Updated Decision Analysis to Inform Multi-Species Salmonine Management in Lake Michigan

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Abstract

The recreational fishery for salmonine species in Lake Michigan (lake trout, Chinook salmon, coho salmon, steelhead, and brown trout) is largely maintained through stocking. Decisions about how many of each species to stock require an understanding of how to maintain a sustainable balance of predators (salmonine species) to prey (alewife) in the lake. The current models used to make these decisions can estimate the ratio of Chinook salmon to alewife in the lake. However, the Lake Michigan Committee's new stocking strategy aims to incorporate the other salmonine species into this predator-prey ratio. We used structured decision making to evaluate potential stocking strategies. We worked with fishery stakeholders and members of the Lake Michigan Committee, conducted participatory modeling to forecast outcomes of stocking scenarios using updated information on fish movement and feeding, and evaluated the risk of these stocking strategies. Most of the stocking practices we evaluated resulted in a high risk of large declines in alewife abundance, negatively affecting future salmon fisheries. The forecasts were substantially more pessimistic than those resulting from a similar analysis conducted a decade earlier, apparently due to more recent alewife assessments indicating lower alewife productivity (recruits per spawner). Alewife recruitment dynamics is an area of substantial uncertainty, with apparently large consequences for management; decision makers on Lake Michigan would benefit from greater understanding of alewife recruitment dynamics to reduce this uncertainty when accounting for risks.

Keywords
Structured decision making, stock assessment models, lake trout, Chinook salmon, coho salmon, steelhead, brown trout, alewife

Executive Summary

Lake Michigan's highly valued salmonine recreational fishery is supported by the stocking of five species: native lake trout (*Salvelinus namaycush*), and introduced Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), steelhead (*O. mykiss*), and brown trout (*Salmo trutta)*. Catch rates and abundance of these five species have varied over time because of among-species differences in stocking practices, survival across species and time, and extent of natural reproduction. Alewife (*Alosa pseudoharengus*), which is non-native to the Great Lakes, has been the main prey source for these species, but alewife abundance has declined since the 1970s. This decline is partially due to the abundance of stocked fish in the lake, which has led fishery managers to consider what stocking rates would be appropriate to maintain balance between the predators (salmonines) and the prey (alewife). The alewife decline has caused concern among fishery managers and stