems, contributing to eutrophication and loss of fish species (Sala *et al.*, 2000). Climate change may potentially exacerbate land use alterations by directly modifying the aquatic environment (i.e. change thermal regime, habitat volume and food resources; (Jones *et al.*, 2006).

In addition to the direct effects of climate change, many fish populations and associated fisheries will be indirectly threatened by the associated environmental changes. These impacts include alterations to water regimes through water use (i.e. agricultural, domestic and industrial use and alterations; (Wilby *et al.*, 2010). Lake Tanganyika, Africa, for example, supported a productive fishery in the 1990s with annual harvests ranging from 165 000 to 200 000 t (Molsa *et al.*, 1999), providing up to 40% of the animal protein consumed in its surrounding countries (O'Reilly *et al.*, 2003) . As a result of climate change and human alteration of the landscape, warmer waters have caused the Lake Tanganyika water column to become stratified (O'Reilly *et al.*, 2003), limiting nutrient circulation between the hypolimnion and epilimnion in lakes, which, in turn, limits primary production in the pelagic zone and the trophic chain dependent upon it. O’Reilly et al. (2003) estimated that decreasing primary production in Lake Tanganyika by 20% has the potential to reduce fisheries yields by up to 30%.

The effects of climate change will also likely increase some inland fish populations and decrease others. For example, if smallmouth bass, *Micropterus dolomieu* (Lacepède), extends its range as projected to inhabit more northern inland lakes of North America (Chu *et al.*, 2005), these fish will likely negatively impact the diverse cyprinid communities that will serve as their forage base (Jackson and Mandrak, 2002). Conversely, cold water stenotherms (i.e. able to survive in a narrow range of cold temperatures) are predicted to retract north as waters warm. Ultimately, ecosystem-scale changes will alter waterscape productivity, opportunities for subsistence, commercial and recreational fisheries to exist and how those fisheries can be managed in sustainable ways.

Managing inland fisheries in a changing climate

The regional to global impacts of climate change will require drastically different approaches to fisheries management than are currently used at local levels (Lynch *et al.*, 2010). Widely used methods, such as site-based management, are largely inefficient and ineffective at addressing regional disturbances because their fragmented approach often does not target the source of large-scale problems because they are beyond the scope of understanding or geo-political jurisdiction. As a result, these methods do not generally provide a solution to regional problems (Verdonschot and Nijboer, 2002). Liu and Taylor (2002) suggested that management should be coordinated through higher levels of governance for landscape-level conservation action. For example, rehabilitation efforts for brook charr in the Eastern US have historically focused on site-specific habitat restoration and these efforts have been generally unsuccessful at reversing population declines (Lynch and Taylor, 2010). In response to these continued declines of brook charr populations, the Eastern Brook Trout [Charr] Joint Venture (EBTJV) formed as a multiorganisation partnership of state and federal agencies, non-governmental organisations and academic institutions to identify and address range-wide threats, such as agricultural practices, climate change and urbanisation to brook charr populations. The EBTJV is an important model for collaborative regional aquatic management because it considers broader scales than site-specific habitat (i.e. stream segment) to manage brook charr across its entire Eastern US range. The Great Lakes Fishery Commission (GLFC) is another success story in multi-jurisdictional management. Although not a regulating body itself, the GLFC facilitates the cooperation among management agencies throughout the Great Lakes basin and is a forum for scientific exchange and basin-wide strategic fisheries planning (Gaden *et al.*, 2012).

Even when attempts are made to address large-scale impacts such as climate change, the question remains of how to incorporate the uncertainty of climate variability into policy (Wilby *et al.*, 2010). Managers must adapt their strategies for organisms and habitats of concern in the face of uncertainty regarding their future states. In addition to the ecosystem impacts, fisheries managers must also consider the social and economic effects on subsistence, commercial and recreational fisheries in the communities they manage. In regards to potential changes, management policies and practices must be realigned for the conservation objectives to be feasible in the face of climate change while still fulfilling societal priorities and needs (Lynch *et al.*, 2010; Wilby *et al.*, 2010). Sustainability of inland fisheries can only be achieved when there is balance between economic development to meet changing human needs and the conservation of natural resources and their habitats to absorb the stressors resulting from these human activities (Hay and Mimura, 2006).

One way of approaching sustainability is the use of adaptive management protocols. These treat management action as an iterative, experimental approach with adjustments to policies and management practices based on the ecological and social responses to initial action (Prato, 2003). Adaptive management considers people an integral part of any system, and as such, their impacts and influence cannot be ignored. As a result, adaptive measures will have the greatest acceptance when they have the greatest benefit to multiple stakeholders over a long period of time (Wilby *et al.*, 2010). Adaptive management is well suited to address the future effects of climate change on fisheries sustainability because it is designed to provide a buffer against ecological and socio-economic uncertainties by adjusting strategies based on informative monitoring systems (Walters, 1986). Management can, consequently, be adaptive but decisive in the face of uncertainty and the current limitations of climate and fisheries projections.

Harvest management of lake whitefish with climate change

The following case study from the Laurentian Great Lakes exemplifies the utility of the emerging interdisciplinary field of fisheries decision support to inland fisheries management in a changing climate. The purpose of its inclusion is to identify the need to develop new tools to address objectives from multiple stakeholders and help optimise management strategies in diverse fisheries ecosystems.

Potential impacts of climate change on lake whitefish

Since 1980, populations of lake whitefish have supported the most economically valuable commercial fishery in the upper Laurentian Great Lakes (Lakes Huron, Michigan and Superior; annual catch value US$16.6 million, averaged over years between 1994 and 2004) (Madenjian *et al.*, 2006; Ebener *et al.*, 2008). Climate change is expected to impact the economic value of this fishery because the success of recruitment to the fishery has been linked with climatic influences, including water temperature, wind speed and ice cover (Miller, 1952; Christie, 1963; Lawler, 1965; Taylor *et al.*, 1987a; Freeberg *et al.*, 1990; Lynch *et al.*, 2010). Climate change is expected to increase surface temperatures of the Great Lakes by as much as 6 °C (Trumpickas *et al.*, 2009), average wind speed is expected to decline (Sousounis and Grover, 2002), and ice cover is expected to be substantially reduced (Assel *et al.*, 2003). In their current habitat space, increased water temperature, decreased wind speed and decreased ice cover are projected to inhibit the success of recruitment to the lake whitefish fishery (Lynch *et al.*, 2010). However, the warming trends associated with predicted climate change should increase suitable thermal habitat volume for lake whitefish (Magnuson *et al.*, 1997) because the species could shift northwards and deeper in the water column to maintain optimal thermal habitat (Regier and Meisner, 1990). Given these changes, the overall amount of new thermal habitat space for lake whitefish in the Great Lakes is projected to exceed reductions that are coincident with the warming of their more nearshore and southern extremes.

Potential impacts on lake whitefish management

Climate change impacts on lake whitefish production dynamics add ecological and social dimensions for consideration in designing and implementing sustainable management programmes. Currently, lake whitefish management spans at least 35 Native American governments, eight US states and the Province of Ontario, Canada (Ebener *et al.*, 2008). Most of the management in the Great Lakes occurs on a stock-by-stock basis without cross-jurisdictional cooperation (Ebener *et al.*, 2008). This type of management is not adequate for addressing large-scale environmental threats such as climate change; management must shift to more regional governance that encourages landscape-level conservation efforts (Liu and Taylor, 2002). Such landscape approaches to fisheries management will help avoid fragmentation of fisheries policies in each jurisdiction, which have historically resulted in the demise of fish populations and their associated fisheries (see (Taylor *et al.*, 2013)). As lake whitefish move deeper and more northerly in these lakes to find optimal habitat as a result of changes in climate, the stock distributions and production dynamics will not remain in their current jurisdictional structure. Managers and society, like the fish themselves, must therefore adapt their strategies to the ecological realities that come with a changing climate. Decision-support tools, based on reliable monitoring and evaluation systems, will be a key feature of future adaptive management strategies for this fisheries ecosystem and will assist policy makers, managers and society in adjusting their behaviours and expectations to allow for productive, sustainable fisheries.

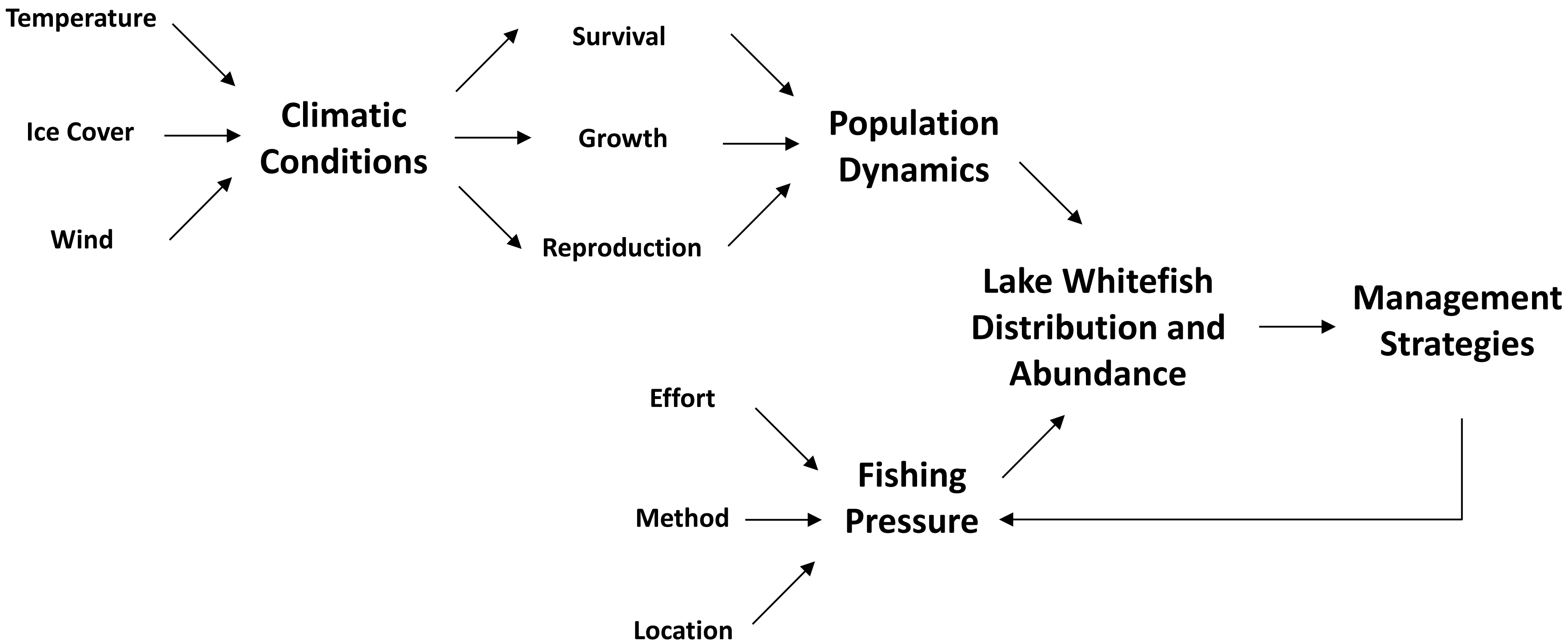

FIGURE 2.2. Schematic of the ecological inputs and anticipated outputs of a mechanistic decision-support tool to sustainably manage lake whitefish (*Coregonus clupeaformis*) production in a changing climate.

Need for decision support

As the public demands a greater voice in decisions over management of natural resources (Lord and Cheng, 2006), it is essential that management incorporates stakeholders into the decision-making process through integrated assessment approaches (MI Sea Grant & Graham Environmental Sustainability Institute 2009). Without general acceptance, management measures have a low probability of acceptance and, consequently, adherence (Decker *et al.*, 2006). Lord and Cheng (2006) argued the main barrier to stakeholder involvement is the lack of public support and understanding of the science, costs and benefits of management options, the decision-making process and monitoring and evaluation systems. By seeking public input on the design of decision-support tools, these tools can better address objectives from multiple stakeholders on an ecosystem level. They can help optimize the most effective management strategies (Azadivar *et al.*, 2009) and likely enable agencies to implement effective monitoring systems to gauge the success of their actions and need for adjustments. With meaningful public integration into the process, decisions will be culturally and socially acceptable while ensuring the resilience and sustainability of the fish populations and their ecosystems.

For lake whitefish, decision-support tools will be informative for managers, policy makers and stakeholders (e.g. commercial fishermen, seafood consumers and community residents). Integrating these key players into the process increases a sense of ownership and accountability (Irvin and Stansbury, 2004) and ensures that proposed solutions address fundamental problems (Roux *et al.*, 2006). As such, decision-support tools can be effective ways to simplify complex ecological processes and social structures (Figure 2.2). They inform the public and the diverse, often non-scientific, audience who is tasked with allocating scarce fisheries and financial resources (Sarkar *et al.*, 2006), allowing for a more informed decision-making dialogue. By comparing scenarios of lake whitefish production with climate projections over ecologically relevant (i.e. generational) timescales, these tools can use science and stakeholder input to assist decision makers with making more informed choices that should increase the sustainability of this species and related human prosperity for current and future generations.

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CHAPTER 3: PERCEPTIONS OF MANAGEMENT AND WILLINGNESS TO USE DECISION SUPPORT: INTEGRATING THE POTENTIAL IMPACTS OF CLIMATE CHANGE ON THE LAKE WHITEFISH (*COREGONUS CLUPEAFORMIS*) FISHERY INTO HARVEST MANAGEMENT IN THE 1836 TREATY WATERS OF LAKES HURON, MICHIGAN, AND SUPERIOR

Lynch, A. J., W. W. Taylor, A. M. McCright. *In Prep*. Perceptions of management and willingness to use decision support: Integrating the potential impacts of climate change on the Lake Whitefish (*Coregonus clupeaformis*) fishery into harvest management in the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior.

Abstract

Decision-support tools are designed to aid decision making by systematically incorporating multiple sources of information, accounting for uncertainty in estimates, or facilitating evaluation of trade-offs between alternatives. However, if they are not implemented with investment from the users, decision-support tools fail to achieve their intended goal. This study investigated the perceptions of fishery management and the willingness to use decision-support tools for fishery management. The survey recommendations informed the development of a decision-support tool for the potential impacts of climate change Lake Whitefish (*Coregonus clupeaformis*) recruitment in the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior, which hosts a significant portion of the economically, socially, and ecologically important Lake Whitefish fishery. Climate change is expected to influence Lake Whitefish recruitment because recruitment has been linked to temperature, wind, and ice cover, variables all projected to alter with climate change. We surveyed researchers, fishery managers, and fishermen affiliated with the fishery to document perceived barriers and opportunities to developing a decision-support tool from a Lake Whitefish climate-recruitment projection model. Survey respondents indicated that decision-support tools can be useful to inform management. But, they highlighted a number of barriers for implementation of decision-support tools, including lack of political will and uncertainty in decision-support outputs. These considerations were incorporated into the design of a decision-support tool for Lake Whitefish in the 1836 Treaty Waters which will provide guidance on anticipated changes in recruitment with a changing climate to ensure a prosperous and sustainable fishery, now and in the future.

KEYWORDS: decision-support tools, fishery management, Lake Whitefish (*Coregonus clupeaformis*), recruitment, climate change, 1836 Treaty Waters

Introduction

The purpose of decision-support tools is to make scientific knowledge more accessible to decision makers (Moser, 2012). Management decisions will be made, with or without the input of adequate science. In order to be useful, decision-support tools must addresses management-informative questions and communicate information to decision makers in a clear, logical manner. To do this most effectively, decision-support tools must be documented and designed with the input from the potential users.

Lake Whitefish and climate change decision support

Lynch *et al.* (2012) suggested that decision-support tools could be useful for informing managers, fishers, and other stakeholders about the potential impacts of climate change on the Lake Whitefish (*Coregonus clupeaformis*) fishery in the Laurentian Great Lakes. This fishery is the largest and most economically valuable commercial fishery in the upper Laurentian Great Lakes (Madenjian *et al.*, 2006; Ebener *et al.*, 2008) and there is concern that climate change could impact the fishery because recruitment of fish to a harvestable size has previously been linked to climatic conditions (Miller, 1952; Christie, 1963; Lawler, 1965; Taylor *et al.*, 1987a; Freeberg *et al.*, 1990; Lynch *et al.*, 2010).

Approximately one quarter of the total Lake Whitefish harvest in the upper Great Lakes comes from The 1836 Treaty Waters of Lakes Huron, Michigan, and Superior (Figure 3.1; M. Ebener, Chippewa Ottawa Resource Authority, *personal communication*). Lynch *et al.* (Chapter 3) suggest that including climate variables, specifically temperature, wind, and ice cover, in stock-recruitment models results in better model fit to the recruitment data than models without climate variables for a majority of the 1836 Treaty Waters management units. Projecting those climate recruitment relationships with the Coupled Hydrosphere-Atmosphere Research Model

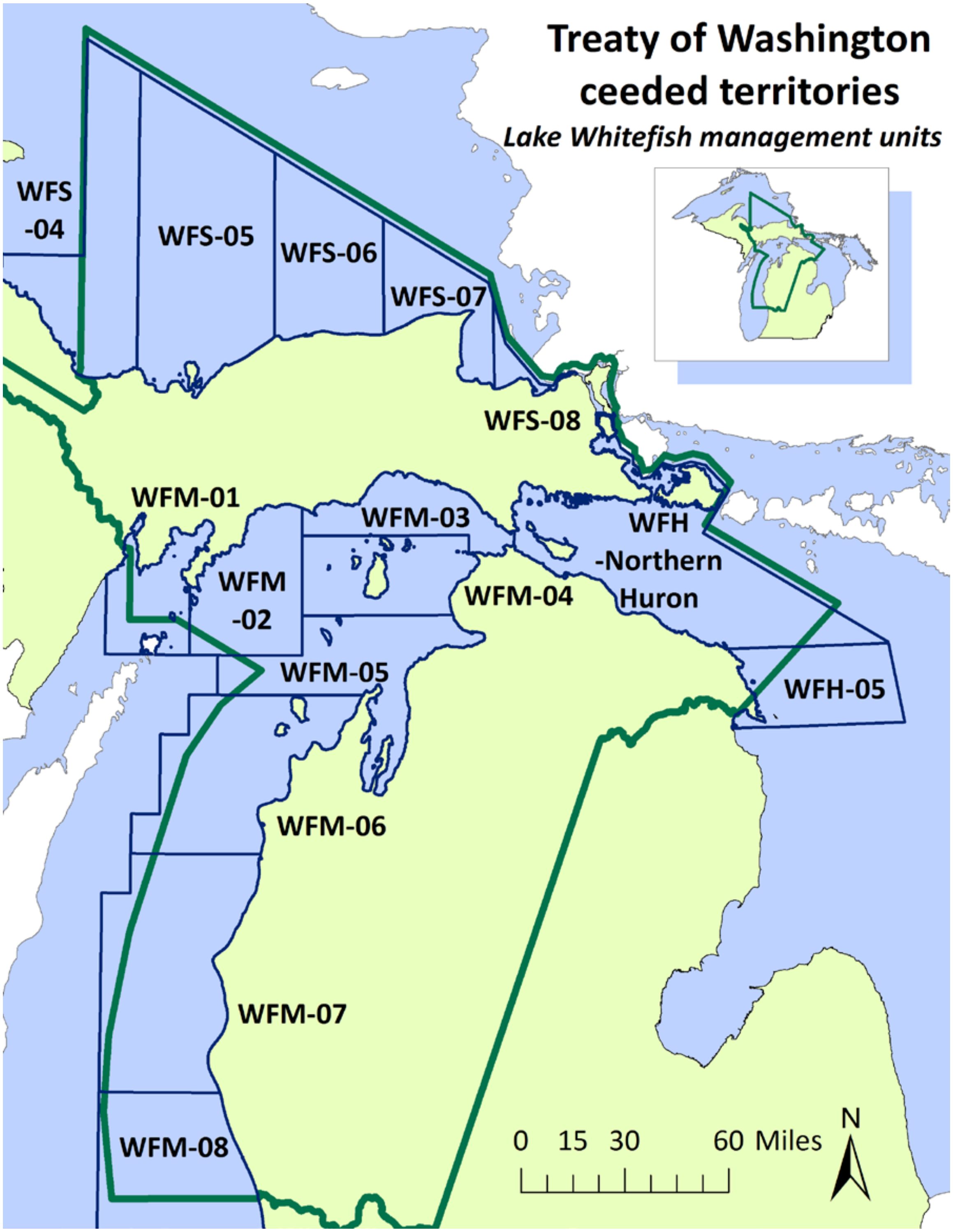

FIGURE 3.1. Land and water territories ceded by the Chippewa and Ottawa nations in the 1836 Treaty of Washington and Lake Whitefish (*Coregonus clupeaformis*) management units managed under the 2000 Consent Decree. For interpretation of the references to color in this and all other tables and figures, the reader is referred to the electronic version of this dissertation.

(Lofgren, 2004), Lynch *et al.* (Chapter 4) found potential for increased Lake Whitefish recruitment with climate change, if stock size was held constant.

The goal of this study was to investigate the perceptions of Lake Whitefish management and willingness to use decision-support tools. The outcomes informed the design of a decision-support tool from the Lynch *et al.* (Chapter 4) model to inform management of Lake Whitefish in the 1836 Treaty Waters of the potential implications of climate change.

Methods

Study location fishery management

The 1836 Treaty Waters of Lakes Huron, Michigan, and Superior are managed by the Chippewa Ottawa Resource Authority (CORA), a cooperative agency among the Bay Mills Indian Community, Grand Traverse Band of Ottawa and Chippewa Indians, Little River Band of Ottawa Indians, Little Traverse Bay Band of Odawa Indians, and the Sault Ste. Marie Tribe of Chippewa Indians. In accordance with the 2000 Consent Decree, CORA is advised by a Technical Fisheries Committee and Modeling Sub-Committee to set harvest quotas. In some of the management units, CORA co-manages with the Michigan Department of Natural Resources. The 2000 Consent Decree directs managers in the 1836 Treaty Waters to maintain profitable and sustainable harvest of Lake Whitefish.

Lake Whitefish management and decision-support survey design

We designed a two pronged survey to document perceived barriers and opportunities for implementing a decision-support tool for Lake Whitefish given changes to climate variables, specifically temperature, wind, and ice cover, in the 1836 Treaty Waters. We chose to use a detailed consent form (Appendix 3.1) to fully explain the purposes of the project to participants and a short survey to encourage broader participation (Appendix 3.2). In addition to five demographic questions, we included five modified Likert-scale questions (Likert, 1932) and two open-ended questions to allow respondents the opportunity to elaborate, if desired. The survey included a sequence of questions related to current Lake Whitefish management:

- How satisfied are you with the management of Lake Whitefish in the 1836 Treaty Waters?
- What could improve *current* management of Lake Whitefish in the 1836 Treaty Waters?
- What issues are important for the *future* management of Lake Whitefish in the 1836 Treaty Waters?

and a sequence of questions on decision-support tools:

- Can decision-support tools be useful for fisheries management?
- What are barriers to use of decision-support tools in fisheries management?
- How well is science integrated into Lake Whitefish management in the 1836 Treaty Waters?
- What factors are important for integrating science into Lake Whitefish management in the 1836 Treaty Waters?

We specifically designed the survey to target Lake Whitefish biologists, managers, and fishers as survey respondents because they are the most likely potential users of a decision-support tool related to Lake Whitefish management in the 1836 Treaty Waters because they influence, define, and accept Lake Whitefish management decisions. We distributed the surveys to the 1836 Treaty Waters Technical Fisheries Committee, Modeling Sub-Committee, Bay Mills Indian Community Conservation Committee, and Great Lakes Fishery Commission Upper Great Lakes Committee Meeting participants. We distributed the survey at events where these potential participants were present, in concert with a presentation on the results of the Lynch *et al.* (Chapter 4) projection model of Lake Whitefish recruitment with climate change. We intentionally linked the survey with this modeling project to provide context for the type of scientific information that could be used in a climate change decision-support tool.

Lake Whitefish management and decision-support survey analysis

The quantitative data from the Likert-scale questions on perceptions of Lake Whitefish management and willingness to use decision-support tools were compiled and evaluated using descriptive statistics (e.g., count, mean, mode). Descriptive statistics are useful for examining the patterns in the data and summarizing the survey samples (Mann, 2012). The qualitative data from the survey complimented the quantitative data by putting the quantitative responses in context. We grouped the open-ended comments by topic and used them to assist with explanatory patterns in the quantitative survey responses. These comments provide rationale for quantitative survey responses which can inform management of Lake Whitefish in the 1836 Treaty Waters and the development of a climate change decision-support tool for Lake Whitefish in the 1836 Treaty Waters.

The Michigan State University Committee on Research involving Human Subjects (IRB# x12-1284e) reviewed the methods and questions posed in this study and deemed them exempt status in accordance with federal regulations.

Results

The survey was completed by 31 individuals between April 2013 and October 2013. Thirty of the 31 survey participants were male. Seven percent of respondents were 18-29; 42% were 30-49; 35% were 50-64; and 9% were 65+ (Figure 3.2; 7% did not indicate age).

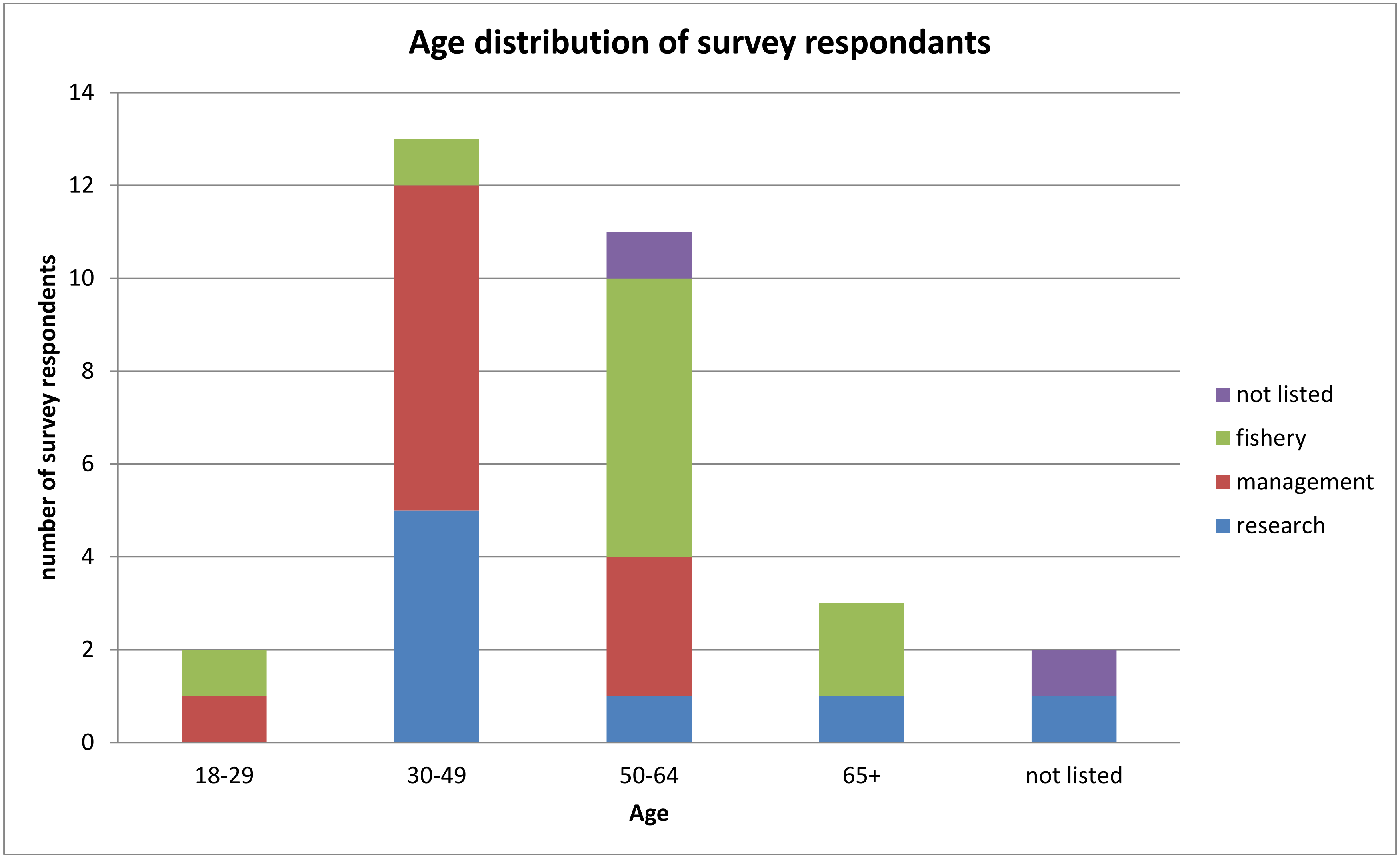

FIGURE 3.2. Age distribution of survey respondents by primary affiliation.

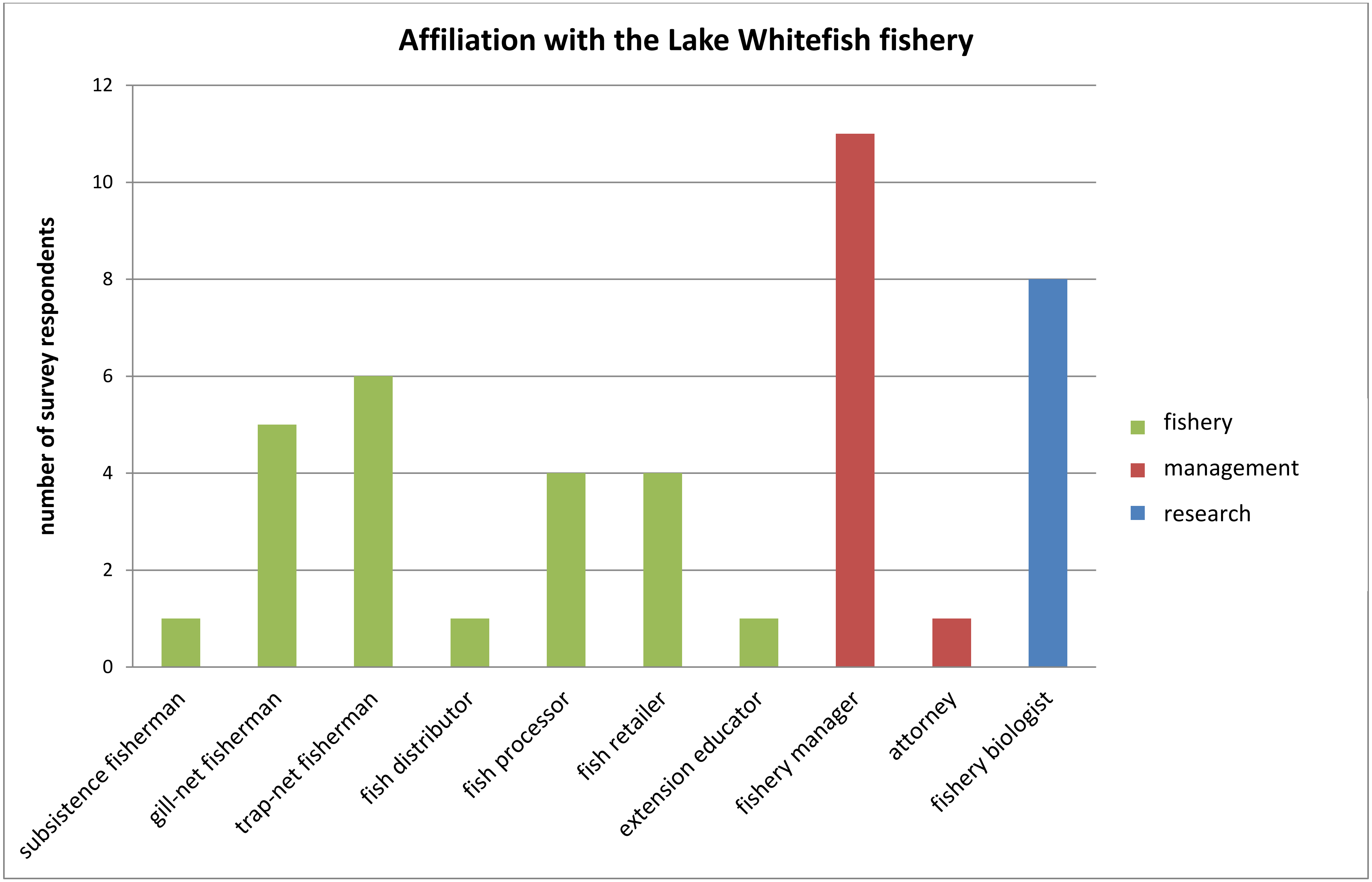

FIGURE 3.3. Lake Whitefish (*Coregonus clupeaformis*) fishery affiliation of survey respondents by affiliation. *Note that respondents could select more than one affiliation.*

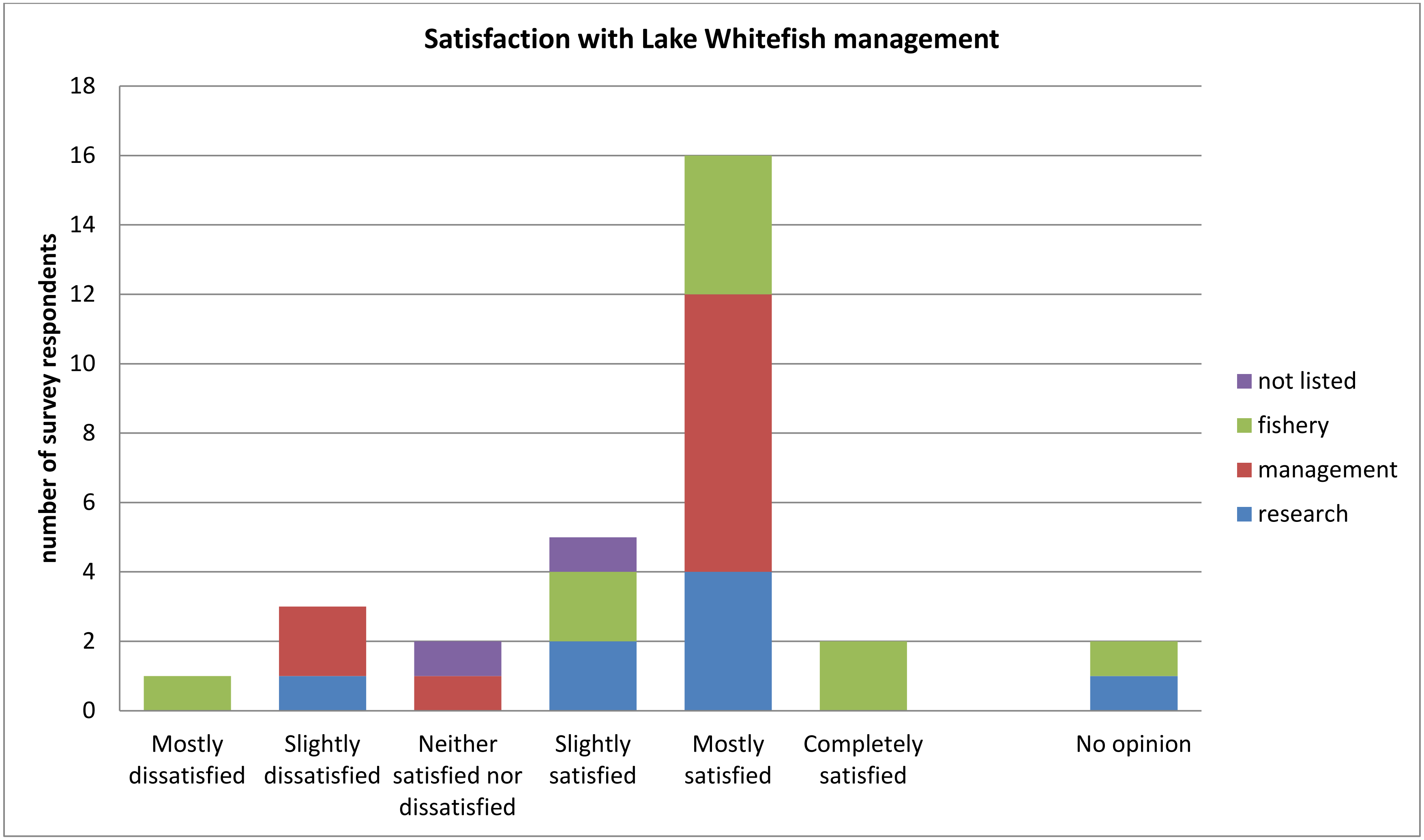

FIGURE 3.4. Satisfaction level of survey respondents with current management of the Lake Whitefish (*Coregonus clupeaformis*) fishery in the 1836 Treaty Waters by primary affiliation.

TABLE 3.1. Survey respondent recommendations for improving management of Lake Whitefish (*Coregonus clupeaformis*) in the 1836 Treaty Waters, grouped by topic.

Research needs

Population models

- "Better population models, if possible."
- "Collect data from all management units."
- "Functioning population models."
- "Knowledge of stock-specific characteristics including size-at-age, maturity schedules, weight at age, age composition structure to compliment mixed stocks analysis results."
- "More accurate models."
- "More comprehensive population level data."

Recruitment estimation

- "A better understanding of recruitment dynamics for all Coregonines."
- "A good pre-recruit survey for scaling the SCAA predictions."
- "Ability to plan ahead in terms of management based on predictions of year class would be great."
- "Better and more timely estimates of year class strength."
- "Better estimates of recruitment!"
- "Better estimates/predictions of recruitment."
- "Better knowledge of early life histories (young fish)."
- "Better recruitment estimates."
- "Better understanding of recruitment indices."
- "Better understanding of recruitment."
- "Better understanding of recruitment."
- "Better understanding of what controls recruitment now that ice cover is infrequent."
- "Without question, a reliable predictive model of recruitment (and I'm not just saying this)."

Additional data needs

- "[Consideration for] multi-species fisheries!"
- "Better estimates of mature mortality lakewide."
- "Better understanding of mechanistic relationships between fisheries population and environmental/food web variables."
- "Fishery independent survey data."
- "Improved/effective fishery independent lake whitefish surveys to track annual changes in abundance and age structure (in some areas)."

Management recommendations

Cooperation

- "[Add a] state fisher person on TFC."
- "Continue cooperation between the tribal and state fisheries management agencies [to] plan ahead for the next consent agreement."
- "Enhanced state tribal regulations and cooperation."

TABLE 3.1 (cont'd).

Cooperation (cont'd)

- "Political will to pursue sustainable management."
- "Stakeholder buy-in on scale and severity of issue."
- "While the biologists get along well, once you bring the attorneys and the various party leaders in, things become more contentious."

Allocation

- "Allocating adequately high TAC while still preserving stock."
- "Application of conditional constant catch policies."
- "Backing off 'the edge' of sustainability to a more 'optimal' yield rather than 'maximum' yield approach."
- "Expand the fishery itself."
- "To be assured that we get all of our treaty water returned."

Funding considerations

- "More funding for research and studies to increase staff and equipment for biological staff."
- "Having our own [tribal] hatchery."
- "There are data gaps which need to be addressed; Staffing reductions are causing [data gaps]."
- "Increased sampling."
- "More funding for fisheries support staff."
- "Less costly methods than SCAA for estimating allowable catch."

Invasive species control

- "Ballast water exchanges farther down river."
- "Controlling the invasive species - like lamprey, zebra mussels, Eurasian Ruffes."
- "Reduce lamprey mortality in some management units."
- "Better understanding of the influence of invasive species on sustainability of stocks."
- "Better estimates of lamprey mortality lakewide."

Eleven individuals self-identified as fishery managers; eight as fishery biologists; and 21 identified as being affiliated with subsistence or commercial fishing (Figure 3.3; *note that survey respondents could identify with more than one category*). Among the survey participants, experience with the Lake Whitefish fishery ranged from less than a year to over 60 years (fourth generation in the fishery).

Perceptions of Lake Whitefish management

Survey respondents were predominately satisfied with current management of the Lake Whitefish fishery in the 1836 Treaty Waters. Twenty-three of the 31 respondents identified with the slightly, mostly, or completely satisfied categories (Figure 3.4). When asked what could improve current management of Lake Whitefish in the 1836 Treaty Waters, respondents made suggestions that fit broadly in the following categories: 1) research needs; 2) management recommendations; 3) funding considerations; and, 4) invasive species control (Table 3.1).

The survey asked participants to indicate the importance of 11 issues selected by researchers and managers as potentially relevant to the future management of Lake Whitefish in the 1836 Treaty Waters:

- Allocation
- Bycatch
- Climate change
- Communication
- Habitat loss or modification
- Human population growth
- Invasive species
- Land-use changes

- Market forces
- Overexploitation
- Water quality and quantity

There was an overall tendency in the survey responses towards listing categories as more important than not important on a four item Likert scale but there was consistency across participants in the designation of important and non-important issues (Figure 3.5). Some of the issues that were stressed in current management, specifically allocation and invasive species control, were also highlighted by survey respondents as issues of future importance. Invasive species was listed as the most important factor for the future management of Lake Whitefish (27 respondents listed it as very or moderately important), followed by bycatch and market forces (26 respondents, each); and allocation, climate change, communication between managers and fishermen (25 respondents, each). Human population growth was overwhelming considered the least important issue (12 respondents listed it as not important), followed by land-use change (8 respondents), and overexploitation (5 respondents).

Willingness to use decision-support tools

While a large majority of survey respondents (26) believed that science is moderately, well, or very well integrated into the management process (Figure 3.6), respondents suggested that improvements can be made. Again, showing a tendency towards listing categories as more important than not important, all but one of the respondents listed all seven factors identified to facilitate the integration of science into Lake Whitefish management (addressing significant management problems; being transparent with research methods and analyses; communicating clearly to fishers and/or managers; creating decision-support tools; ensuring incorporation into long-term management; involving fishers and/or managers in the research process; and,

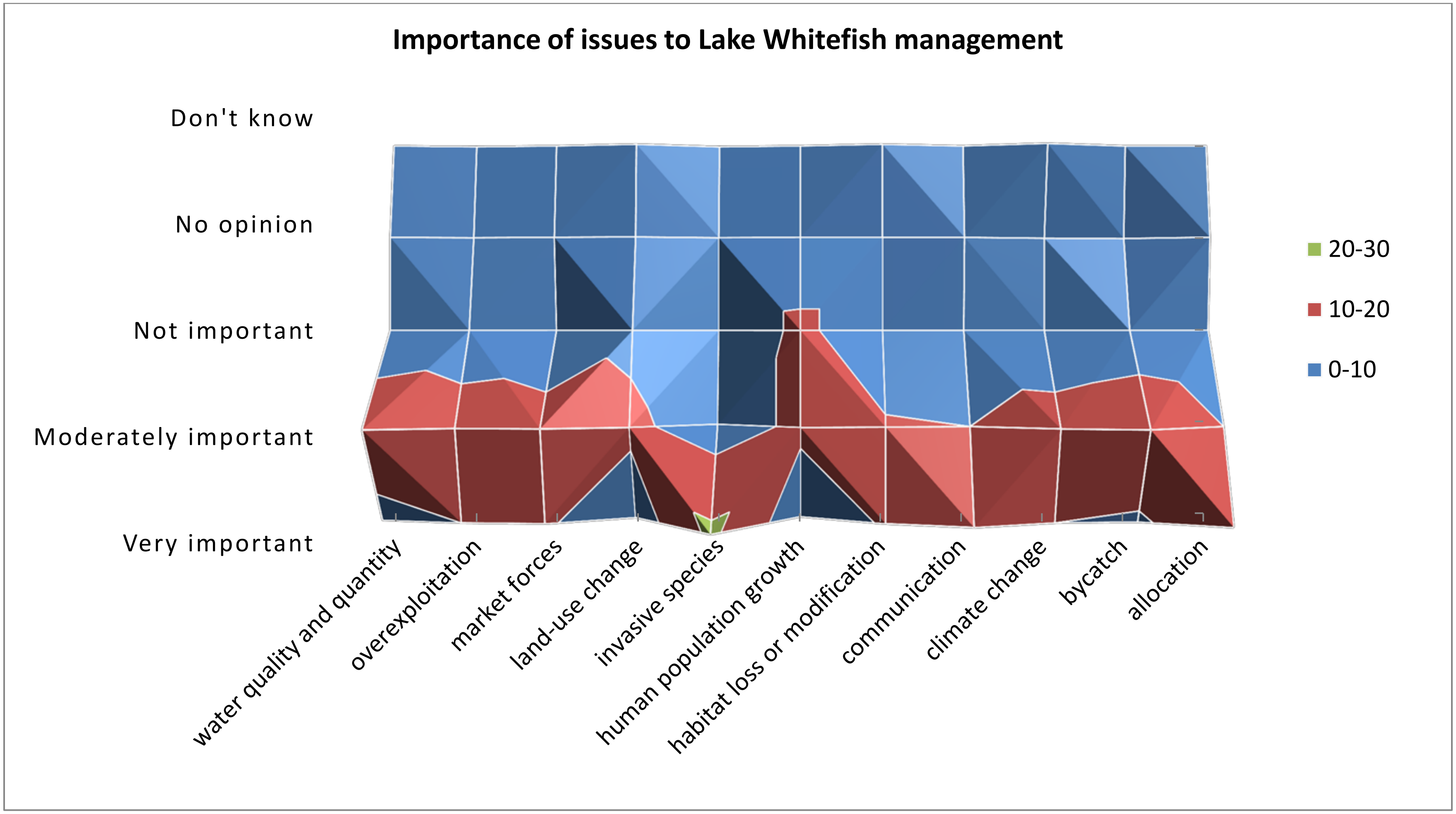

FIGURE 3.5. Heat map of survey responses to the importance level (not important, moderately important, very important) for 11 issues to the future management of Lake Whitefish in the 1836 Treaty Waters: allocation, bycatch, climate change, communication, habitat loss or modification, human population growth, invasive species, land-use changes, market forces, overexploitation, and water quality and quantity. A heat map is three dimensional with the height and color indicating intensity of importance for each issue: green = 20-30 respondents, red = 10-20 respondents, and blue = 0-10 respondents.

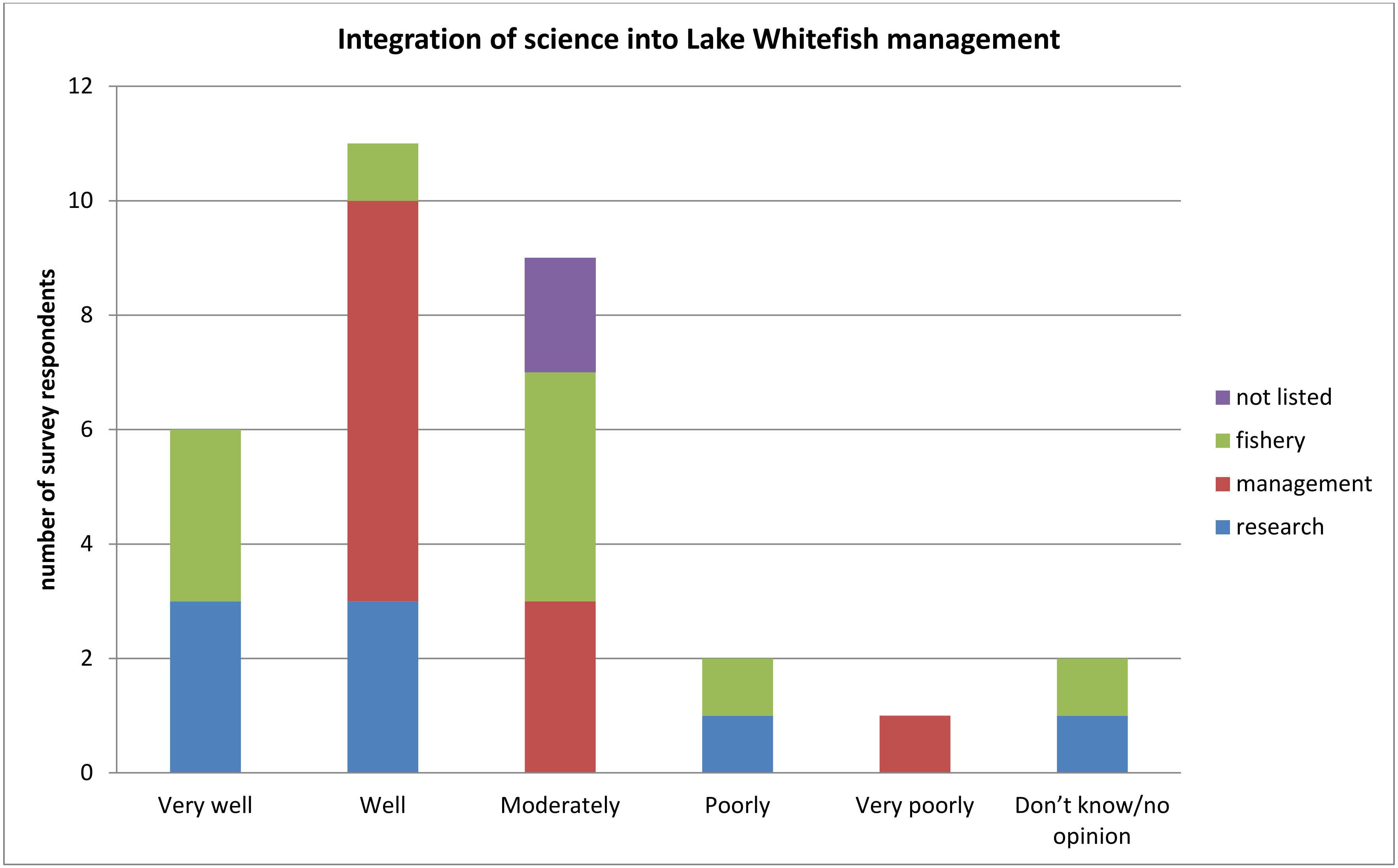

FIGURE 3.6. Survey responses to how well integrated science is into Lake Whitefish (*Coregonus clupeaformis*) management in the 1836 Treaty Waters (very well; well; moderately; poorly; very poorly; don’t know/no opinion) by primary affiliation.

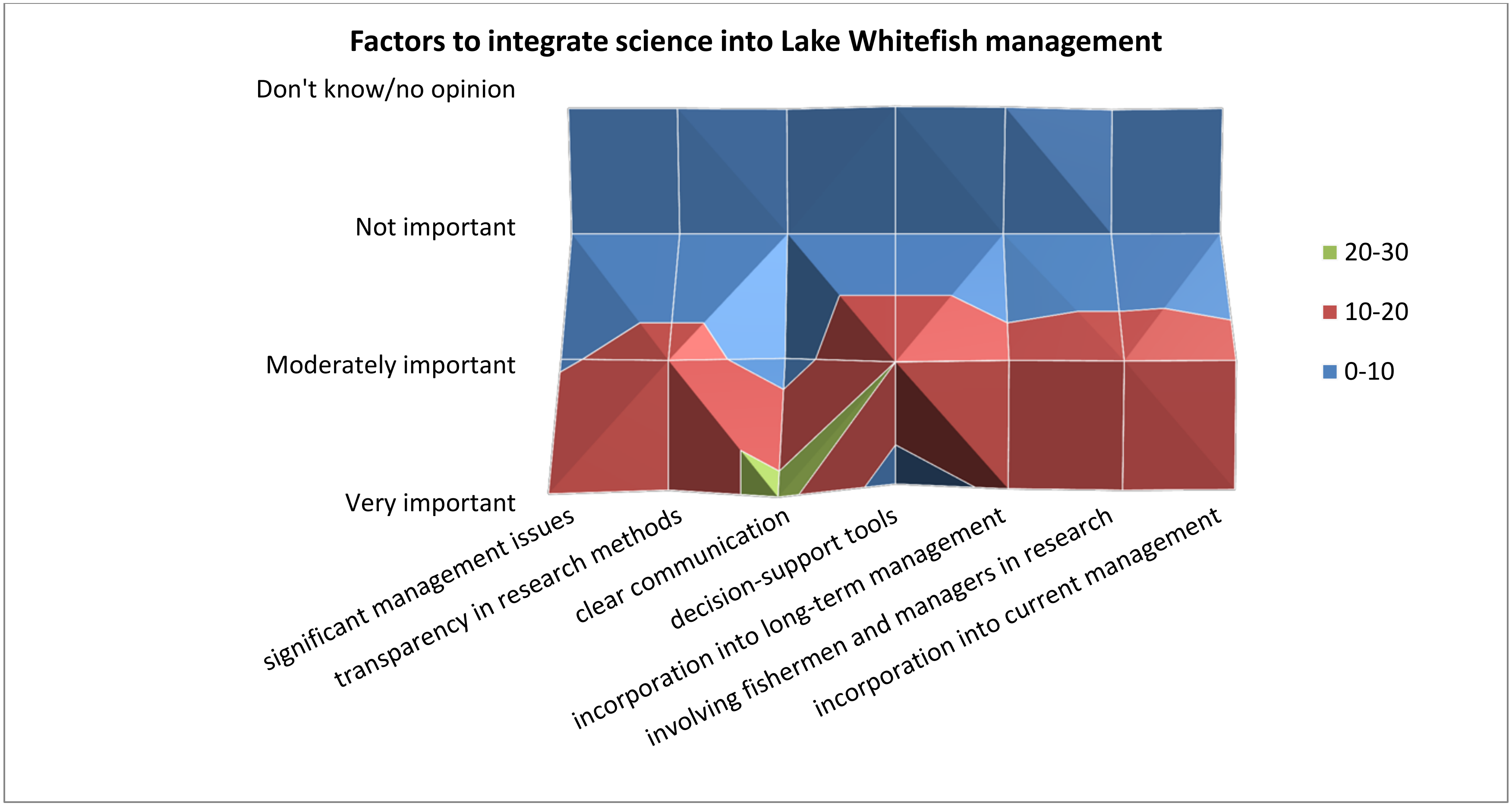

FIGURE 3.7. Heat map of survey responses to the importance level (not important, moderately important, very important) for seven factors to facilitate integration of science into Lake Whitefish management in the 1836 Treaty waters: addressing significant management problems; being transparent with research methods and analyses; communicating clearly to fishers and/or managers; creating decision-support tools; ensuring incorporation into long-term management; involving fishers and/or managers in the research process; and, providing recommendations within the structure of current management. A heat map is three dimensional with the height and color indicating intensity of importance for each issue: green = 20-30 respondents, red = 10-20 respondents, and blue = 0-10 respondents.

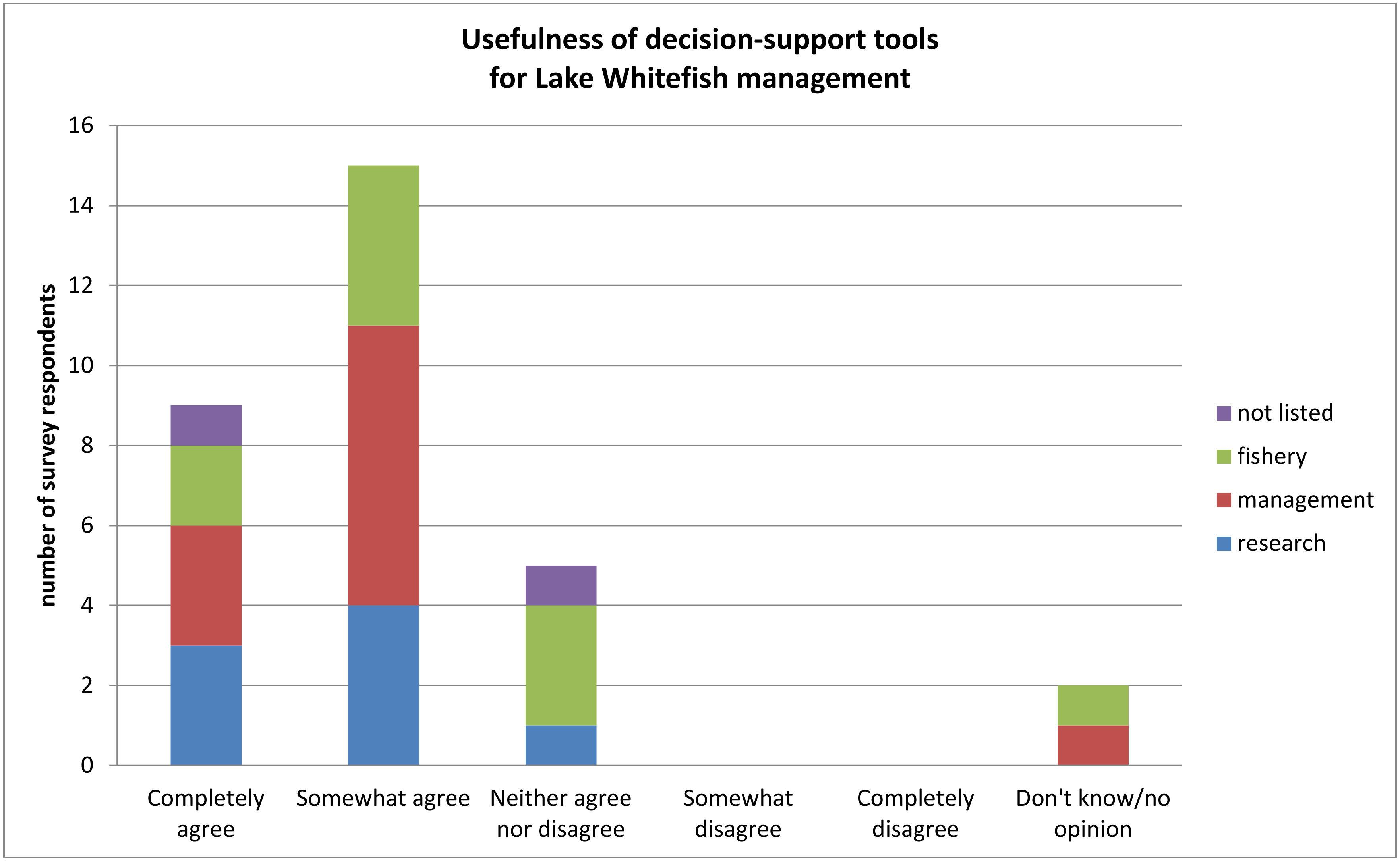

FIGURE 3.8. Survey responses to the usefulness of decision-support tools to Lake Whitefish (*Coregonus clupeaformis*) management in the 1836 Treaty Waters (completely agree; somewhat agree; neither agree nor disagree; somewhat disagree; completely disagree; don't know/no opinion) by primary affiliation.

TABLE 3.2. Survey respondent listed barriers implementing decision-support tools in Lake Whitefish (*Coregonus clupeaformis*) management in the 1836 Treaty Waters, grouped by topic.

Political will

Communication

- "Communication and understanding."
- "Difficult to communicate with fishers."
- "Direct interaction with the fishers [to] give more "real time" data on what is going on with fishing capacity."
- "Poor communication."

Control

- "I think people are generally unwilling to relinquish control and allow objective tools to weigh in on decisions. Management is largely politics, and the objective decision is often not the preferred decision."
- "Political process."
- "Reliance on single method for decision-making."

Participation

- "Acceptance of the process."
- "Agency buy-in."
- "Buy-in."
- "Lack of participation at all levels of interested parties."
- "Making sure participants are objective in their thinking."
- "Making sure you get management and fishermen buy in before getting too far. Don't want to finish only to have them reject it for lack of involvement."
- "Participation by certain stakeholder groups."

Unfamiliarity

- "Has not been widely used in the past and may not be readily accepted in the future."
- "Misunderstanding about function and application of tools."
- "Understanding of process and data/fisheries management, etc."

Data issues

Uncertainty

- "Adequate fisheries information system (information system does not equal common or even centralized database)."
- "Appropriate underlying models."
- "Do they address real world situation?"
- "It's sometimes easier to assume we have one outcome; it makes action easier. Uncertainty is messy and often requires making qualitative judgments, which is hard."
- "Lack of consensus on 'unknowns'."
- "Model assumptions and over generalities."
- "Models represent a larger area than what is actually being used."

TABLE 3.2 (cont'd).

Uncertainty (cont'd)

- "Over parameterization."
- "Requir[ing] a lot of information."
- "The utility of such tools is somewhat dependent on the data inputs used to design the tool. If appropriate data are used, then the tool can be robust."
- "There are still data limitations (data gaps) to deal with in the current models."
- "Too variable."
- "Unclear objectives."
- "Whether you have the equipment for the right places; whether the fish are going to be where you think they should be."

Logistical considerations

- "Huge investment to run models/tool."
- "Implementation (no agency expertise in decision-support tools)."
- "Time."
- "Using SCAA is almost too costly for agencies; [They require] intense annual levels of stock assessment."

providing recommendations within the structure of current management) as moderately or very important (Figure 3.7). Clear communication of research was the most important factor (23 respondents listed it as very important) followed by addressing significant management problems (19 respondents).

Decision-support tools can assist with both clearer communication and addressing significant management problems. In the listing of factors identified to facilitate integration of science into Lake Whitefish management, 5 respondents also identified decision-support tools as very important and 20 listed them as moderately important. When directly asked, survey respondents overwhelmingly agreed that decision-support tools can assist management for Lake Whitefish in the 1836 Treaty Waters. Twenty-four of the 31 respondents somewhat or completely agreed that decision-support tools can be useful for Lake Whitefish management and no respondents disagreed (Figure 3.8). The respondents qualified the utility of decision-support tools with potential barriers to implementation that fit broadly into the following categories: 1) political will, including communication, decision control, participation, and uneasiness with using decision-support tools, and, 2) data issues, including uncertainty and logistical considerations, such as time and cost to develop harvest allocations (Table 3.2).

Discussion

The survey responses were well representative of the three major potential user groups for a decision-support tool concerning Lake Whitefish in the 1836 Treaty Waters: fishers, managers, and researchers. Our targeted survey distribution ensured almost complete representation of managers in addition to representative samples of fishermen and researchers. While researchers and managers are well distributed among the younger age brackets, 80% of those identifying primarily with the fishery were over 50 years old (Figure 3.2). This age distribution may be a significant concern for management engagement and the longevity of the fishery because the younger fishers are either not actively involved in management or not present in the fishery.

Perceptions of Lake Whitefish management

Overall, survey participants were more satisfied than dissatisfied with management (Figure 3.4). Those affiliated with the fishery had the widest range (from “mostly dissatisfied” to “completely satisfied”) and, perhaps not surprisingly, managers were the most satisfied with the work they were conducting (73% of surveyed managers were “mostly satisfied”). Nonetheless, all survey respondents had recommendations for ways to improve Lake Whitefish management in the 1836 Treaty Waters (Table 3.1). These recommendations fell broadly into four broad categories:

- Research needs
- Management recommendations
- Funding considerations
- Invasive species control

Research recommendations primarily focused on the need for better population models and better estimates of recruitment. “Without question, a reliable predictive model of recruitment,” wrote one respondent; “better population models,” wrote another.

The management recommendations focused on the need for better cooperation between managers and fishers and some even gave specific suggestions for allocation changes. These comments well-aligned with the importance of allocation and communication indicated in Figure 3.5. Survey respondents cited “political will” and “stakeholder buy-in” to support more effective management. Without public input, management measures have low probability of acceptance

(Decker *et al.*, 2006). The additional layer of complication for the 1836 Treaty Waters is the tribal-state management dynamic. "Continued cooperation between the tribal and state fisheries management agencies" will be particularly necessary with the upcoming reauthorization of the 2000 Consent Decree. Allocation will also surely be a topic with reauthorization of the Consent Decree. Survey recommendations for allocation were diverse; from "expand[ing] the fishery" to focusing on "more 'optimal' yield rather than 'maximum' yield;" with optimal yield, effort is maximized rather than yield. As shown from these recommendations, meaningful public integration and management cooperation will be necessary to make culturally and socially acceptable allocation decisions which also ensure the resilience and sustainability of Lake Whitefish populations and their ecosystems through long-term, rather than short-term planning.

As with many management needs, changes generally require funding. The survey recommendations emphasized the need for more "staff and equipment for biological staff," "increased sampling," and even suggested considering adding a tribal hatchery or considering less costly methods than statistical catch-at-age models to determine harvest quotas. While the survey respondents agreed on the need for funding, the diverse suggestion of needs highlighted that they do not all agree on the same management objectives.

One item the survey respondents could agree on was that invasive species is an important concern to Lake Whitefish management. Invasive species was the most important issue listed in Figure 3.5 and numerous comments in Table 3.1 concerned invasive species. The survey comments underscored that invasive species are still an unknown with respect to Lake Whitefish management. Sea Lamprey (*Petromyzon marinus*), in particular, parasitize Lake Whitefish and the estimates of Sea Lamprey induced mortality are poor. M. Ebener (Chippewa Ottawa Resource Authority, *personal communication*) hypothesized, for example, that increased mortality on Lake Whitefish in Lake Huron is a result of stocking an alternative strain of Lake

Trout (*Salvelinus namaycush*), which has a depth preference beyond that of Sea Lamprey. Lake Whitefish may serve as an alternative host in the absence of Lake Trout availability and, as a result, may be subject to greater parasitism, reduced health, reduced fitness, reduced recruitment and, ultimately, reduced harvest.

Willingness to use decision-support tools

As evidenced by the survey recommendations for improvement, Lake Whitefish management in the 1836 Treaty Waters is no simple task, with or without considering climate change. Perhaps not surprisingly, researchers thought science is well integrated into management more than managers do and fishers were split on their perception (Figure 3.6). Nonetheless, they all recognized the importance of considering science and they overwhelming agree that decision-support tools can be useful in assisting management (Figure 3.8). Respondents cited political will and data issues as broad-scale potential barriers to the use of these tools (Table 3.2).

Political will pertains to the support needed for acceptance of decision-support tools by users, namely managers and fishers. The research cannot be applied to management if it remains only in the research arena. To effectively garner this political will, decision-support tools must overcome control barriers, lack of participation, poor communication, and the uneasiness of potential users because of unfamiliarity with the tools. Survey participants continuously noted the importance of communication between fishers and managers (Figure 3.7; Table 3.2). Managers can express an “unwillingness to relinquish control and allow objective tools to weigh in on decisions,” especially if the developed tool is poorly communicated and they do not understand the “function and application.”

Unfamiliarity can often result from data barriers to the development of decision-support tools, in particular uncertainty and logistical considerations in designing decision-support tools. One respondent questioned if decision-support tools can "address real world situations." Another believed that the utility of decision-support tools is "dependent upon the data inputs used to design the tool[s]." And logistically, decision-support tools require "time," a "huge investment to run," and "expertise" to implement. These are all very important concerns to effective implementation.

Communicating the objectives and process to design a decision-support tool to managers and fishermen so that they can participate in the design process will help ensure proper utlization. While uncertainty in the outputs and assumptions in the methods may be broad, uncertainty can sometimes serve as an impetus for contingency planning (Marx and Weber, 2012). An informed decision, even if it is qualified by significant assumptions, is generally better than an uninformed decision.

Integration into climate change decision support

Climate change poses to be a significant, long-term influence on the biological, economic, and social functioning of the Great Lakes fisheries ecosystems (Lynch *et al.*, 2010). But, there is no "clear, natural, or easy fit" between climate change research and decision making because climate change impacts will be diverse (Moser, 2012). Unlike, for example, aquatic invasive species, which have immediate and obvious effects on ecosystems and economies, climate change effects will be long-term (Lynch *et al.*, 2010). The timescale of these effects makes climate change a particularly difficult concept for the public to grasp. This is where decision support can be most useful. Decision-support tools can translate and communicate available science to improve the abilities of decision makers to make informed decisions

(Scheraga, 2012). For example, Winkler *et al.* (2012) developed a climate change decision-support tool, through the Pileus Project, to examine the potential impacts of climate change on the yield of Michigan tart cherries. Through this online tool, farmers and municipal managers can make long-term decisions in anticipation of the potential impacts of climate change on the industry.

The recommendations from this study are being incorporated into the development of a climate change decision-support tool, the Lynch *et al.* (Chapter 4) climate-recruitment model. This tool is housed on the Michigan Sea Grant website (http://www.miseagrant.umich.edu/) with an interactive, user-friendly interface to display the recruitment projections with anticipated climate change. We anticipate that this tool will be used to inform adaptive decision making for Lake Whitefish fishers and fishery managers as well as to educate the public about the potential impacts of climate change on this important fishery to the Great Lakes region. It may also serve as a model for other climate change issues in fisheries management beyond the Great Lakes basin. Ultimately, this tool aims to support informed decision making for sustainable and prosperous fishery resources and coastal communities by providing guidance on the potential impacts of climate change to recruitment of Lake Whitefish.

Acknowledgments

Dave Caroffino, Mark Ebener, Mark Holey, Ron Kinnunen, Eric MacMillan, Paul Ripple, So-Jung Youn, CSIS, MIRTH, 1836 Treaty Waters Technical Fisheries Committee and Modeling Subcommittee, and the survey participants without whom this analysis could not exist. Funding for this project was provided by a Michigan Sea Grant Coastal Communities Development Grant.

APPENDICES

Appendix 3.1. Survey Consent Form

Lake whitefish and climate change: On-Site CONSENT FORM

Improving decision-support tool design: case study on lake whitefish (*Coregonus clupeaformis*) and climate change

You are being asked to take part in a research study **on how to improve the design of fisheries decision-support tools**. *Decision-support tools aid decision making by systematically incorporating information, accounting for uncertainties, and/or facilitating evaluation of trade-offs between alternatives.* However, if they are not implemented properly, decision-support tools can fail to achieve their intended goal.

Please read the information listed below carefully.

RESEARCH OBJECTIVE: This project will investigate perceptions and recommendations for **how to successfully develop a fisheries decision-support tool**. We seek to document perceived **barriers** and **opportunities** to implementing a decision-support tool for lake whitefish and climate change.

YOUR ROLE: If you choose to participate, you will be asked to fill out **a voluntary, anonymous, 10 minute survey** on your perceptions of lake whitefish management and decision support. Your answers will be confidential. Your participation in the project is completely anonymous, voluntary, uncompensated, and **will NOT impact your involvement with the lake whitefish fishery and its management**. Your participation **will assist with the development of a decision-support tool to inform lake whitefish management given a changing climate**. *There is no penalty or loss of benefits if you chose not to participate.*

QUESTIONS? Please ask any questions you have now. If you have any questions later about the research study, please contact Abby Lynch (lynchabi@msu.edu), Bill Taylor (taylorw@msu.edu), or Aaron McCright (mccright@msu.edu). If you have any questions or concerns about your role and rights as a research participant, would like to obtain information or offer input, or would like to register a complaint about this research study, you may contact, anonymously if you wish, the Michigan State University Human Research Protection Program at PHONE: 517-355-2180, FAX: 517-432-4503, EMAIL: irb@msu.edu, or REGULAR MAIL: 207 Olds Hall, MSU, East Lansing, MI 48824. *Please ask any questions you may have before agreeing to participate in this study. Thank you for your contribution to this important study.*

STATEMENT OF CONSENT: I have read the above information and have received answers to any questions I asked. I consent to take part in this study.

Your Signature ____________________________________ Date _________________________
Your Name (printed) ____

Are you willing to be contacted for a project follow-up? If so, what is the best way to reach you?

□ email: _______________________________
□ phone: _______________________________
□ mail: _________________________________

Appendix 3.2. Survey instrument

SURVEY

LAKE WHITEFISH MANAGEMENT:

1. How satisfied are you with the management of lake whitefish in the 1836 Treaty Waters?

No opinion	Completely dissatisfied	Mostly dissatisfied	Slightly dissatisfied	Neither satisfied nor dissatisfied	Slightly satisfied	Mostly satisfied	Completely satisfied
☐	☐	☐	☐	☐	☐	☐	☐

2. What issues are important for the FUTURE management of lake whitefish in the 1836 Treaty Waters?

	No opinion	Don't know	Not important	Moderately important	Very important
Allocation	☐	☐	☐	☐	☐
Bycatch	☐	☐	☐	☐	☐
Climate change	☐	☐	☐	☐	☐
Communication between managers and fishermen	☐	☐	☐	☐	☐
Habitat loss or modification	☐	☐	☐	☐	☐
Human population growth	☐	☐	☐	☐	☐
Invasive species	☐	☐	☐	☐	☐
Land-use change	☐	☐	☐	☐	☐
Market forces	☐	☐	☐	☐	☐
Overexploitation	☐	☐	☐	☐	☐
Water quality and quantity issues	☐	☐	☐	☐	☐

3. What could improve CURRENT management of lake whitefish in the 1836 Treaty Waters?

DECISION SUPPORT:

**Decision-support tools* aid decision making by systematically incorporating information, accounting for uncertainties, and/or facilitating evaluation of trade-offs between alternative choices.

4. Can decision-support tools be useful for fisheries management?

Don't know/ no opinion	Completely disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Completely agree
☐	☐	☐	☐	☐	☐

5. What are **barriers** to use of decision-support tools in fisheries management?

6. How well is *science* integrated into lake whitefish management in the 1836 Treaty Waters?

Don't know/ no opinion	Very poorly	Poorly	Moderately	Well	Very well
☐	☐	☐	☐	☐	☐

7. What factors are important for integrating science into lake whitefish management in the 1836 Treaty Waters?

	Don't know/ no opinion	Not important	Moderately important	Very important
Addressing significant management problems	□	□	□	□
Being transparent with research methods and analyses	□	□	□	□
Communicating clearly to fishers and/or managers	□	□	□	□
Creating decision-support tools	□	□	□	□
Ensuring incorporation into long-term management	□	□	□	□
Involving fishers and/or managers in the research process	□	□	□	□
Providing recommendations within the structure of current management	□	□	□	□
Other (*please list*):	1) ______________________________ 2) ______________________________ 3) ______________________________			

DEMOGRAPHICS:

1. Gender:
   - ☐ Female
   - ☐ Male

2. Age:
   - ☐ 18-29
   - ☐ 30-49
   - ☐ 50-64
   - ☐ 65+

3. How many years have you lived in the Great Lakes basin?

   _______years

4. How many years have you worked with lake whitefish?

   _______years

5. Occupation? *Check all that apply*.
   - ☐ Fish distributor
   - ☐ Fishery manager
   - ☐ Fish processor
   - ☐ Fish retailer
   - ☐ Gill-net fisher
   - ☐ Trap-net fisher
   - ☐ Other: ________________

LITERATURE CITED

LITERATURE CITED

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CHAPTER 4: PROJECTED CHANGES IN LAKE WHITEFISH (*COREGONUS CLUPEAFORMIS*) RECRUITMENT WITH CLIMATE CHANGE IN THE 1836 TREATY WATERS OF LAKES HURON, MICHIGAN, AND SUPERIOR

Lynch, A. J., W. W. Taylor, T. D. Beard, and B. M. Lofgren. *In Prep*. Projected changes in Lake Whitefish (*Coregonus clupeaformis*) recruitment with climate change in the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior.

Abstract

Lake whitefish (*Coregonus clupeaformis*) is an ecologically, culturally, and economically important species to the Laurentian Great Lakes. Lake Whitefish have been a staple food source for those in the region for thousands of years and, since 1980, have supported the most economically valuable (annual catch value ≈ US$16.6 million) and productive (annual harvest ≈ 15 million lbs.) commercial fishery in the upper Great Lakes (Lakes Huron, Michigan, and Superior). Climate change, specifically change in temperature, wind, and ice cover, is expected to impact the ecology, production dynamics, and value of this fishery, because the success of recruitment to the fishery has been linked with these climatic factors. We used linear regression to determine the relationship between fall and spring temperature indices, fall wind speed, winter ice cover, and Lake Whitefish recruitment in 13 management units located in the 1836 Treaty Waters. Corrected Akaike's Information Criterion comparisons indicated that the inclusion of selected climate variables significantly improved model fit in eight of the 13 management units. Isolating the climate-recruitment relationship and projecting recruitment using the Coupled Hydrosphere-Atmosphere Research Model (CHARM) suggested increased Lake Whitefish recruitment in the majority of the 1836 Treaty Waters management units. These results can inform adaptive management strategies to ensure a sustainable and prosperous Lake Whitefish fishery, now and in the future.

KEYWORDS: Lake Whitefish (*Coregonus clupeaformis*), recruitment, climate change, 1836 Treaty Waters.

Introduction

Lake Whitefish (*Coregonus clupeaformis*) are an ecologically, culturally, and economically important species in the upper Laurentian Great Lakes (Lakes Huron, Michigan, and Superior). Ecologically, Lake Whitefish transfer energy from lower, benthic food webs to the upper, pelagic food webs (Nalepa *et al.*, 2005). Culturally, they have been a staple food source and traditional icon for aboriginal people in the region for thousands of years (Cleland, 1982). Economically, Lake Whitefish support the largest and most valuable commercial fishery in the upper Laurentian Great Lakes (annual catch value ≈ US$16.6 million; annual harvest ≈ 15 million lbs.; Madenjian *et al.*, 2006; Ebener *et al.*, 2008).

Observational studies of Great Lakes Lake Whitefish indicate that climatic factors are also important drivers of recruitment, but these field studies have yet to be scaled up to a management unit scale (Christie, 1963; Lawler, 1965; Taylor *et al.*, 1987a; Freeberg *et al.*, 1990). According to these studies, the most influential of climate factors on Lake Whitefish recruitment include: fall and spring temperature, fall wind, and ice cover.

Temperature

Within the Great Lakes, which are located at either the southern or northern limits for many resident fish species, temperature is considered one of the most important abiotic factors governing their distribution and growth (Shuter *et al.*, 2002). The Great Lakes serve as a glacial refuge for coldwater fish and an expansion zone for warmer water fish (Magnuson *et al.*, 1990). In comparison to other variables, temperature can have a disproportionate influence on production, biomass, and abundance of fish within the Great Lakes (Hayes *et al.*, 2009). For example, in his re-examination of published environment-recruitment correlations, Myers (1998) found that nearly all of the temperature-recruitment correlations at the southern and northern limits of a species range were verified, whereas the re-test of other environment variable-recruitment correlations were not.

Lake Whitefish are no exception, the Great Lakes are at the southern extent of their range and observational studies suggest that recruitment variability may be linked to fall and spring temperatures (Christie, 1963; Lawler, 1965; Freeberg *et al.*, 1990; Brown *et al.*, 1993). Christie (1963) found that cold fall temperatures and warm spring temperatures were correlated with strong year classes in Lake Ontario and the reverse combination produced weak year classes. He hypothesized that fast cooling in the fall may encourage peak concentrations of spawning fish at an optimum temperature (generally below 6^{o}C; Hooper *et al.*, 2001) and slow spring warming may increase the likelihood of readily available food for hatchlings (Christie, 1963). Lawler (1965) found a similar correlation in Lake Erie and attributed the relationship to optimal spawning temperature, incubation, and development, but suggested that a slow increase in spring temperatures would allow for a prolonged incubation period and full absorption of the yolk sac so that larvae are larger and more proficient feeders. Freeberg et al. (1990) proposed that the correlation between recruitment and spring temperatures in Lake Michigan was more indirect, related to the timing and production of copepod zooplankton, prey for larval Lake Whitefish.

Wind and waves

Wind and wave circulation patterns are transport pathways for ecological systems (Beletsky *et al.*, 1999), including nutrients and larval fish. While larval fish can have some directional mobility, fish eggs and larvae are plankton and, consequently, subject to large-scale wind events, waves, and circulation. Because of their large size, the Great Lakes circulation patterns more closely resemble a marine system than many smaller freshwater systems. The Great Lakes have greater thermal inertia and longer wind fetches than smaller lakes (Magnuson *et al.*, 1997). As a result, wind and the resultant waves and current have a larger influence on the physical environment and biota of the Great Lakes than they likely would on smaller systems.

Wind intensity has been shown to influence Lake Whitefish egg deposition, larval movement, and recruitment (Brown *et al.*, 1993). Wind and wave action during the late fall and winter can cause physical, potentially fatal, trauma to eggs (Taylor *et al.*, 1987a). This impact has been shown to be particularly pronounced when eggs are deposited in marginal rearing habitat (Freeberg *et al.*, 1990). Freeberg et al. (1990) further hypothesized that currents could influence egg survival by shifting eggs from good to poor incubation habitat.

Ice cover

Ice cover can mediate some of the impacts of wind and waves in the Great Lakes. It can dampen the magnitude of wind-driven waves and turbulence by reducing friction over the lake surface. Ice cover can also affect mass and energy exchanges between the lakes and atmosphere (Assel *et al.*, 2003) and can protect the lakes from winter evaporation and helps maintain lake levels (Lofgren *et al.*, 2002).

Lake Whitefish are fall spawners with peak aggregations generally occurring in November; the eggs overwinter before hatching in the spring with peak hatching in April (Ebener *et al.*, 2008). Lake Whitefish spawn in nearshore (< 2km) waters over small to moderate-sized cobble and, less preferably, over sand (Ebener *et al.*, 2008). Observational studies of Lake Whitefish suggest that recruitment variability may be linked to ice cover which can moderate the impacts of wind-driven waves over recently deposited eggs (Taylor *et al.*, 1987a; Freeberg *et al.*, 1990). Brown *et al.* (1993) found that ice cover was the most significant factor predicting recruitment between two Lake Whitefish spawning areas of Lake Michigan. In high recruitment years with egg deposition in marginal habitat, ice cover can dampen currents and wave action, reduce overall egg mortality, and increase recruitment (Freeberg *et al.*, 1990).

Climate change

By the end of this century, the Great Lakes are projected to be warmer, with more wind and less ice cover. Climate change is expected to increase surface temperatures of the Great Lakes by as much as 6^{o}C (Trumpickas *et al.*, 2009). Ice cover is expected to be substantially reduced from these projected temperature increases (Lofgren *et al.*, 2002; Assel *et al.*, 2003). With warmer temperatures and a smaller air-to-lake temperature gradient, there is less friction at the water surface and wind speeds have already been increasing by nearly 5% each decade (Desai *et al.*, 2009).

Climate change is hypothesized to impact the magnitude and value of the Lake Whitefish fishery, because the success of recruitment to the fishery has been linked with climatic influences, including fall and spring water temperature, fall wind and waves, and ice cover (Table 4.1). Increased water temperature and decreased ice cover could inhibit the success of recruitment to the Lake Whitefish fishery with greater egg mortality (Lynch *et al.*, 2010). However, the warming trends associated with predicted climate change could increase overall suitable thermal habitat volume for Lake Whitefish (Magnuson *et al.*, 1997) because the species is expected to shift northwards and deeper in the water column to maintain optimal thermal habitat (Regier and Meisner, 1990). While thermal suitability is an important component of habitat, Lake Whitefish stocks are characterized by spatial and temporal variation (Deroba and Bence, 2012). For example, Brenden et al. (2010) found substantial variability in the relative abundance and size of Lake Whitefish recruits within even the same sampling sites. As a result, forecasts based only on temperatures are likely to be ecologically incomplete projections (Jones *et al.*, 2006).

TABLE 4.1. Projected impacts of changes in ice cover, wind and waves, fall temperature, and spring temperature on Lake Whitefish (*Coregonus clupeaformis*).

Climate factor	**Projected change**	**Anticipated impact on Lake Whitefish**
Ice cover	↓ ice cover	Lake Whitefish spawn in the fall and their eggs stay through the winter, hatching in the spring. Ice cover has been shown to protect eggs in sub-optimal spawning habitat. Reduced ice cover could lead to lower lake whitefish recruitment (survival) from habitat that is considered sub-optimal.
Wind and waves	↑ wind and waves	Wind and waves can damage lake whitefish eggs and increase egg mortality. Strong storm events before the onset of ice cover have been linked to reduced survival of eggs to hatching. Increased wind and waves could lead to lower Lake Whitefish recruitment.
Fall temperature	↑ temperature	Warmer fall temperatures are often associated with increased wind and waves. Because storm events reduce egg survival, warmer fall temperatures could lead to lower Lake Whitefish recruitment.
Spring temperature	↑ temperature	Lake Whitefish hatch into larvae in the spring. The survival of larvae is very dependent on finding food (i.e., plankton). Warmer spring temperatures generally lead to higher densities of plankton and have been linked with stronger Lake Whitefish survival because of increased availability of food resources. Warmer spring temperatures could lead to higher Lake Whitefish populations.

Lake Whitefish in the 1836 Treaty Waters

The 1836 Treaty Waters are regions of Lakes Huron, Michigan, and Superior that were ceded from the Ottawa and Chippewa nations to the United States of America. Until the 1970s, the Treaty Waters were managed by the Michigan Department of Natural Resources because the Michigan Supreme Court declared that the tribes had no special fishing or hunting rights in this region, though the Treaty did not specifically cede Tribal fishing rights to the state. When the state began limiting entry into the commercial fishery, the tribes challenged the court ruling and, in 1979, *United States v. State of Michigan* (the Fox Decision) reaffirmed the rights of the tribes to fish for Lake Whitefish. Fishing rights were not a negligible concession; the harvest from the 1836 Treaty Waters currently comprises approximately a quarter of the total harvest of Lake Whitefish in the upper Great Lakes (M. Ebener, Chippewa Ottawa Resource Authority, *personal communication*).

To ensure that the fishery is managed for long-term profitable yields and ecosystem integrity, the 2000 Consent Decree established guidelines for management under the purview of the Chippewa Ottawa Resource Authority (CORA), a cooperative tribal management agency. Currently, a Technical Fisheries Committee recommends total allowable catches and harvest regulations for the 15 Lake Whitefish management units located in these waters using the guidance from a Modeling Sub-Committee. The Modeling Sub-Committee fits statistical catch-at-age (SCAA) models to the commercial fishery data to estimate population metrics, including population abundance and recruitment (Deroba and Bence, 2009).

For these models, recruitment is defined as the number of individuals in a population that reach the legally defined fishable size (17 inch total length; Ebener *et al.*, 2008). Recruitment is a particularly important metric to estimate because “the regenerative process of a population is critical to the maintenance of the population” (Quinn and Deriso, 1999). The SCAA models use a Ricker (1954) stock-recruitment relationship because Lake Whitefish recruitment is density dependent (Henderson *et al.*, 1983) and the Ricker model accounts for density dependence. Using fishery dependent data, the models estimate population abundance, mortality (natural, lamprey, trap net, and gill net), fishery harvest, among other population parameters (Deroba and Bence, 2009) , but do not include environmental factors, which may influence the productivity of these fish.

The goal of this study was to examine the relationship between climate variables and Lake Whitefish recruitment in the 1836 Treaty Waters of the Great Lakes. Specifically, this study investigated the relationship between recruitment and temperature indices, wind, and ice cover, which have all been cited as influential in Lake Whitefish recruitment dynamics. Projecting the relationship between these climate variables and recruitment forward with climate change will help the fishery and fishery managers anticipate changes in recruitment and prepare adaptive management strategies to maintain sustainable harvest of the fishery into the future.

Methods

SCAA models have been developed to establish total allowable catches and designate harvest regulations for 13 of the 15 Lake Whitefish management units in the 1836 Treaty Waters by the Modeling Subcommittee to the Technical Fisheries Committee (Figure 4.1). Using fishery data, the models estimate population abundance, mortality (natural, lamprey, trap net, and gill net), fishery harvest, and other population parameters (Deroba and Bence, 2009). The details of this modeling approach are described in Ebener *et al.* (2005). This study examined if the inclusion of climate variables could significantly improve recruitment estimates, accounting for the increase in parameters.

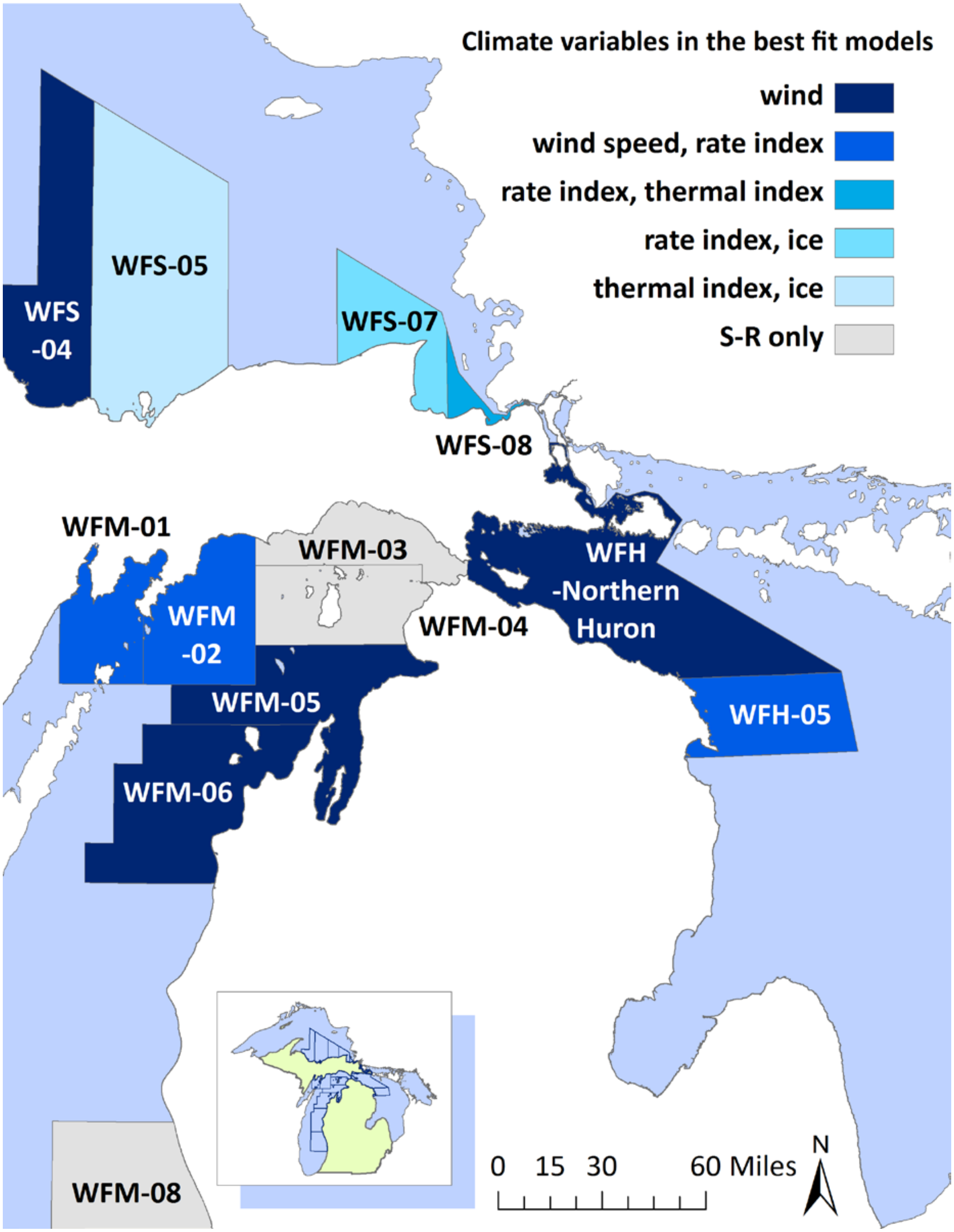


FIGURE 4.1. Lake Whitefish (*Coregonus clupeaformis*) management units for the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior color coded by the best fit linear regression model for recruitment as selected by Corrected Akiake's Information Criterion.

Spawning stock biomass and recruitment

Spawning stock biomass and recruitment estimates were calculated using the Modeling Sub-Commitee SCAA models for each management unit. Data spanned from 1976-2011, depending on the management unit (Appendix 4.1). We truncated the dataset at 2007 as SCAA models perform inconsistently with recent data due to insufficient population data inputs to run the analysis (J. Bence, Michigan State University, *personal communication*). Spawning stock biomass was measured as spawning stock biomass per kg recruit and recruitment is measured as number of individuals that reach a fishable size (17 inch total length; Ebener *et al.*, 2008), which generally occurs at age 3 or age 4, depending on the management unit (Appendix 4.1). For the purposes of this analysis, we calculated recruitment without the penalty for recruitment deviations used in harvest quota estimation. In the SCAA models, spawning stock biomass is used as a constraining parameter to minimize recruitment fluctuation and stabilize estimation. Because our linear regression analysis was outside of the SCAA framework, we decoupled the interaction between spawning stock biomass and recruitment so that the variables were independently considered in our analysis.

Climate variables

To determine if key climate variables improve the SCAA recruitment estimates, we examined the following variables for inclusion in multiple linear regressions: Temperature, wind speed and wave height, ice cover.

Temperature

In order to compare recruitment with temperature, we used composite indices of temperature because indices reduce the likelihood of multicollinearity (Farrar and Glauber, 1967). To calculate the composite temperature indices, we first calculated mean, minimum, and maximum monthly air temperature estimates (^{O}F) from the land-based National Climate Data Center station data within a five mile buffer of each management unit in ArcMap 10 (ESRI, 2011). Using available data, this analysis spanned from 1980-2010 (Appendix 4.1). To match recruitment values with the temperature conditions the recruits experienced as eggs and hatchlings (i.e., their most vulnerable life stages; Freeberg *et al.*, 1990), we linked recruitment estimates for a given year with fall (October-December) temperatures during the year those recruits were spawned (three or four years prior, depending on management unit) and spring temperatures (March-May) during the year they hatched (two or three years prior, depending on management unit). These temperature values were then converted to the following composite temperature indices: thermal index and rate index.

Thermal index is the deviation of a given year's April mean temperature from the dataset's mean of all April temperatures minus the deviation of the previous year's November mean temperature from the dataset's mean of all November temperatures (Christie, 1963). April and November were chosen as representative seasonal indicators because Lake Whitefish spawning peaks in November and hatching peaks in April. Positive thermal index values occur when a cooler-than-average November is followed by a warmer-than-average April. Rate index is the deviation of a given year's spring warming rate (maximum May temperature – minimum March temperature) from the data set's mean spring warming rate minus the deviation of the previous year's fall cooling rate (maximum October temperature – minimum December temperature) from the data set's mean spring warming rate.

Wind speed and wave height

In order to compare recruitment with wind intensity, we examined wind speed and wave height from 1983-2011 (Appendix 4.1). Mean November wind speed (m/s) and wave height (m) estimates were calculated for each management unit from the closest National Data Buoy Center offshore buoy (buoy id: 45002, 45003, 45004, and 45007). Wind and wave action are correlated over large spatial scales (2,500 km+; Koenig, 2002). November was chosen because it is the peak of the spawning season when the majority of eggs are deposited. To match recruitment values with the wind conditions the recruits experienced as eggs, we linked recruitment for a given year to wind speed and wave height from the year fish were spawned (two or three years prior, depending on management unit).

Ice cover

In order to compare recruitment with ice cover, we clipped ice cover estimates by management unit from the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Ice Atlas (Assel *et al.*, 2003) using ArcMap 10 (ESRI, 2011). Data used in our analysis spanned from 1972-2008 (Appendix 4.1). We calculated the proportion of ice cover at the 10m depth contour as close to December 1st as possible based on available data. We chose the 10m depth contour because this generally represents the outer margin of Lake Whitefish spawning habitat at the end of the spawning season. To match recruitment values with the ice cover the recruits experienced as eggs, we linked recruitment for a given year to ice cover from the year fish were spawned (two or three years prior, depending on management unit).

Pearson correlation

We used the Pearson correlation coefficient, *r,* to examine pairwise correlation between the thermal index, rate index, ice cover, wind speed, and wave height. The Pearson correlation coefficient compares two variables, x_i and y_i, by using contour ellipse of a two dimensional normal distribution to describe the relationship:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

The Pearson correlation coefficient evaluates linear relationships, like the linear Ricker stock-recruitment model (Ricker, 1954) used for Lake Whitefish because they exhibit density dependent recruitment (Henderson *et al.*, 1983). If both variables are scaled to have a variance of 1, then a correlation of zero corresponds to circular contours, as the correlation increases, the ellipses narrow, and finally collapse into a line segment as the correlation approaches ±1, a perfect linear relationship (Dalgaard, 2008).

To determine if any of the examined variables were correlated, we calculated the Pearson correlation coefficient using pairwise complete observations for ice cover, thermal index, rate index, November wind speed, and November wave height with the **Rcmdr** package (Fox, 2005) and plotted them using the **corrgram** package (Wright, 2006) in Tinn-R GUI 2.4.1.7 (Faria, 2013).

Variance inflation factors

While pairwise collinearity can be determined with the Pearson correlation coefficient, we calculated Variance inflation factors (VIF) to examine higher-order collinearity (Zuur *et al.*, 2009):

$$VIF_i = \frac{1}{1 - R_i^2}$$

For a given independent variable, i, VIF_i is the comparison of the proportion of variance a variable shares with the other independent variables to the situation in which it shares none of its variance with the other independent variables (O'Brien, 2007). A VIF of 10, for example, indicates that the variance of the regression coefficient, R_i, is 10 times greater than if the variable had been linearly independent of the other independent variables in the analysis. VIF values of 4 or 10 are often cited as "rules of thumb" to consider variables for removal from an analysis (O'Brien, 2007). We calculated VIF values using multiple linear regression including the following predictor variables: stock-dependent ice cover, thermal index, rate index, November wind speed, and November wave height with the **car** package (Fox and Weisberg, 2011) in Tinn-R GUI 2.4.1.7 (Faria, 2013).

Lake Whitefish recruitment model selection

Lake Whitefish exhibit density dependent recruitment (Taylor *et al.*, 1987a) and, consequently, a standard Ricker stock-recruitment model (Ricker, 1954) is used as the foundation for the Modeling Subcommittee's SCAA modeling efforts. Because lognormal variability is appropriate for stock-recruitment relationships (Hilborn and Walters, 1992), we transformed the Ricker model into a linear function by taking the natural log of both sides of the equation. We used linear regression techniques to evaluate the relationship between recruitment (*R*), stock (*S*), and additional climate variables (*Var*), where α is a productivity parameter, β is a density dependent shape parameter, and ε is normally distributed random error:

$$log\frac{R_i}{S_i} = log\alpha_i - \beta_1 S_i + \gamma_1 Var_i \ldots + \gamma_i Var_i + \epsilon_i$$

The full model used in this study included density-dependent ice cover (*ice*), density-independent thermal index (*t_index*), rate index (*r_index*), and wind speed (*W*):

$$log\frac{R_i}{S_i} =$$

$$log\alpha_i - \beta_1 S_i + \beta_2 ice_i S_i + \gamma_1 t\_index_i + \gamma_2 r\_index_i + \delta_1 W_i + \epsilon_i$$

To determine the best fitting model for each management unit, we compared all possible combinations of models including climate variables to the standard stock-recruitment Ricker model (without the addition of any climate variables) using corrected Akaike's Information Criterion (AICc) in R 2.4.1.7 (R Core Management Team, 2008). We used *corrected* AIC to avoid overparameterization for small sample sizes, with *k* parameters, an *L* likelihood of the model representing the data, and *n* observations:

$$AIC_c = 2k - 2\ln(L) + 2k\frac{k+1}{n-k-1}$$

Projecting recruitment with climate

To project the relationships described by the best fitting models of climate and recruitment, we used the Coupled Hydrosphere-Atmosphere Research Model (CHARM), a simulation model of climate and water resources in the Great Lakes Region (Lofgren, 2004). CHARM uses the Regional Atmospheric Modeling System (Pielke *et al.*, 1992) with lake thermodynamics, surface temperature, heat transfer, and a model of land processes specifically for the Great Lakes. The regional approach allows for enhanced spatial resolution at the atmosphere-water interface. The model is resolved to 40 km grids (smaller than the smallest management unit) and simulated at six hour intervals for two twenty year periods, 1981-2000 and 2050-2070. We extracted the following CHARM outputs: fall and spring air temperatures, November wind speed, and December ice cover, for each management unit using the **stringr** package (Wickham, 2012) in Tinn-R GUI 2.4.1.7 (Faria, 2013). We calculated thermal index and rate index using the annual deviation from the 20 year monthly mean, maximum, and minimum CHARM temperature simulation, depending on the month and metric. We calculated wind speed from the U (east) and V (north) vector components generated by the CHARM model.

The CHARM model simulated ice cover in mean meters thickness. While this metric is different than what we used in the climate-recruitment regression model, the proportional relationship (i.e., amount of ice cover) is still analogous for the purposes of this comparison.

We projected Lake Whitefish recruitment for each management unit using these CHARM outputs as inputs into the models identified through AIC_C selection for each management unit to generate projections of Lake Whitefish recruitment for 2050-2070. To constrain simulated variability to only climate causes, we held spawning stock size constant at the 2007 estimate. Since simple back-transformation of log-transformed linear regression estimates is biased, producing the geometric rather than arithmetic mean (MacCall and Ralston, 2002), the value is not analogous to recruitment. We corrected for this back-transformation bias by including the addition of recruitment variance, σ^2, as a variable to project recruitment:

$$R_i = S_i e^{\alpha_i - \beta_1 S_i \beta_2 ice_i S_i + \gamma_1 t\_index_i + \gamma_2 r\_index_i + \delta_1 W_i + \sigma^2/2}$$

Results

Climate variable selection

We used the Pearson correlation coefficient and VIF values to determine if there was any reason to remove a climate variable from our climate-recruitment model. For each of the 13 management units, the Pearson correlation coefficient was significant ($p < 0.05$) between November wind speed and November wave height; 10 other pairwise comparisons resulted in a significant correlation ($p < 0.05$) but not consistently across management units (Table 4.2; Appendix 4.2). Because wind speed and wave height are both measures of storm intensity and wind speed is often more readily available, wave height was removed from subsequent analyses. Though O'Brien (2007) cautions against using a "rule of thumb" VIF value to remove variables from an analysis, all of the VIF values in this analysis were below 10 and most of them were below 4 (Table 4.3). Consequently, these results did not indicate than any variables should be removed from use in this analysis because of higher order collinearity. The climate variables included in the AIC_C model comparisons were thermal index, rate index, wind speed, and ice cover.

Lake Whitefish recruitment model selection

The AICc comparisons between the stock-recruitment model and the best fit model including selected climate variables ranged between 0 (where the stock-recruitment model, alone, was the best fit) and 20.91 (Table 4.4). In eight management units, the AICc comparisons were higher than three, indicating significant improvement of model fit when climate variables were included (Burnham and Anderson, 2002). For six of those eight management units across all three lakes, November wind speed was an included variable; rate index was an included variable in four management units across all three lakes; ice cover was included in two Lake Superior management units; and thermal index was included in one Lake Superior management unit (Table 4.5; Figure 4.1).

Lake Whitefish climate-recruitment projection

Of the eight management units identified to have improved model fit with the inclusion of climate variables, six (WFH-05, WFH-Northern Huron, WFM-01, WFM-02, WFS-04, and WFS-07) are projected to have increases in Lake Whitefish recruitment and two units (WFM-06 and WFS-05) are projected to have decreases in Lake Whitefish recruitment (Figure 4.2). The WFM-06 model includes wind speed and the WFS-05 model incudes ice cover and thermal index. Projected recruitment changes range from over 250% increase to almost 80% declines (Table 4.6; Figure 4.3).

TABLE 4.2. Pearson correlation coefficients (below diagonal) and *p*-values (above diagonal; **<0.05 bolded**) for potentially relevant climate variables by 1836 Treaty Waters Lake Whitefish (*Coregonus clupeaformis*) management unit: ice cover (December 10m depth contour), thermal index (April temperature deviation – November temperature deviation), rate index (spring warming rate – fall cooling rate), November wind speed (monthly average), and November wave height (monthly average). *Note WFM-03 temperature data unavailable.*

WFH_05		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.1498	0.5458	0.6853	0.2265
	thermal index	-0.2967		0.188	0.9239	0.135
	rate index	0.1268	-0.2722		0.1039	0.059
	wind speed	0.094	0.0222	-0.3648		**<.0001**
	wave height	-0.2757	0.3372	-0.4185	0.7495	
WFH_Northern_Huron		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.4282	0.0486	0.5888	0.4036
	thermal index	-0.1696		0.1098	0.1463	0.5787
	rate index	-0.4066	-0.3348		0.4228	0.7939
	wind speed	0.1251	-0.3283	0.1847		**<.0001**
	wave height	-0.1923	-0.1285	0.0607	0.7495	
WFM_01		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.9209	0.2382	**0.0103**	0.8492
	thermal index	-0.0209		**0.0281**	0.6145	0.8746
	rate index	-0.2561	-0.4578		0.4008	0.1165
	wind speed	0.5878	0.1274	-0.2256		**0.0128**
	wave height	0.0442	0.0367	-0.3722	0.5739	
WFM_02		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.0593	0.1452	**0.0103**	0.8491
	thermal index	-0.4082		0.9142	0.9162	0.627
	rate index	-0.3291	-0.025		0.5668	0.2134
	wind speed	0.5878	-0.0267	-0.1495		**0.0128**
	wave height	0.0442	0.1126	0.2909	0.5739	

TABLE 4.2 (cont'd).

WFM_03		**ice**	**wind speed**	**wave height**
	ice		**0.0078**	0.7489
	wind speed	0.6209		**0.0206**
	wave height	0.0764	0.5555	

WFM_04		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		**0.0335**	0.6727	**0.0082**	0.9931
	thermal index	-0.4265		0.5867	0.8283	0.5902
	rate index	-0.0889	-0.1142		0.6034	0.4233
	wind speed	0.6018	-0.055	-0.1314		**0.0128**
	wave height	0.002	0.1247	-0.1845	0.5739	

WFM_05		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.9988	0.5053	**0.0173**	0.9407
	thermal index	0.0003		0.3282	0.1055	0.2002
	rate index	-0.1397	-0.2039		0.5493	0.2355
	wind speed	0.553	0.3942	-0.1512		**0.0128**
	wave height	-0.0173	0.2913	-0.2706	0.5739	

WFM_06		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.0756	0.5546	**0.0106**	0.922
	thermal index	-0.3776		0.8647	0.4782	0.4299
	rate index	-0.1332	0.0386		0.942	0.4342
	wind speed	0.5859	0.1786	-0.0191		**0.0128**
	wave height	-0.0227	0.1819	-0.1853	0.5739	

WFM_08		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.5027	0.7218	**0.0222**	0.7043
	thermal index	-0.1472		0.6504	0.7762	0.4973
	rate index	0.0785	-0.0998		0.7803	0.8978

TABLE 4.2 (cont'd).

		ice	thermal index	rate index	wind speed	wave height
WFM_08 (cont'd)	**wind speed**	0.496	0.066	-0.0648		**0.0032**
	wave height	-0.0905	0.1612	0.0307	0.6259	
WFS_04		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.1158	0.1976	0.1162	0.9463
	thermal index	-0.3451		0.1898	0.7419	0.1979
	rate index	-0.2929	-0.2978		0.2853	0.2873
	wind speed	0.4229	0.0929	-0.3072		**0.0005**
	wave height	-0.0183	0.3398	-0.2941	0.8064	
WFS_05		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.3566	0.3574	0.119	0.9424
	thermal index	-0.2385		0.221	0.8425	0.473
	rate index	-0.2465	-0.3358		0.2564	0.2527
	wind speed	0.4201	0.068	-0.3967		**0.0005**
	wave height	-0.0197	0.2295	-0.3584	0.8064	
WFS_07		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.1711	0.4489	0.1298	0.9185
	thermal index	-0.2888		**0.0332**	0.7815	0.2167
	rate index	0.1661	-0.4454		0.3449	0.1656
	wind speed	0.4093	0.0783	-0.2623		**0.0005**
	wave height	-0.0278	0.3268	-0.3642	0.8064	
WFS_08		**ice**	**thermal index**	**rate index**	**wind speed**	**wave height**
	ice		0.8642	0.8738	0.284	0.4548
	thermal index	-0.0369		0.0693	0.8922	0.2547
	rate index	-0.0342	-0.3771		0.4756	0.1003
	wind speed	0.2961	-0.0383	-0.1997		**0.0005**
	wave height	-0.2013	0.3026	-0.4256	0.8064	

TABLE 4.3. Variance Inflation Factors for potentially relevant climate variables by 1836 Treaty Waters Lake Whitefish (*Coregonus clupeaformis*) management unit: density-dependent ice cover (S:ice; December 10m depth contour), thermal index (April temperature deviation – November temperature deviation), rate index (spring warming rate – fall cooling rate), and November wind speed (monthly average). *Note WFM-03 temperature data unavailable.*

	thermal index	**rate index**	**wind speed**	**S:ice**
WFH_05	1.23	1.52	1.25	1.16
WFH_Northern_Huron	1.19	1.24	1.54	1.26
WFM_01	2.27	2.33	1.7	1.96
WFM_02	1.57	1.46	1.74	2.83
WFM_03			1.9	1.68
WFM_04	1.67	1.55	1.99	3.76
WFM_05	1.39	1.08	1.98	1.81
WFM_06	1.32	1.06	1.71	1.86
WFM_08	1.19	1.26	1.35	1.79
WFS_04	2.97	2.94	1.54	**12.74**
WFS_05	2.17	**4.16**	1.4	3.51
WFS_07	2.38	1.9	1.45	**4.1**
WFS_08	1.56	1.07	1.17	2.43

TABLE 4.4. The difference between corrected Akaike's Information Criterion (AICc) values between the Lake Whitefish (*Coregonus clupeaformis*) stock-recruitment (S-R) model and the best fit model including climate variables: ice cover (December 10m depth contour), thermal index (t_index; April temperature deviation – November temperature deviation), rate index (r_index; spring warming rate – fall cooling rate), and November wind speed (wind; monthly average) for each of the 13 management units of the 1836 Treaty Waters evaluated. Parameter estimates are listed (blue = positive; red = negative). Management units with AICc comparisons < 3 are gray. *Note WFM-03 temperature data unavailable.*

	Δ AIC_C	variables included	Intercept	S	t_index	r_index	wind	S:ice	residual SE	variance
WFH_05	15.33	rate index, wind speed	-0.9621	5.91E-08		-0.02713	-0.2728		0.5217	0.272171
WFH_Northern_Huron	12.28	wind speed	-0.9742	3.12E-08			-0.1455		0.4429	0.19616
WFM_01	20.01	rate index, wind speed	0.0567	1.48E-07		-0.01889	-0.2439		0.5649	0.319112
WFM_02	20.91	rate index, wind speed	-0.7606	8.03E-07		-0.08493	-1.599		5.536	30.6473
WFM_03	0.00	S-R only	-1.69E+00	-3.24E-08					0.3428	0.117512
WFM_04	0.00	S-R only	-5.90E-01	2.20E-07					0.3008	0.090481
WFM_05	1.83	wind speed	-1.10E+00	4.92E-07			-8.21E-02		0.2953	0.087202
WFM_06	11.31	wind speed	-1.41	1.57E-06			-0.2401		0.7009	0.491261
WFM_08	0.00	S-R only	-1.97E+00	-7.36E-08					0.6479	0.419774
WFS_04	4.77	wind speed	-2.601	-1.13E-06			0.07233		0.3129	0.097906

TABLE 4.4 (cont'd).

	Δ AIC_C	variables included	Intercept	S	t_index	r_index	wind	S:ice	residual SE	variance
WFS_05	13.60	ice, thermal index	-1.319	1.13E-06	9.29E-04			2.782 E-16	0.2564	0.06574 1
WFS_07	11.53	ice, rate index	0.5525	1.58E-06		0.00043 2		5.778 E-17	0.2148	0.04613 9
WFS_08	0.85	thermal index, rate index	-7.79E-01	1.79E-06	2.99E-02	8.68E-03			0.5772	0.33316

TABLE 4.5. Variables used in best fit linear regression models for the 1836 Treaty Waters Lake Whitefish (*Coregonus clupeaformis*) management units. Values in parentheses indicate management units with a difference between corrected Akaike's Information Criterion (AICc) values between the stock-recruitment (S-R) model and the best fit model of > 3, indicating significant improvement in model fit. *Note that some models contain more than one variable.*

	Lake Huron	Lake Michigan	Lake Superior	Total
stock-recruitment only		3		3
ice			2 (2)	2 (2)
thermal index			2 (1)	2 (1)
rate index	1 (1)	2 (2)	2 (1)	5 (4)
wind speed	2 (2)	4 (3)	1 (1)	7 (6)

TABLE 4.6. Comparison of Lake Whitefish (*Coregonus clupeaformis*) recruitment estimates from the best fit linear regression models including climate variables for 2007 with the projected estimates for 2052-2070, by management unit. Values are displayed as a proportion of the 2007 estimate for each management unit (blue = projected increase; red = projected decrease).

	WFH-Northern_Huron	WFH-05	WFM-01	WFM-02	WFM-06	WFS-04	WFS-05	WFS-07
2007	1	1	1	1	1	1	1	1
2052	2.23	2.22	1.54	1.29E+13	0.43	1.41	0.78	1.22
2053	1.94	2.08	1.48	1.59E+13	0.36	1.48	0.78	1.22
2054	2.58	3.29	2.22	1.71E+14	0.62	1.38	0.78	1.22
2055	2.5	3.41	2.75	3.38E+14	0.77	1.3	0.78	1.22
2056	2.09	1.63	1.35	7.33E+12	0.42	1.45	0.78	1.22
2057	2.39	2.72	1.97	9.60E+13	0.56	1.35	0.78	1.22
2058	2.04	1.34	1.13	5.10E+12	0.43	1.48	0.78	1.22
2059	2.29	2.39	1.57	2.38E+13	0.53	1.37	0.78	1.22
2060	1.84	1.5	1.26	3.67E+12	0.34	1.6	0.78	1.22
2061	2.82	3.59	3.05	6.28E+14	0.84	1.26	0.78	1.22
2062	2.48	2.35	2.05	8.12E+13	0.66	1.38	0.78	1.22
2063	1.94	1.57	1.23	6.49E+12	0.34	1.5	0.78	1.22
2064	2	3.45	1.65	2.36E+13	0.42	1.5	0.78	1.22
2065	1.96	1.89	1.23	9.42E+12	0.36	1.55	0.78	1.22
2066	2.16	2.19	1.32	8.09E+12	0.38	1.45	0.78	1.22
2067	2	1.77	1.62	1.29E+13	0.41	1.48	0.78	1.22
2068	2.06	2.14	1.61	1.90E+13	0.45	1.48	0.78	1.22
2069	1.59	1.19	1	1.46E+12	0.27	1.68	0.78	1.22
2070	2.08	1.95	1.2	3.61E+12	0.4	1.54	0.78	1.22

A)

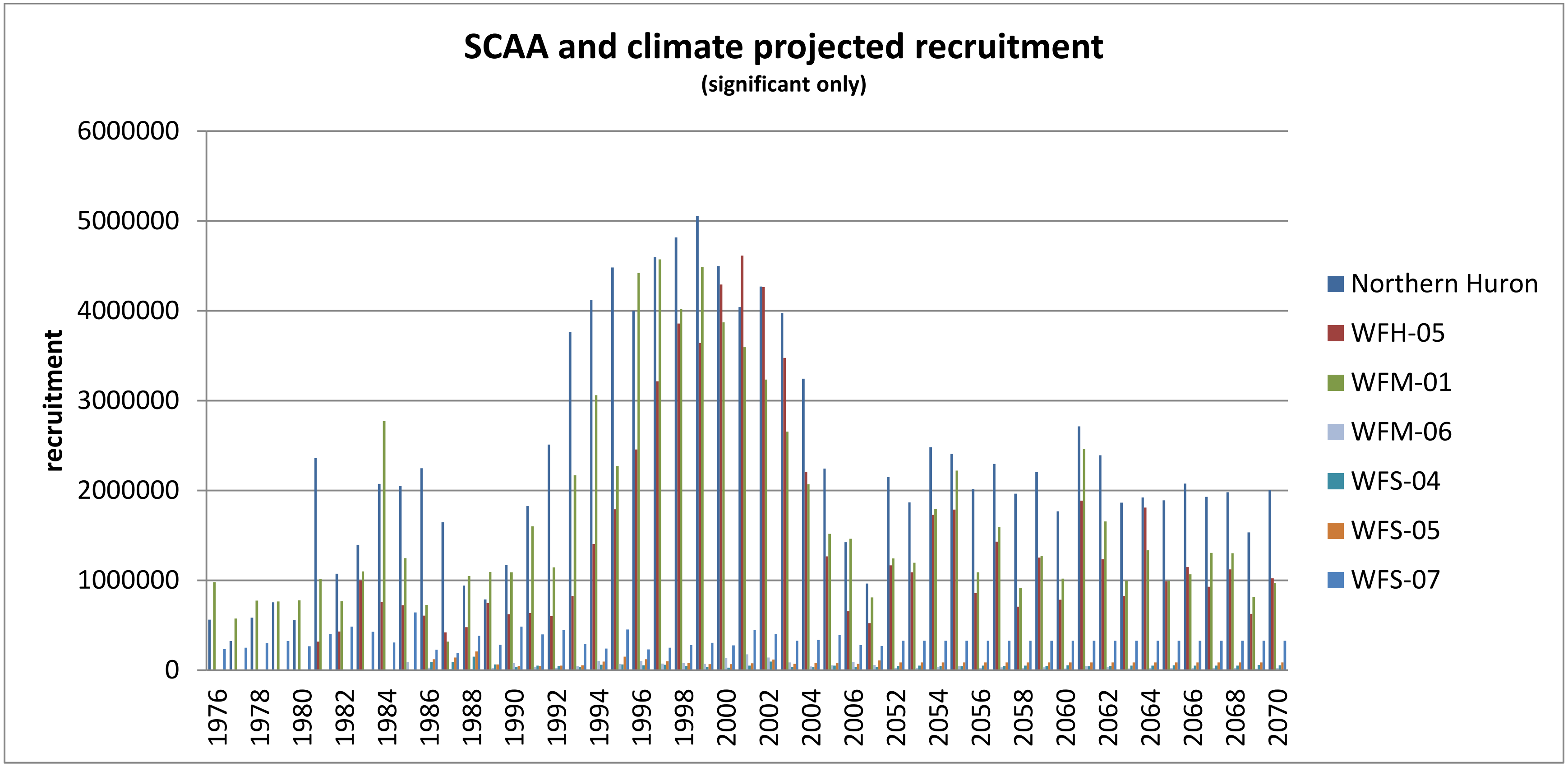


FIGURE 4.2. Lake Whitefish (*Coregonus clupeaformis*) recruitment estimates from the 1836 Treaty Waters Modeling Subcommittee Statistical Catch-at-Age (SCAA) models (2007 and earlier) and projections using CHARM inputs into the best fit linear regression models including climate variables (2052-2070) by management unit. A) management units with a difference between corrected Akaike's Information Criterion (AICc) values between the stock-recruitment (S-R) model and the best fit model of > 3, indicating significant improvement in model fit; B) all Lake Huron management units; C) all Lake Michigan management units; and D) all Lake Superior management units. Note that stock size in projection years was held constant at 2007 levels to isolate climate effects and WFM-02 was removed because of high variance ($\sigma^2 = 30.64$).

FIGURE 4.2 (cont'd).

B)

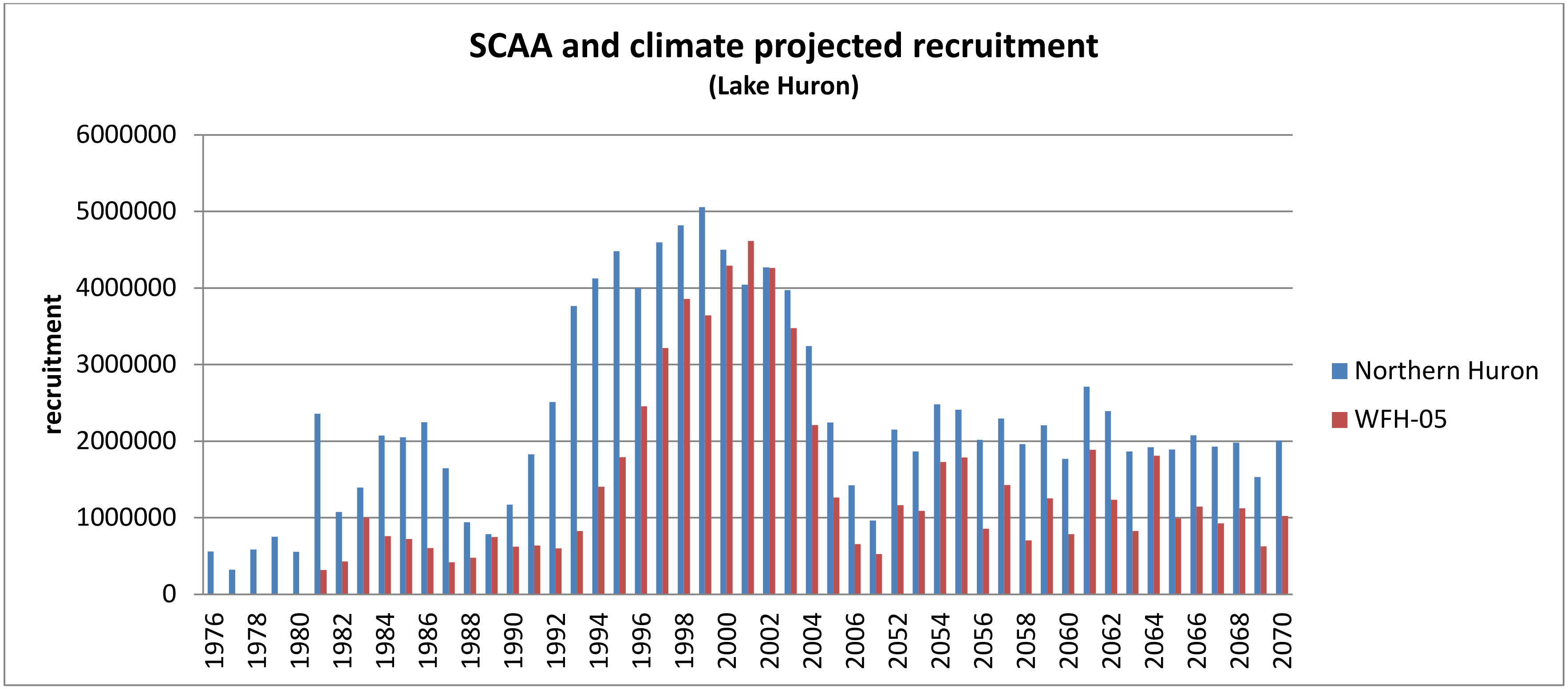


FIGURE 4.2 (cont'd).

C)

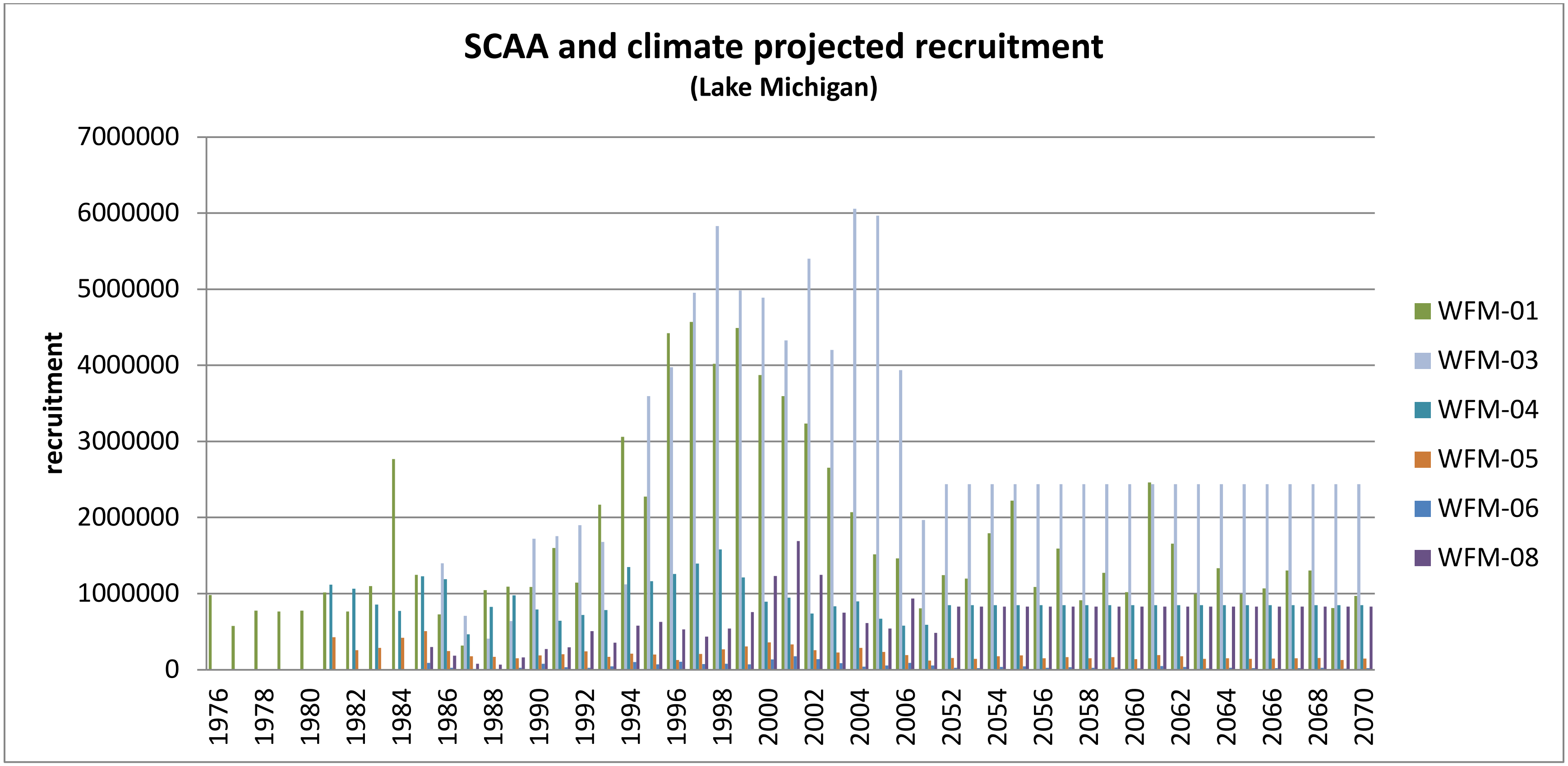
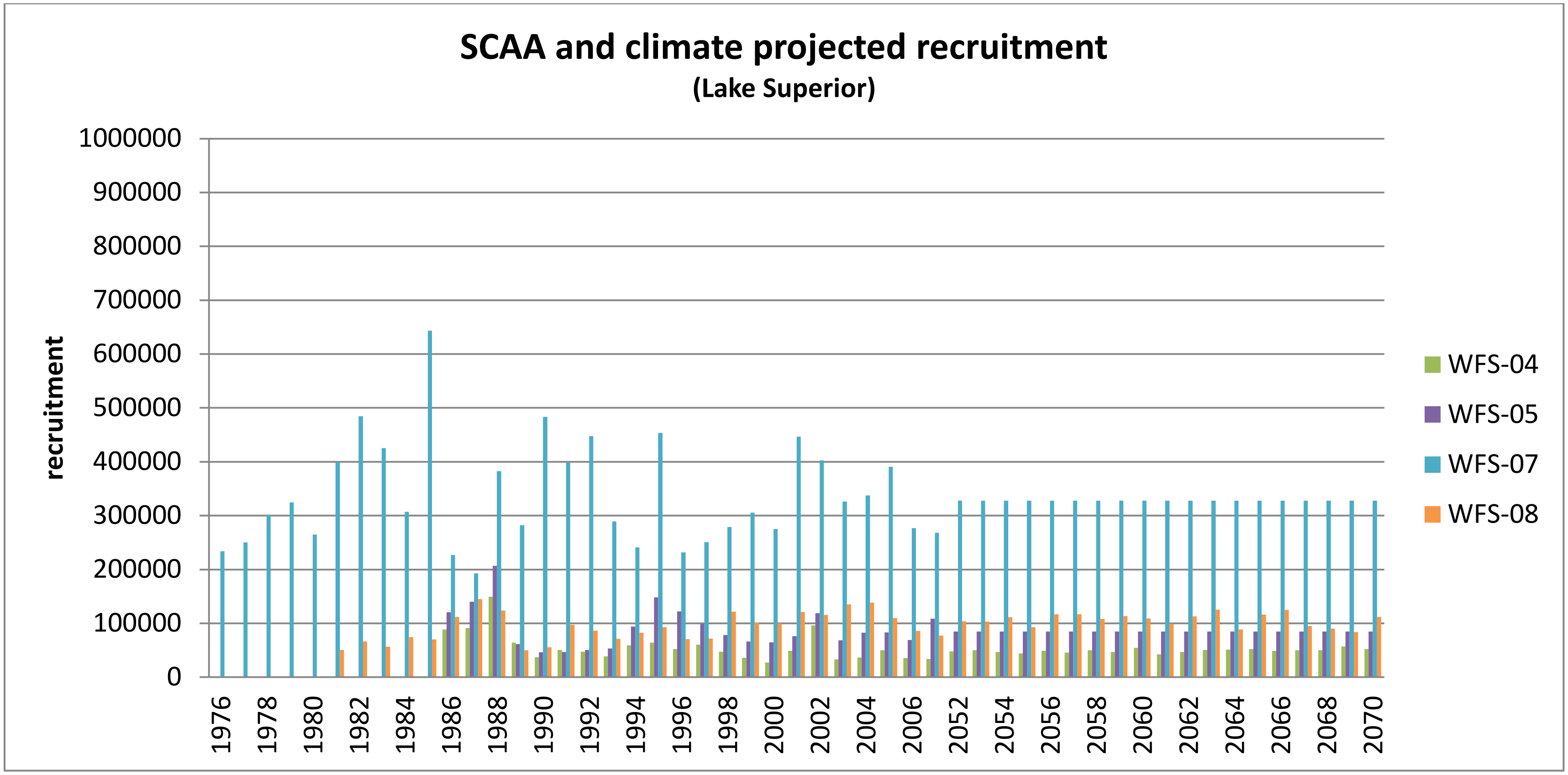


FIGURE 4.2 (cont'd).

D)



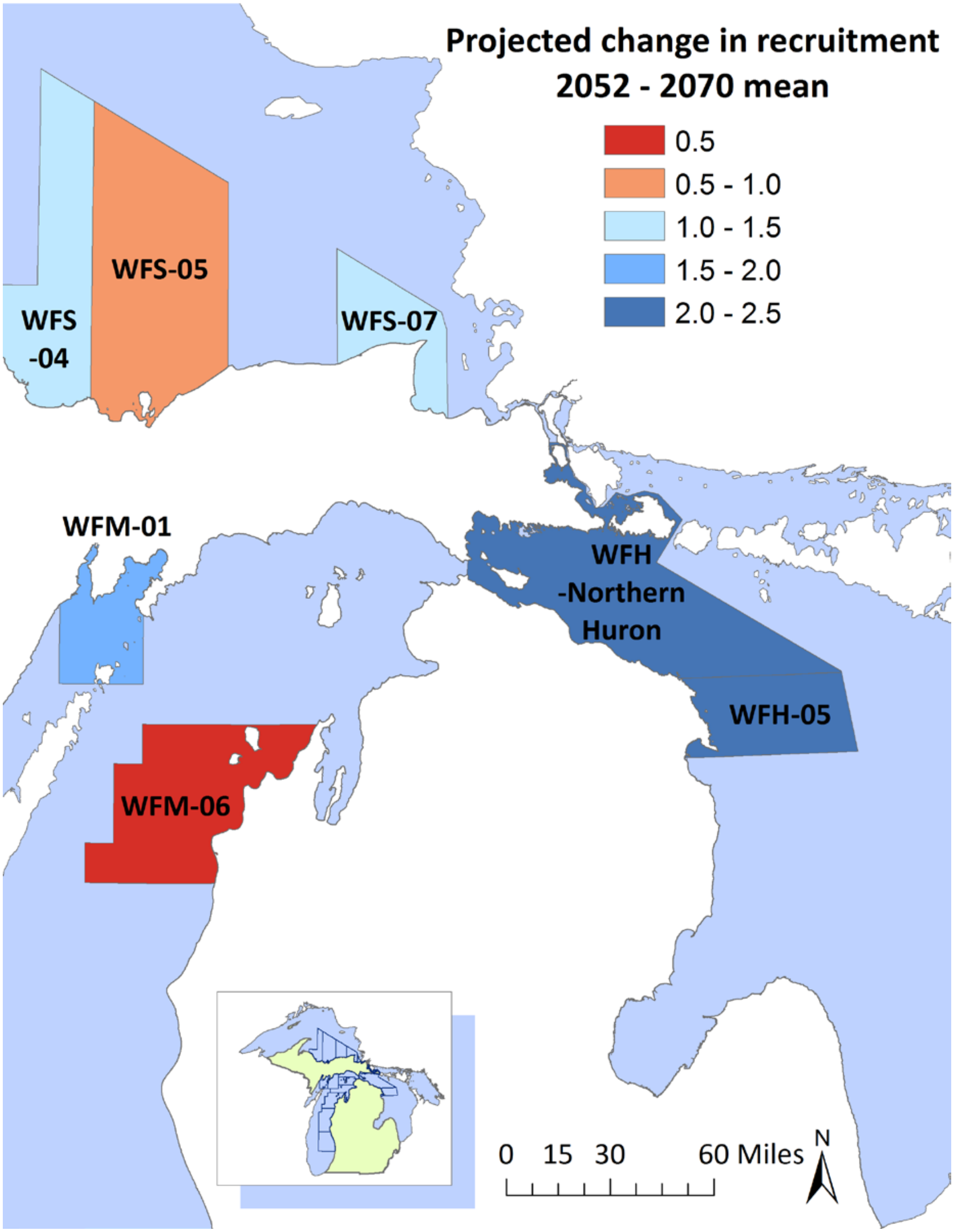


FIGURE 4.3. Lake Whitefish (*Coregonus clupeaformis*) management units for the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior color coded by the 2052-2070 mean projected change in recruitment (blue = projected increase; red = projected decrease).

Discussion

Lake Whitefish recruitment model selection

Differences in variables included in the best fit model are expected between the management units because Great Lakes Lake Whitefish stock-recruitment dynamics are characterized by spatial and temporal variation (Deroba and Bence, 2012). Because of spatial variability and population dynamics, climate factors will not have the same influence on recruitment in different management units that have different conditions. For five of the 13 management units, climate variables did not improve recruitment estimation; other population drivers, not investigated in this study, are more strongly coupled with recruitment in these management units.

However, the results of this study support including climate variables in the Lake Whitefish stock recruitment models in the 1836 Treaty Waters of the Great Lakes. The addition of climate variables in eight of the 13 management units assessed improved model fit, meaning that climate is an important driver of recruitment in these management units. November wind speed was the most commonly included climate variable, present in six of the eight significant management units, followed by rate index in four, ice cover in two, and thermal index in one. While previous site-based correlational studies have also indicated that climate variables influence year class strength and future recruitment (Christie, 1963; Lawler, 1965; Taylor *et al.*, 1987a; Freeberg *et al.*, 1990; Brown *et al.*, 1993), this analysis was important because it expanded upon these historical studies by integrating climate variables and recruitment on a much larger spatial scale that is more applicable to the current methods of how Lake Whitefish are managed.

Ecologically, our modeling results indicated that climate variables influence the magnitude of Lake Whitefish recruitment in the 1836 Treaty Waters. Our analysis suggested that, across all three lakes wind events during the November peak spawning period have a negative relationship with recruitment. High wind events can lead to physical trauma, burial in sediments, and higher mortality for Lake Whitefish eggs after deposition (Taylor *et al.*, 1987a).

The rate index, the rate at which temperatures cool in the fall compared with the rate at which temperatures warm in the spring (spring warming – fall cooling), also influenced recruitment in all three lakes. Fast fall cooling followed by slow spring warming, measured by the rate index, promotes strong Lake Whitefish year classes. This scenario concentrates spawning at optimal temperatures in the fall (generally below 6^{o}C; Hooper *et al.*, 2001) and allows larval Lake Whitefish to absorb their yolk sac more slowly in the spring so that they are larger, faster feeders when the yolk sac is fully absorbed (Lawler, 1965). Warming rate has also been shown to be influential in recruitment of walleye in western Lake Erie and is hypothesized to be a result of shortening the period of vulnerability of walleye eggs to storm events (Madenjian *et al.*, 1996; Roseman *et al.*, 1996).

In this study, ice cover and thermal index influenced recruitment in management units in Lake Superior only. This relationship is likely because these management units are the farthest north in the study and more often have ice cover present over the spawning grounds (due to cold temperatures) before spawning occurs. When ice is present, particularly over marginal spawning habitat, it can diminish the impacts of wind, current, and wave action improving Lake Whitefish egg survivability (Freeberg *et al.*, 1990) and, hence, recruitment.

A)

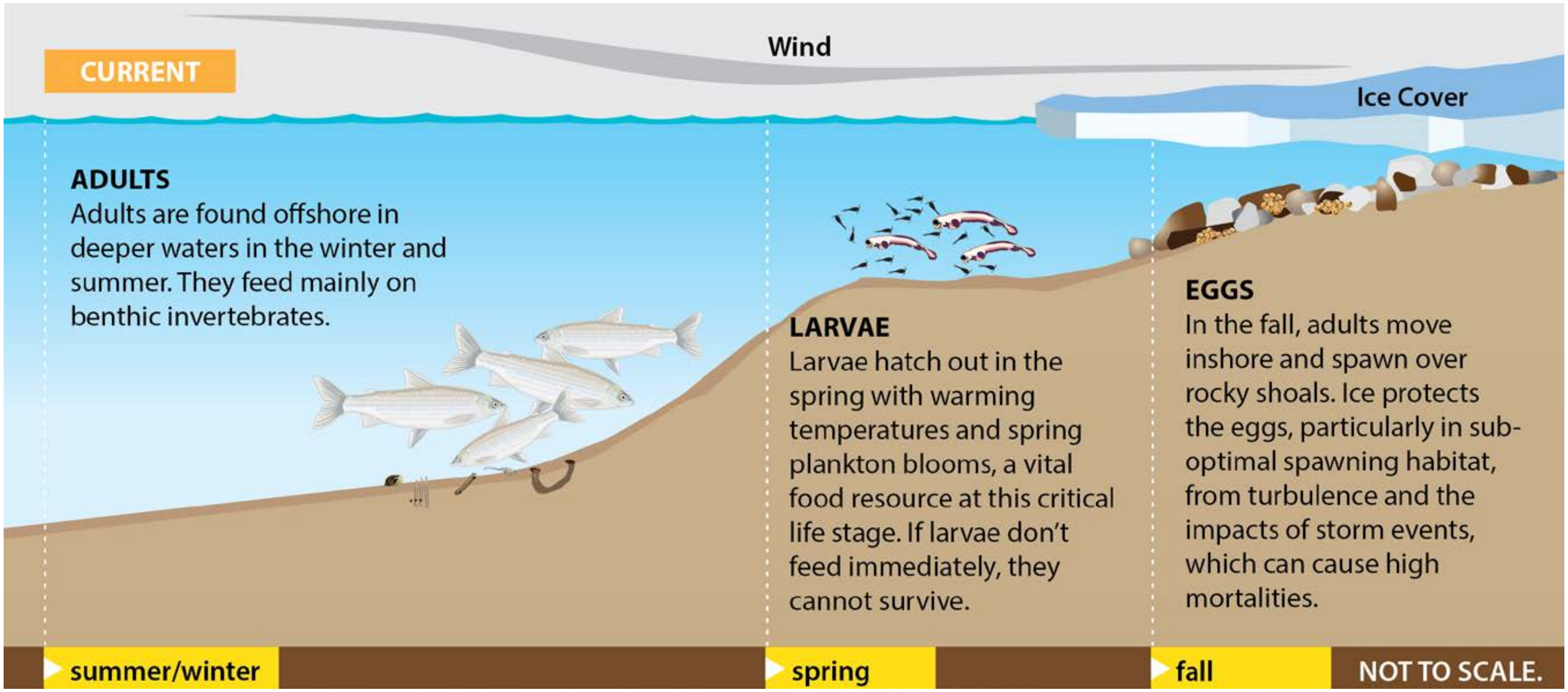
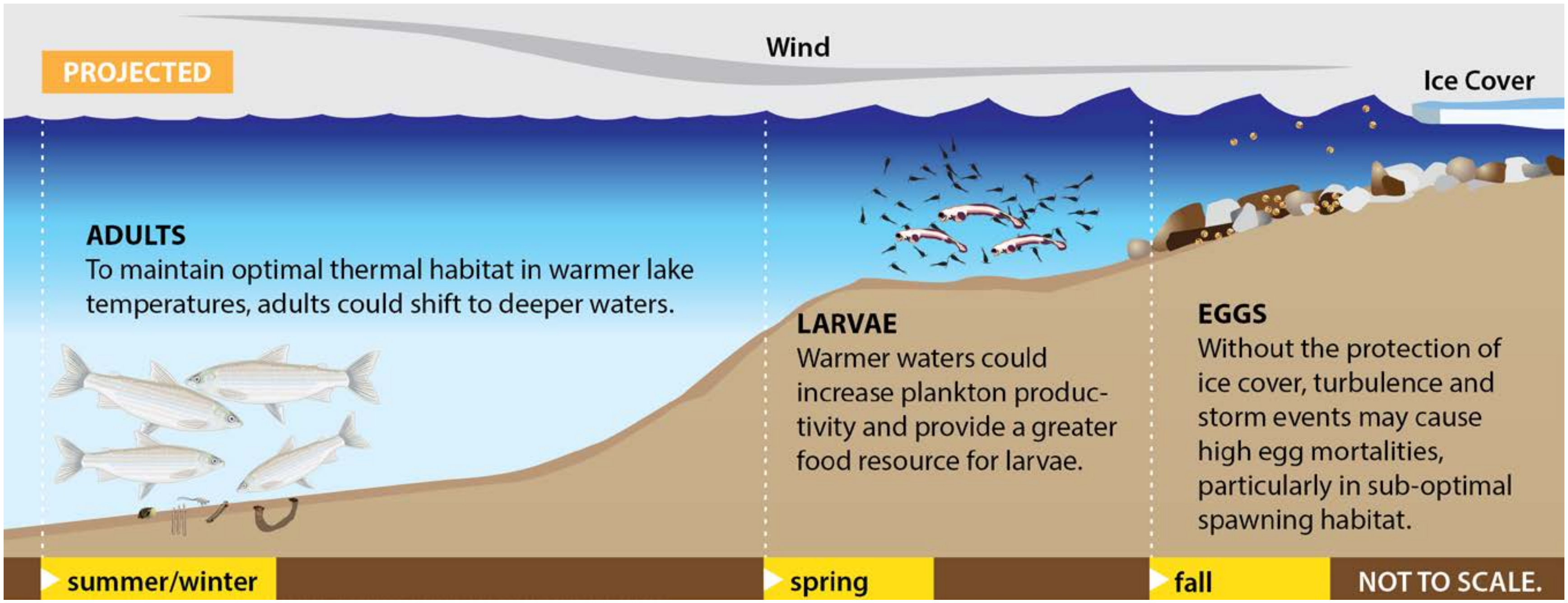


FIGURE 4.4. A) Current and B) Projected change in Lake Whitefish (*Coregonus clupeaformis*) recruitment with climate conditions: temperature, wind, and ice cover (*Todd Marsee*, Michigan Sea Grant).

FIGURE 4.4 (cont'd).

B)



Lake Whitefish climate-recruitment projection

Using the CHARM model of future climatic conditions in the Great Lakes region, our results indicated that climate change has the potential to increase Lake Whitefish recruitment in the 1836 Treaty Waters (Figure 4.4). It is important to note that these projections were simulations given a constant stock size. This approach isolated the change in projected recruitment to only change directly related to climate. Stock-recruitment relationships are highly complex and the influence of stock size on recruitment is not negligible (Taylor *et al.*, 1987a). Nonetheless, this study suggests that Lake Whitefish recruitment in the 1836 Treaty Waters is affected by variables that will be influenced by changes in climate.

Of the eight management units where the addition of climate variables significantly improved model fit, six of them saw increases in recruitment, though the projection for WFM-02 has a large amount of variance in the estimates ($\sigma^2 = 30.64$), indicating that other factors drive its recruitment. The projected increase in recruitment within the 1836 Treaty Waters aligns with the hypothesis that climate change will increase optimal thermal habitat for Lake Whitefish at all life stages (Magnuson *et al.*, 1990; Magnuson *et al.*, 1997). Though rate index, a composite temperature variable, was included in the best fit models for four of these six management units, it is important to note that other climate variables, namely wind and ice cover, were also important variables. Wind was included in five of the six models and ice cover was included in one Lake Superior management unit model.

Our modeling analysis suggests recruitment declines for the remaining two management units, WFM-06 and WFS-05, given projected climate conditions (Figure 4.1). The best fit model for WFM-06 included wind and the best fit model for WFS-05 included ice cover and thermal index. Recruitment in WFM-06 has a negative relationship with wind speed and the negative impacts on recruitment may be a result of projected increases in wind. Because WFS-05 is a Lake Superior unit, ice cover and cold temperatures before spawning occurs are likely to be important influences on recruitment. As a result, reduced ice cover and warmer temperature changes may result in a decline in recruitment. WFS-05, in particular, is management unit with high harvest rates. Projected decreases of almost 78% will likely severely change the Lake Whitefish population dynamics and dependent fisheries in the area.

Implications for Lake Whitefish management

The potential changes in Lake Whitefish recruitment have significant implications for the ecosystem, Lake Whitefish fishers, and the communities dependent upon the fishery. These results are not aimed at providing exact estimates of Lake Whitefish abundance in a given year but rather provide information to help managers allocate resources in a sustainable manner with changing conditions in the future. Management of Lake Whitefish in the 1836 Treaty Waters, using the Modeling Sub-Committee guidance for setting harvest limits in tribal and shared (tribal and state) zones, provides an example of the type of collaborative management that will likely become more necessary as Lake Whitefish populations shift locations to maintain optimal environmental conditions. Most management units are projected to have increased recruitment but two management units, WFM-06 and WFS-05, are projected to have decreased recruitment because of changing climate conditions. Managers can use the results of this study to anticipate general changes to the resource and adjust harvest strategies from management units that will decrease in productivity to those that will increase, ensuring that the fishery is sustainable and profitable now and in the future.

Acknowledgments

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APPENDICES

Appendix 4.1. Data ranges by 1836 Treaty Water Lake Whitefish (**Coregonus clupeaformis*****) management unit.***

Spawning stock biomass (SSB) and recruitment (R) are from the Modeling Sub-Committee statistical catch-at-age models; temperature is from land-based National Climate Data Center station data within a five mile buffer of each management unit; ice cover is from the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Ice Atlas; and wind speed and wave height are from the closest National Data Buoy Center offshore buoy. *Note that fall climate variables are linked to recruitment corresponding to the year fish were spawned and spring climate variables are linked to the year fish hatched.*

	Recruitment age	SSB/R	Temperature	Ice cover	Wind/wave
WFH_05	3	1981-2011	1980-2010	1972-2012	1983-2011
WFH_Northern_Huron	4	1976-2011	1980-2010	1972-2012	1983-2011
WFM_01	3	1976-2011	1980-2010	1972-2012	1983-2011
WFM_02	3	1986-2011	1980-2010	1972-2012	1983-2011
WFM_03	4	1986-2011	1980-2010	1972-2012	1983-2011
WFM_04	3	1981-2011	1980-2010	1972-2012	1983-2011
WFM_05	3	1981-2011	1980-2010	1972-2012	1983-2011
WFM_06	3	1985-2011	1980-2010	1972-2012	1983-2011
WFM_08	3	1985-2011	1980-2010	1972-2012	1983-2011
WFS_04	4	1986-2011	1980-2010	1972-2012	1983-2011
WFS_05	4	1986-2011	1980-2010	1972-2012	1983-2011
WFS_07	4	1976-2011	1980-2010	1972-2012	1983-2011
WFS_08	4	1981-2011	1980-2010	1972-2012	1983-2011

Appendix 4.2. Plots of Pearson correlation coefficients for potentially relevant climate variables by 1836 Treaty Waters Lake Whitefish (**Coregonus clupeaformis*****) management unit.***

FIGURE 4.5. Plots of Pearson correlation coefficients for potentially relevant climate variables: ice cover (December 10m depth contour), thermal index (April temperature deviation – November temperature deviation), rate index (spring warming rate – fall cooling rate), November wind speed (Nov_WSPD; monthly average), and November wave height (Nov_WVHT; monthly average) by 1836 Treaty Waters Lake Whitefish (*Coregonus clupeaformis*) management units. Confidence ellipses (*above* diagonal) demonstrate correlation magnitude and direction where a circle corresponds to zero correlation and as the correlation increases, the ellipse narrows, and finally collapses into a line segment as the correlation approaches ±1, a perfect linear relationship. Pie graphs (*below* diagonal) indicate the magnitude of the pairwise correlation (blue = positive; red = negative).

A)

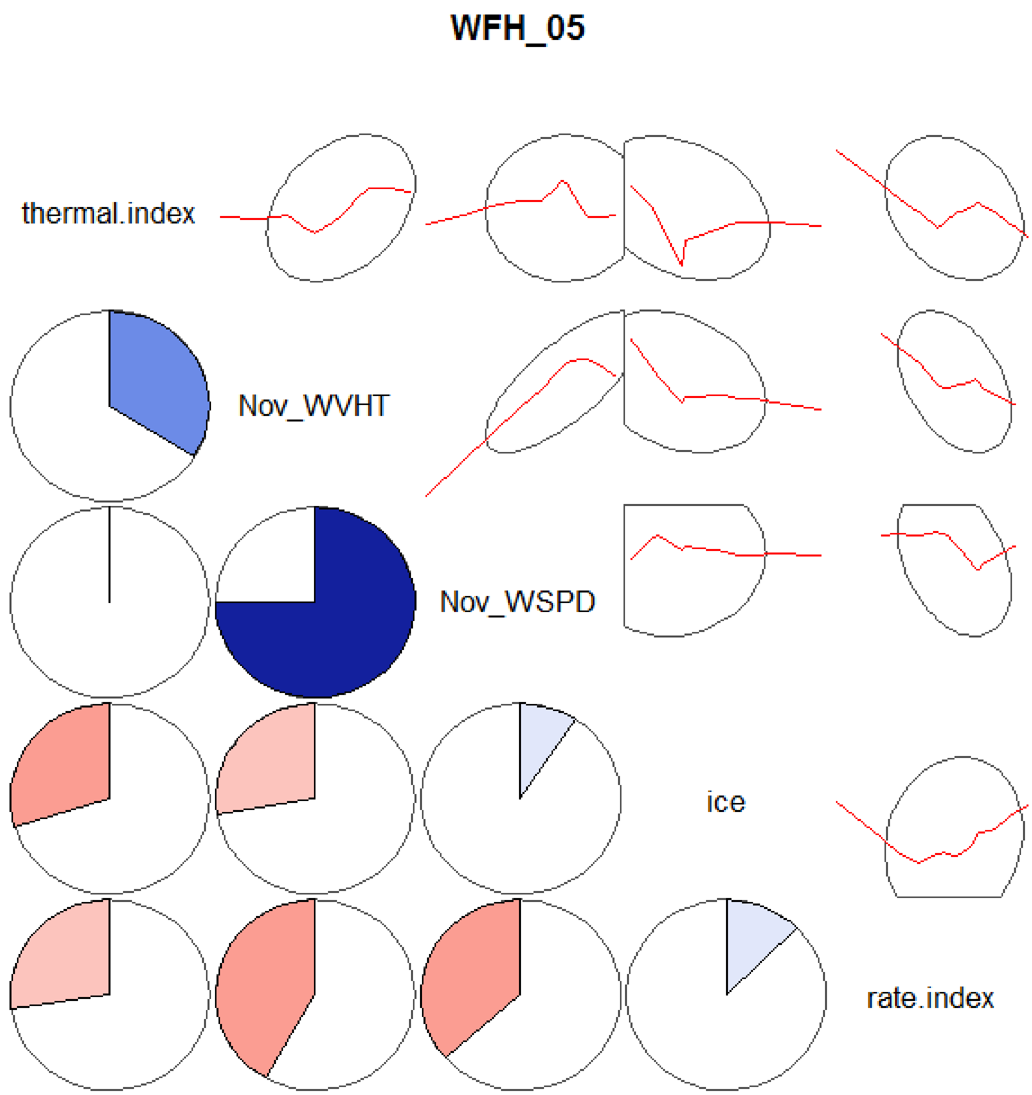


FIGURE 4.5 (cont'd).

B)

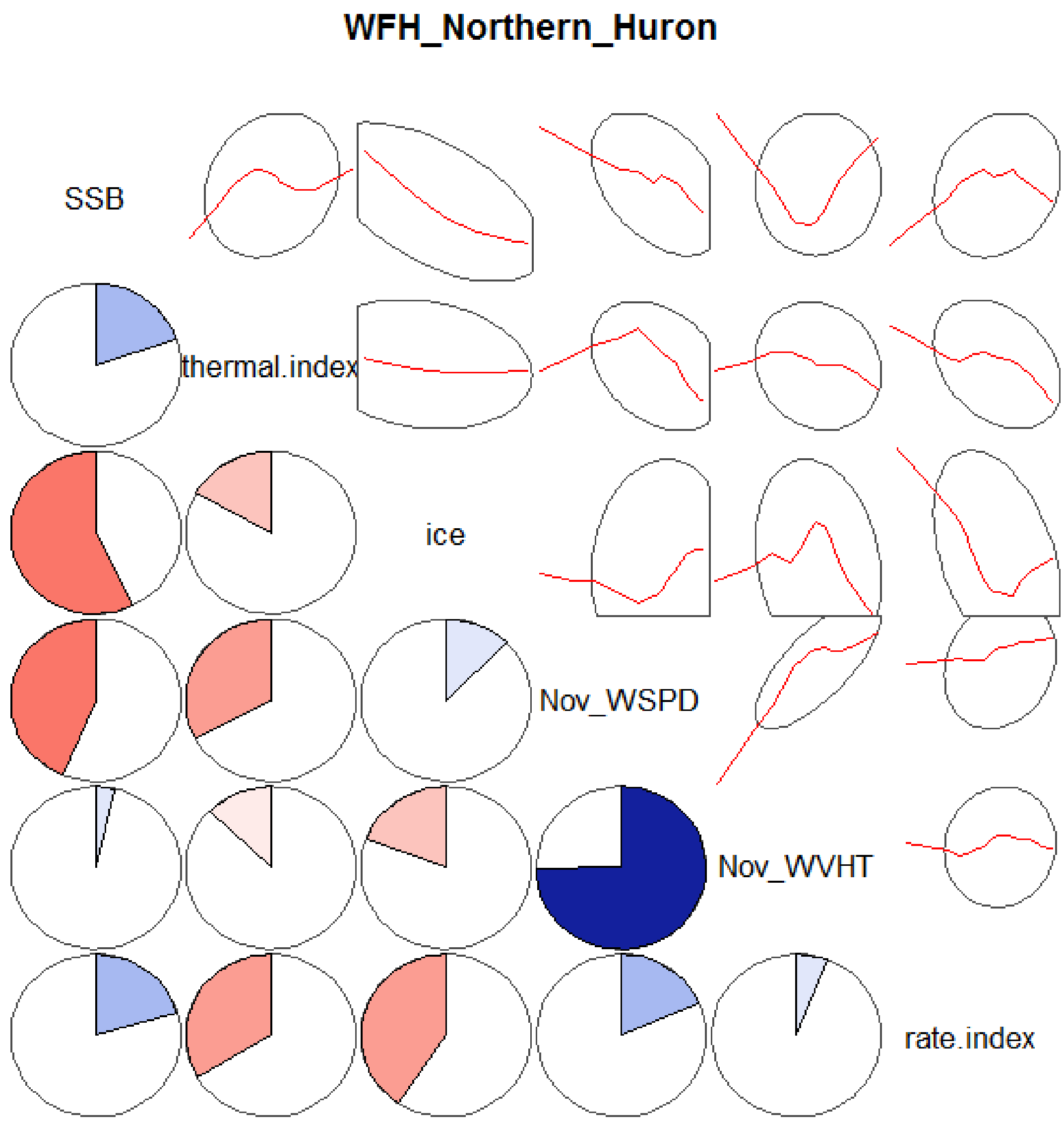


FIGURE 4.5 (cont'd).

C)

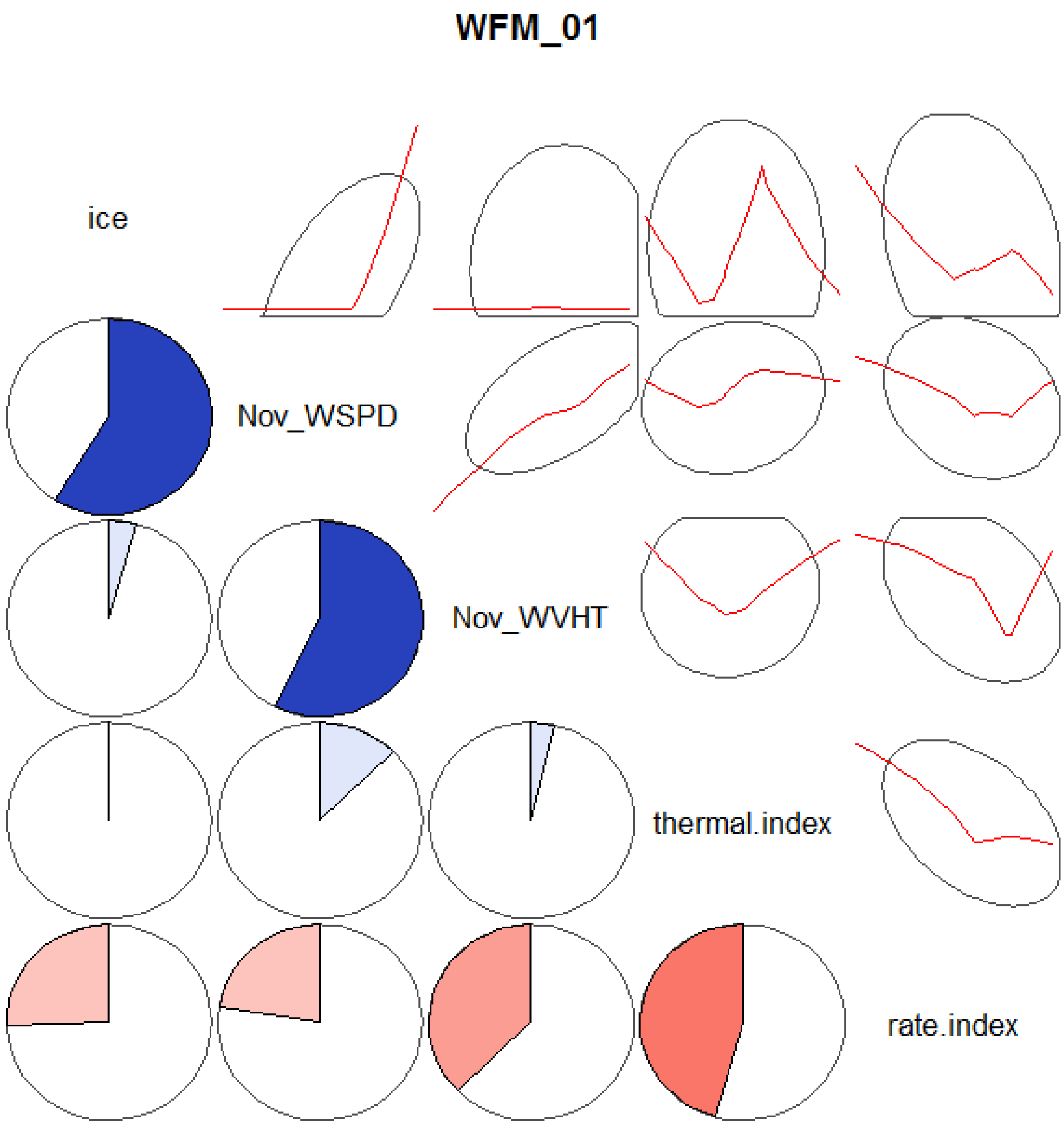


FIGURE 4.5 (cont'd).

D)

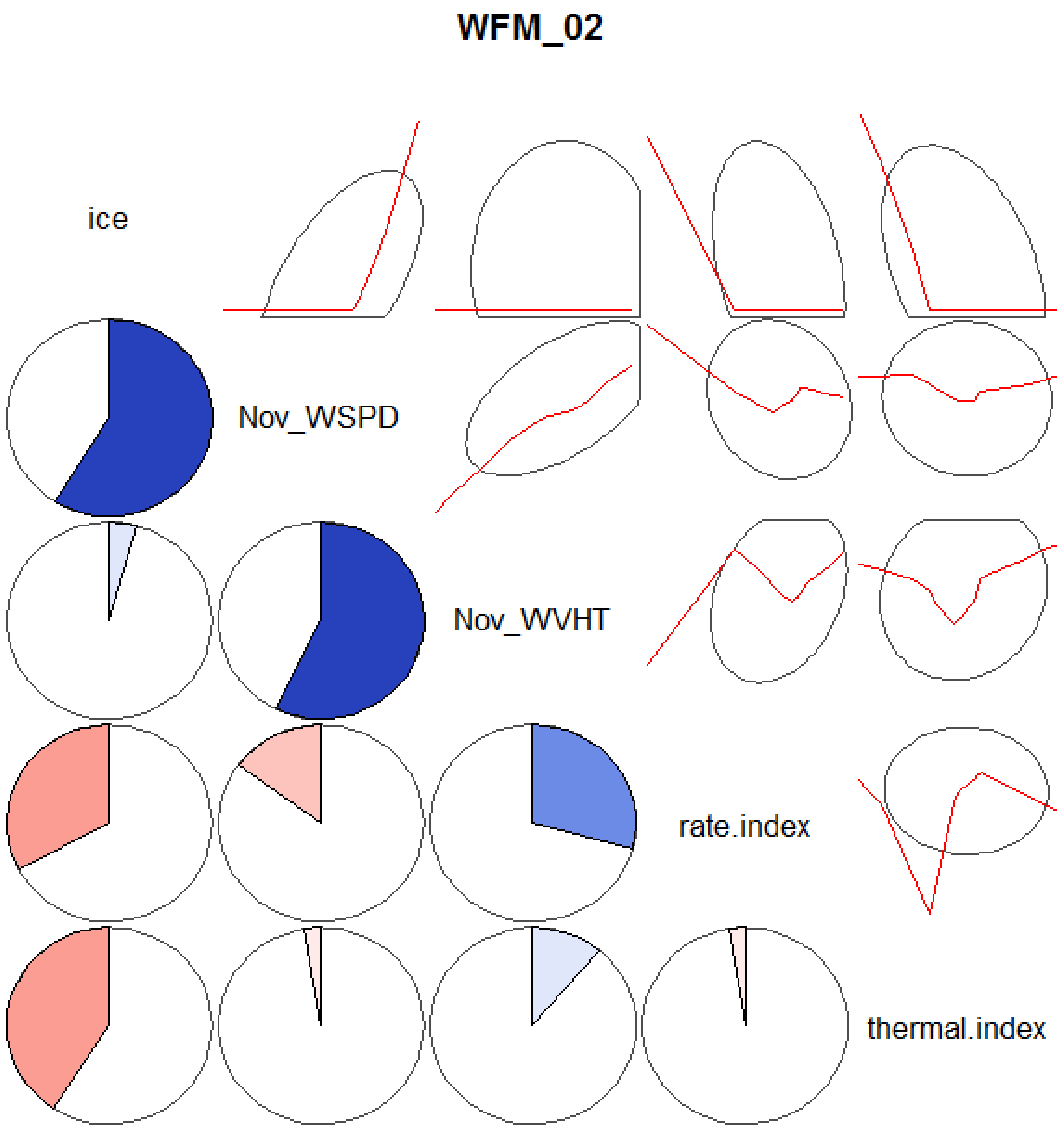


FIGURE 4.5 (cont'd). *Note WFM-03 temperature data unavailable.*

E)

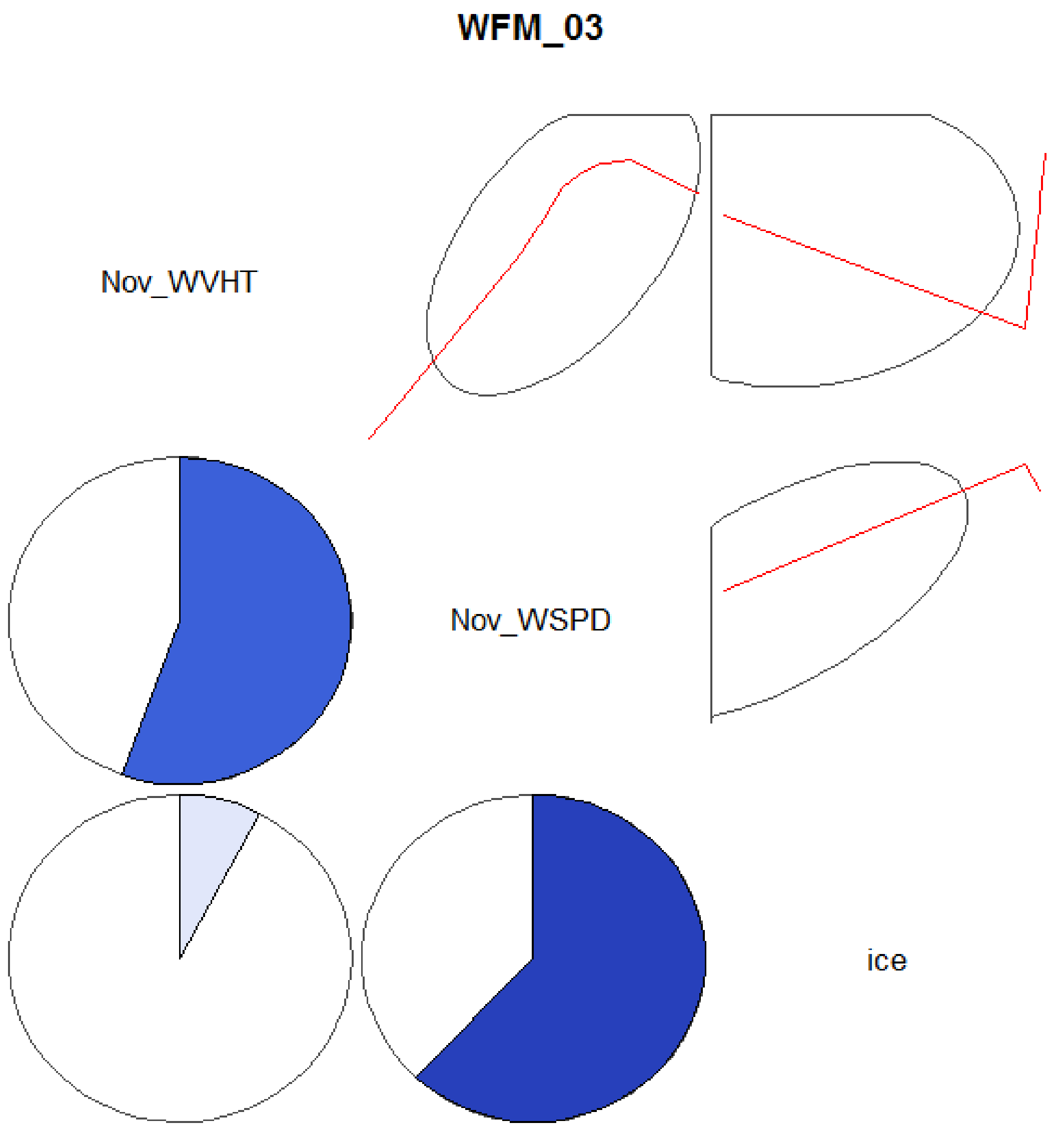


FIGURE 4.5 (cont'd).

F)

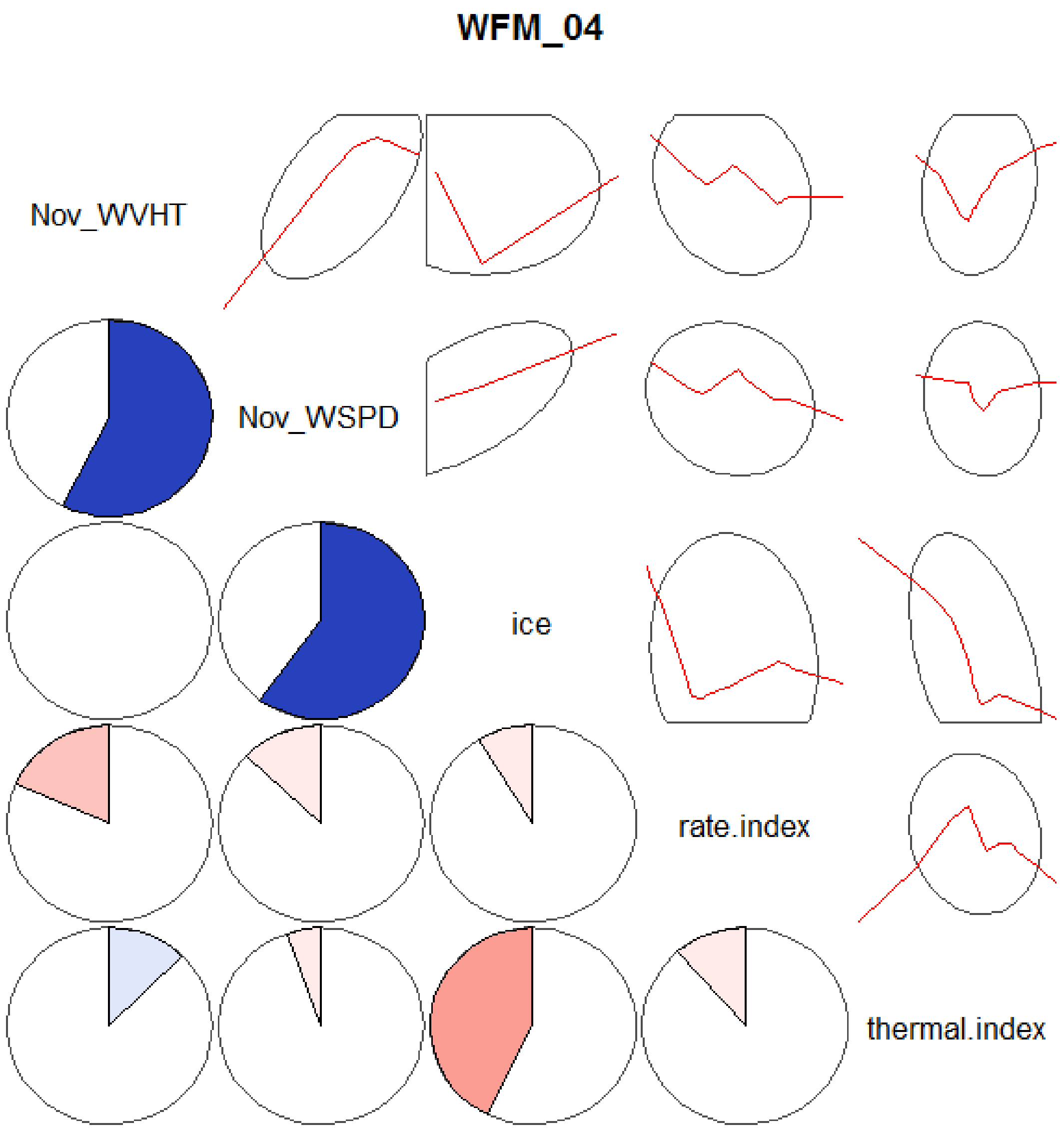


FIGURE 4.5 (cont'd).

G)

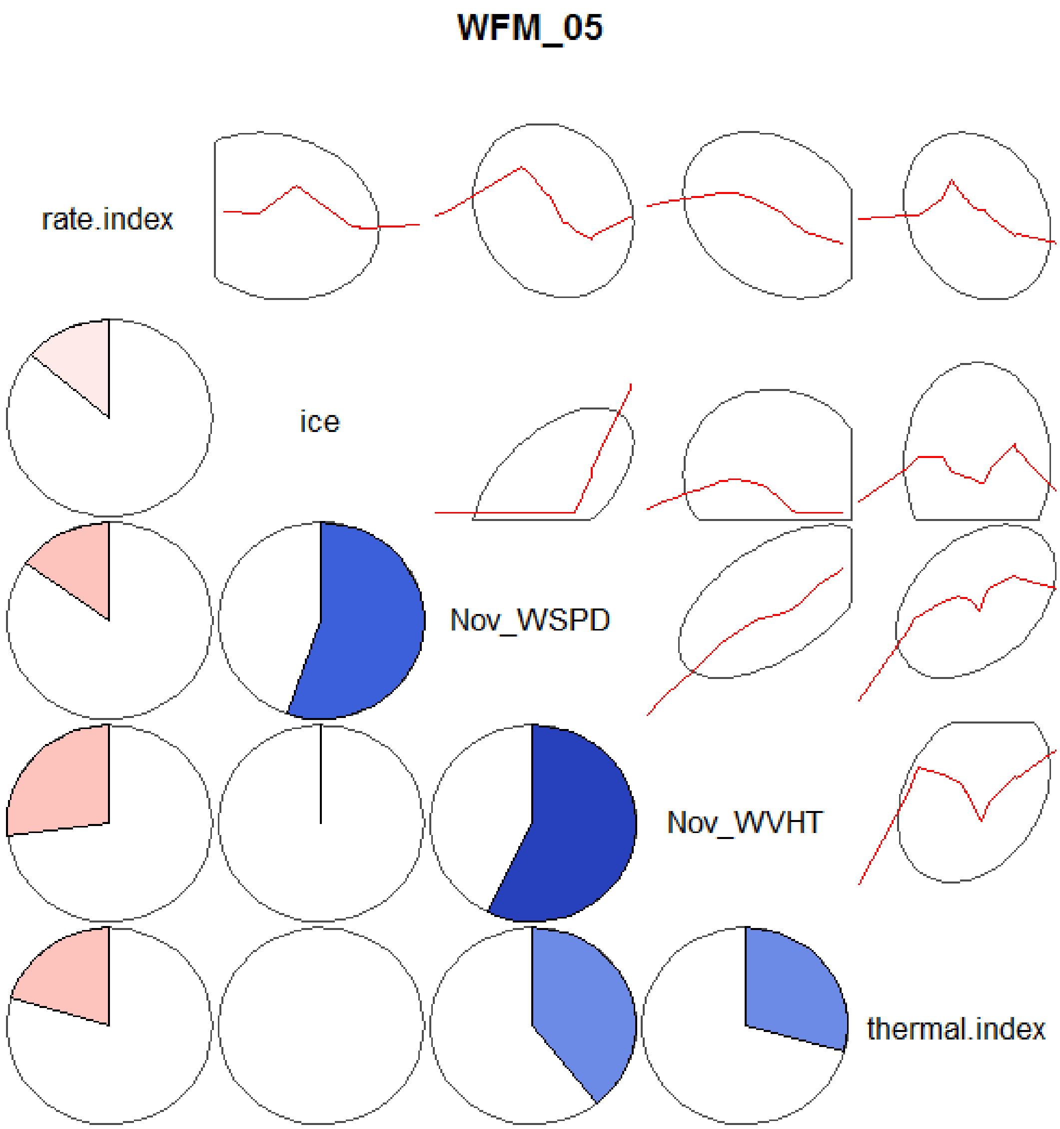


FIGURE 4.5 (cont'd).

H)

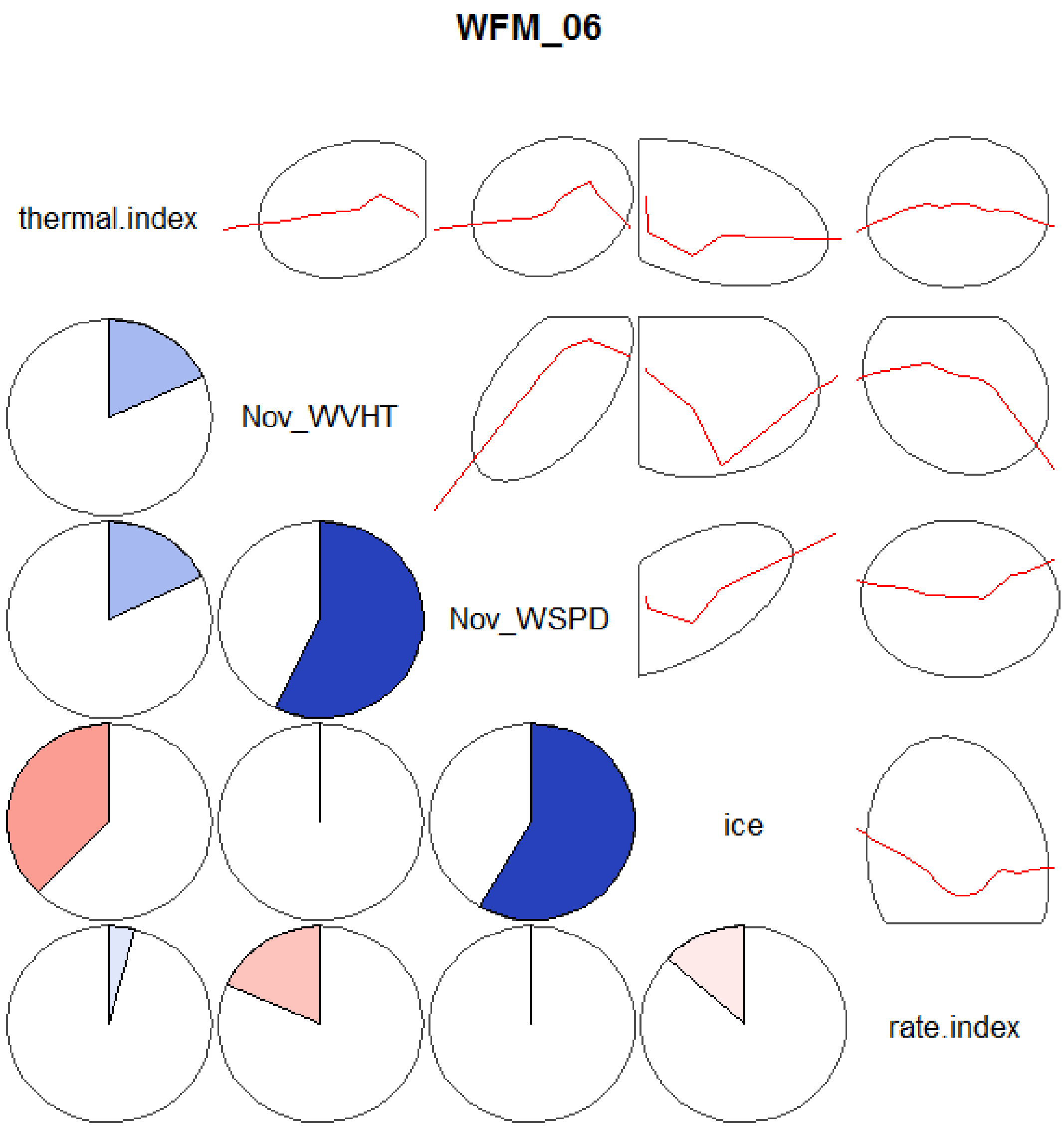


FIGURE 4.5 (cont'd).

I)

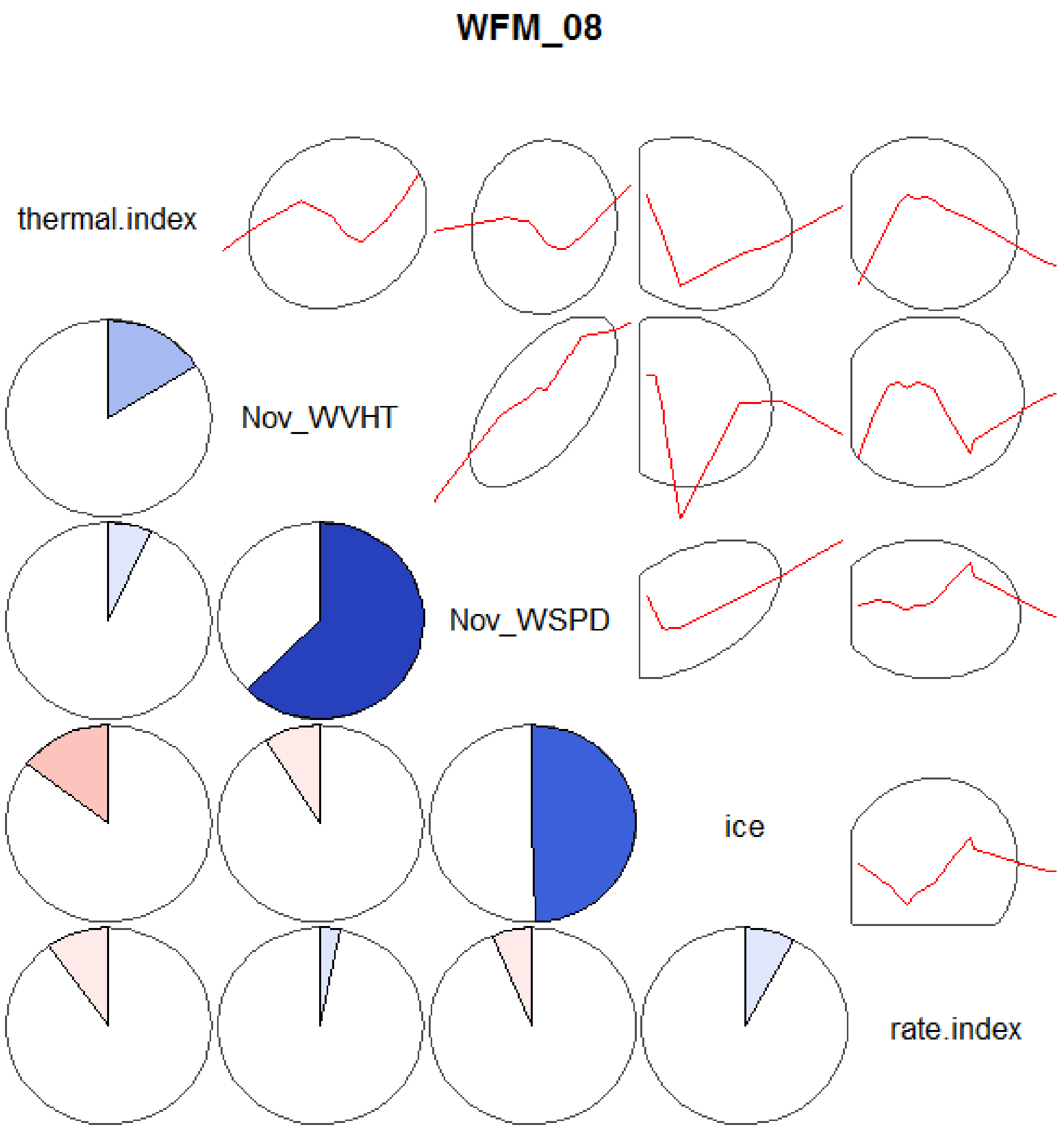


FIGURE 4.5 (cont'd).

J)

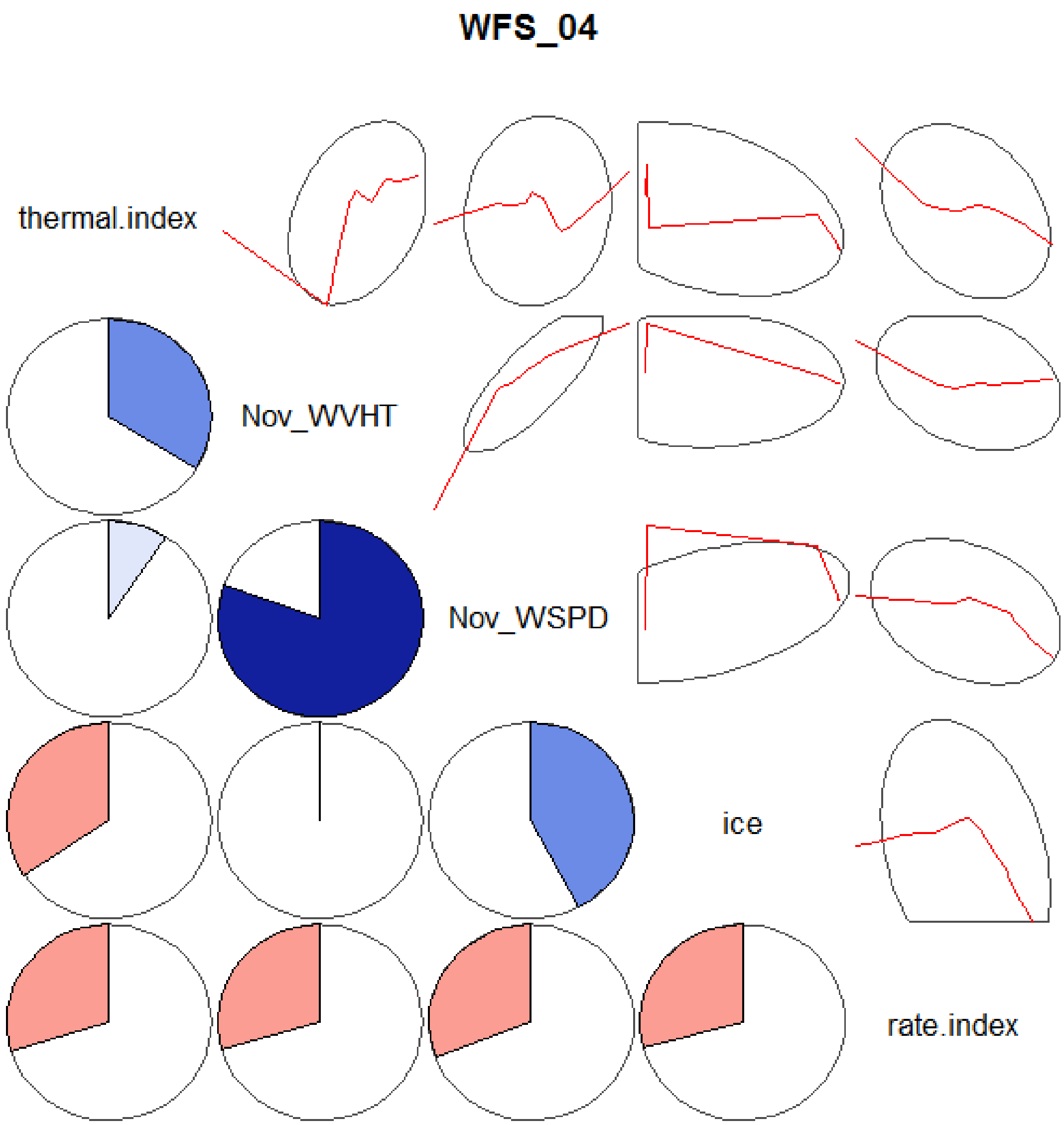


FIGURE 4.5 (cont'd).

K)

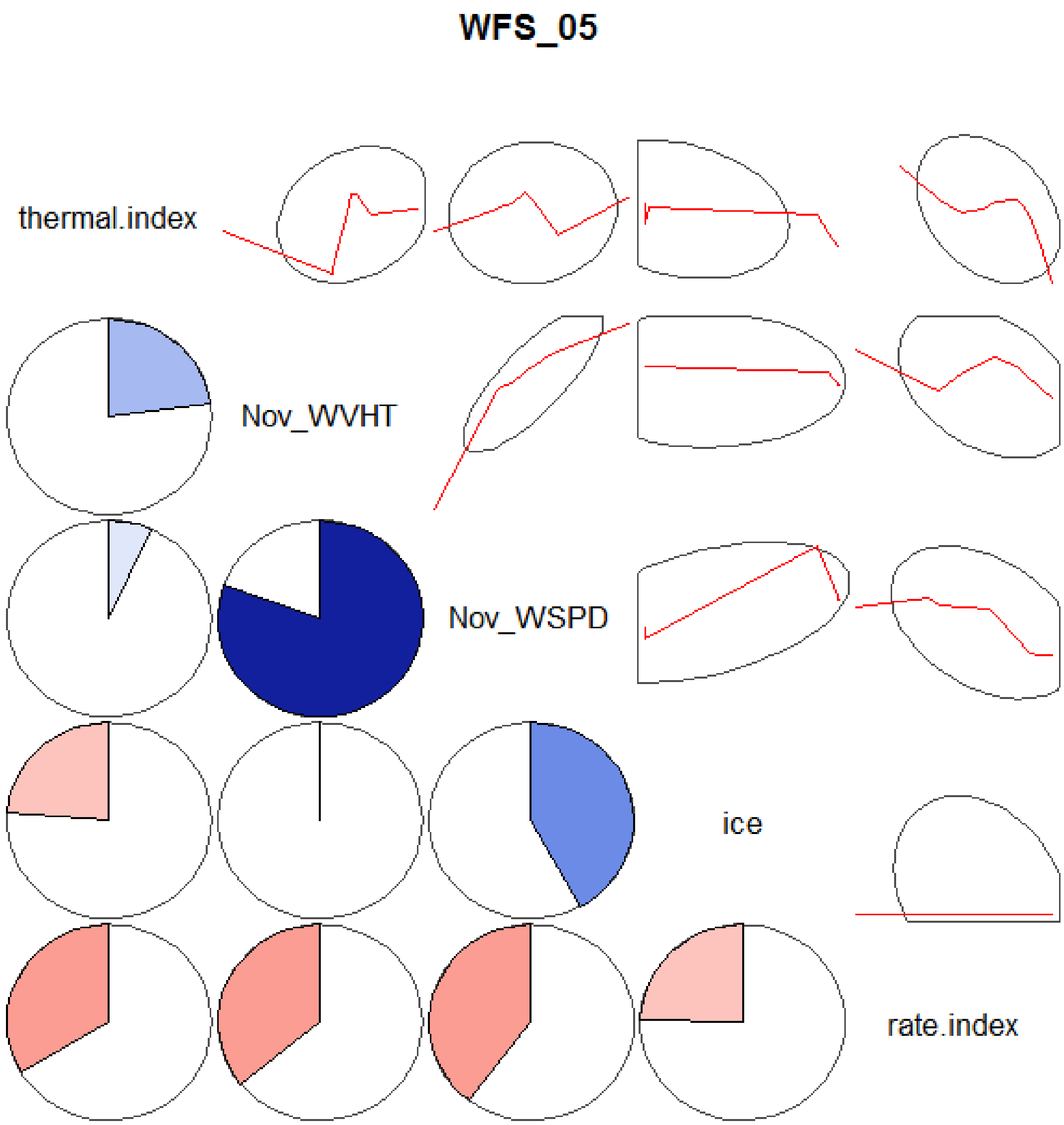


FIGURE 4.5 (cont'd).

L)

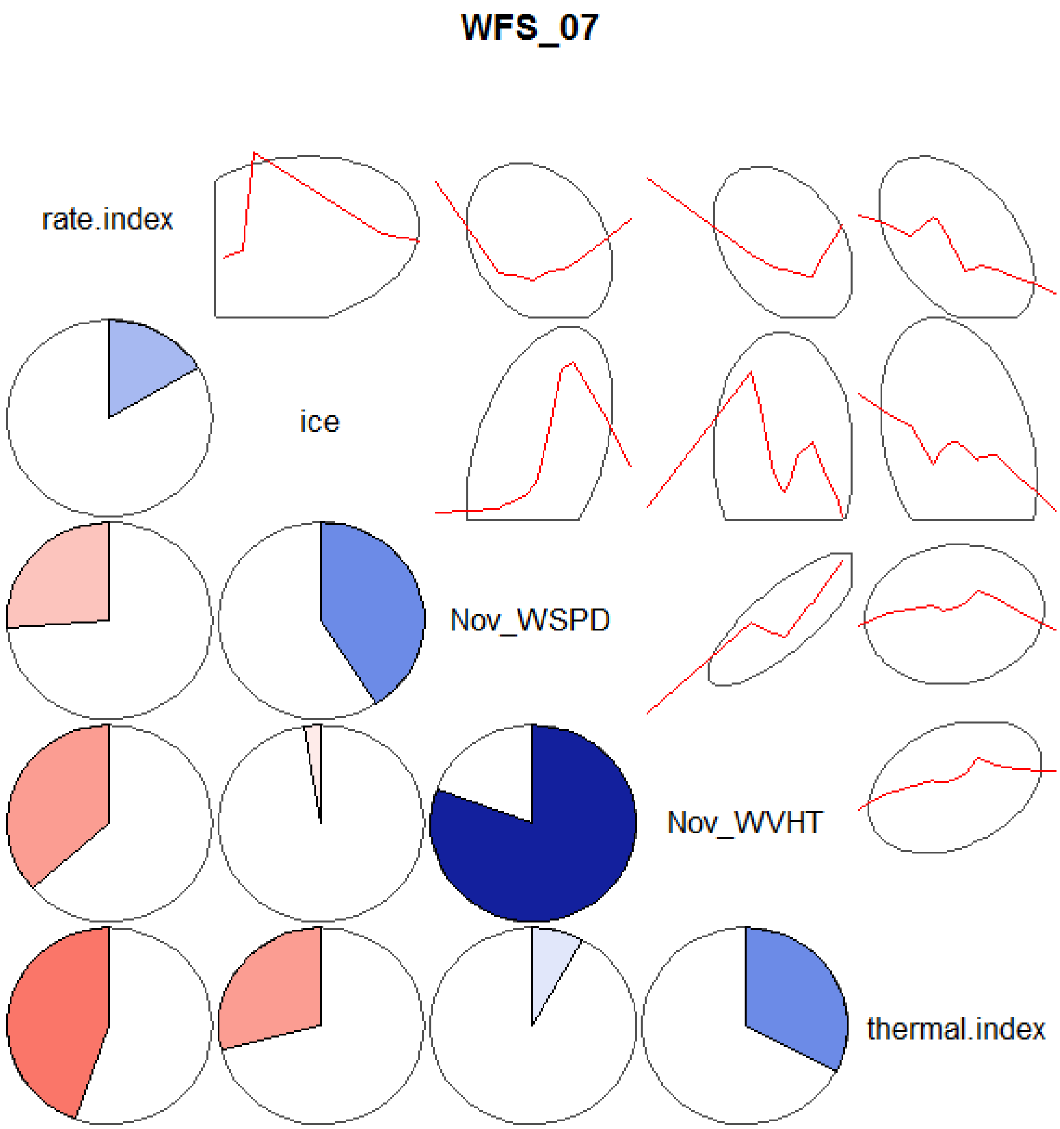
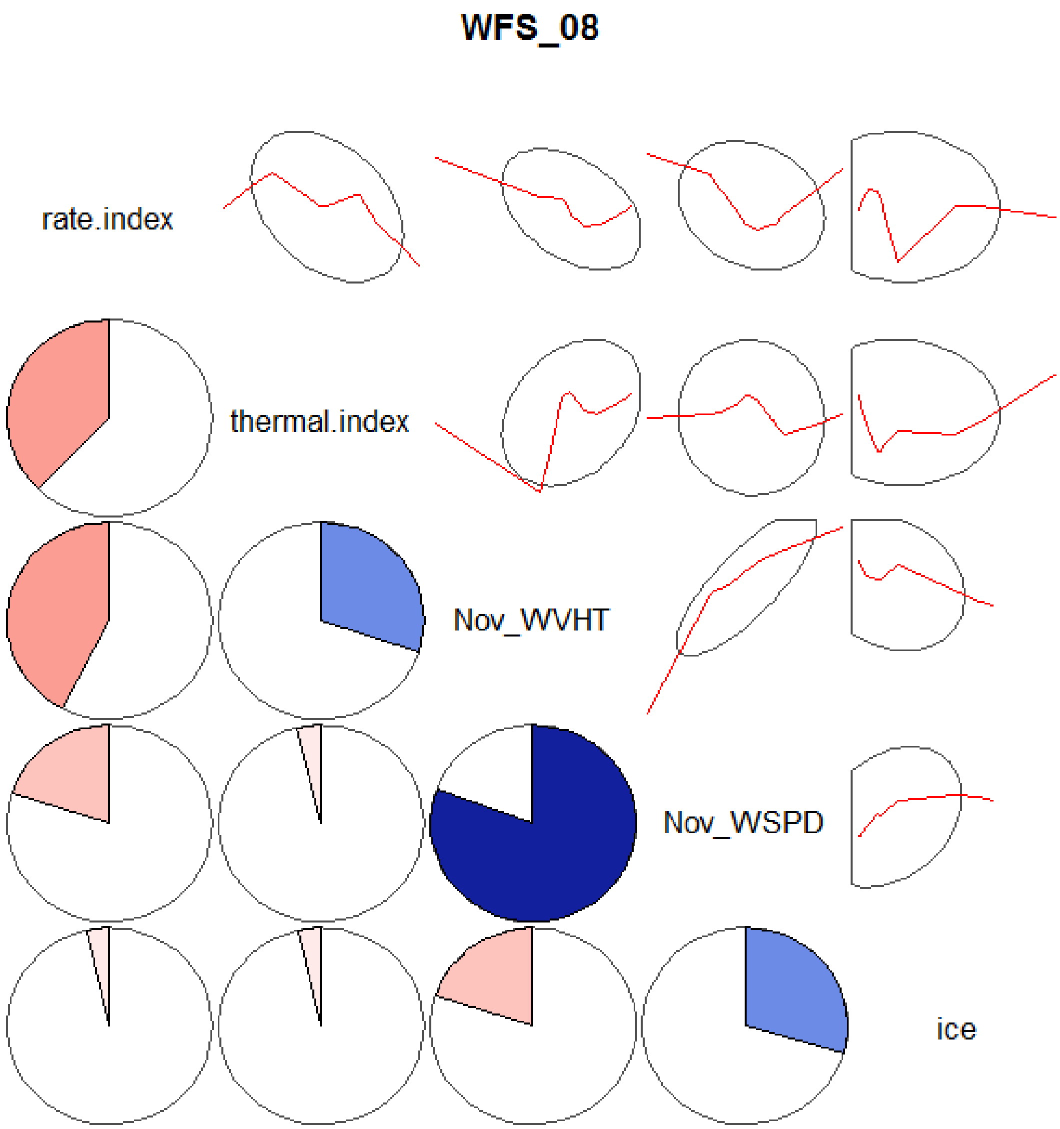


FIGURE 4.5 (cont'd).

M)



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SYNTHESIS

Climate change will affect the Great Lakes. The habitat will be different for Great Lakes fishes, including Lake Whitefish. Because Lake Whitefish recruitment is linked to climate variables, including temperature, wind, and ice cover, climate change will impact the productivity of the Lake Whitefish fishery. Modeling can project these changes in Lake Whitefish recruitment with climate change. Decision-support tools can help integrate these Lake Whitefish climate change projections into harvest management.

Climate change will affect the Great Lakes

Research evaluating the long-term changes in climate patterns project that the Laurentian Great Lakes region will be warmer, windier, with less ice cover by the end of the 21st century (Lynch *et al.*, 2010). Temperature, wind, and ice cover are all defining factors of fish habitat. Air temperatures are expected to increase by 3-7^{o}C in winter and 4-11^{o}C in summer (Wuebbles and Hayhoe, 2004) which will impact water temperatures. Surface temperatures of the Great Lakes are expected to increase by as much as 6^{o}C (Trumpickas *et al.*, 2009). With increased air and water temperatures, there will be less difference in the temperatures of the atmosphere and aquatic environments which will likely result in the more frequent occurrence of stronger winds and wind-driven waves (Desai *et al.*, 2009). All of the Great Lakes are expected to be ice-free year round, except for Lake Erie, the shallowest lake (Howe *et al.*, 1986) and Lake Erie is expected to have substantial reductions in ice cover (Lofgren *et al.*, 2002); certain coldwater species of fish depend on ice cover for protection of vulnerable life stages.

Climate influences the productivity of the Lake Whitefish fishery

Since 1980, populations of lake whitefish (*Coregonus clupeaformis*) have supported the most economically valuable commercial fishery in the upper Laurentian Great Lakes (Lakes Huron, Michigan, and Superior; Madenjian *et al.*, 2006; Ebener *et al.*, 2008). The success of recruitment to the fishery has been linked with climatic influences, including temperature, wind, and ice cover (Miller, 1952; Christie, 1963; Lawler, 1965; Taylor *et al.*, 1987b; Freeberg *et al.*, 1990). Lynch *et al.* (Chapter 4) found that including temperature, wind speed, and ice cover as variables in stock-recruitment modelling improves model fit and estimation of recruitment for Lake Whitefish in the majority of management units examined. Namely, temperature, wind speed, and ice cover are important drivers of Lake Whitefish recruitment in these management units (see Figure 4.4).

Lake Whitefish spawn in the fall and the eggs overwinter before hatching in the spring. As a result, fall and spring are critical periods to determining recruitment success because high levels of mortality can occur at these life-stages, depending on environmental conditions. Warmer spring water temperatures have been linked to Lake Whitefish larval growth and survival through increased availability of plankton prey resources (Brown *et al.*, 1993). Ice cover has been linked to Lake Whitefish egg survival by mediating the damaging impacts of wind and wave action to overwintering eggs, particularly eggs in sub-optimal rearing habitat (Taylor *et al.*, 1987a; Freeberg *et al.*, 1990). Lynch *et al.* (Chapter 4) confirmed the positive relationship between recruitment and temperature and ice cover and the negative relationship between recruitment and wind speed using corrected Akaike's Information Criterion for model selection. In eight of the 13 management units examined in the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior, climate variables significantly improved model estimation of Lake Whitefish recruitment (see Figure 4.1). In the remaining units, climate did not explain recruitment variability; this is likely because other factors not considered in this analysis are more strongly coupled with recruitment.

Modeling can project changes in Lake Whitefish recruitment with climate change

Climate change is expected to impact the Lake Whitefish fishery because temperature, wind, and ice cover are important drivers of recruitment (Lynch *et al.*, 2012). Thermal niche modeling for the Great Lakes indicates that there will be a greater volume of optimal thermal habitat for Lake Whitefish at all life stages (Magnuson *et al.*, 1990). It is important to note that realized habitat is composed of abiotic and biotic elements and interactions beyond just temperature (Hudson *et al.*, 1992). Less ice cover (Lofgren *et al.*, 2002) and stronger winds (Desai *et al.*, 2009) may result in lower survival of Lake Whitefish eggs to hatching.

Lynch *et al.* (Chapter 4) evaluated the combined impact of the conflicting influences of temperature, wind, and ice cover on Lake Whitefish recruitment in the 1836 Treaty Waters of Lakes Huron, Michigan, and Superior. The climate-recruitment relationships and climate projections for the Great Lakes indicate the potential for increase in Lake Whitefish recruitment with climate change and the potential for a change in the distribution of the fishery. Some management units will expect up to a 50% decline and others up to a 220% increase because of spatial variability in the climate-recruitment relationships and climate projections (see Figure 4.3).

Decision-support tools can help integrate Lake Whitefish climate change projections into harvest management

Decision-support tools can aid decision making by systematically incorporating information, accounting for uncertainties, and facilitating evaluation of trade-offs between alternative choices. Lynch *et al.* (Chapter 3) examined perceptions of the Lake Whitefish fishery management and the willingness of Lake Whitefish fishermen, researchers, and managers to utilize decision-support tools, such as the model developed by Lynch *et al.* (Chapter 4), to increase the availability of research to assist harvest management decisions for Lake Whitefish in the Great Lakes. The survey participants (Lake Whitefish fishermen, researchers, and managers) indicated that they agreed with the statement that decision-support tools can be useful for fisheries management (see Figure 3.8). The survey participants were given the opportunity to provide suggestions for successful implementation of decision-support. The recommendations included the following general categories: 1) fostering communication between managers and fishermen; 2) addressing significant management questions; and, 3) using a user-friendly, low-maintenance format.

The survey recommendations were used to develop the online user-interface for the Lynch *et al.* (Chapter 4) decision-support tool, which is housed on the Michigan Sea Grant website (http://www.miseagrant.umich.edu/) for ease of access and use by fishermen, fishery managers, scientists, students, and the public. This tool will be a means to communicate the potential impacts of climate change on the Lake Whitefish fishery with fishermen, fishery managers, and scientists to help them anticipate changes to the distribution and abundance of the fishery. The aim of the tool is to support an ecologically sustainable, prosperous Lake Whitefish fishery and promote the well-being of associated coastal communities. Further, this tool can be used to educate students and the public on potential impacts of climate change to the Great Lakes region using Lake Whitefish as a case-study. More broadly, it can serve as a model for other fisheries that have the potential to be impacted by global environmental processes, such as climate change. The ultimate goal of this research is to support scientifically-informed decision making and ensure sustainable use of fisheries resources, now and in the future.

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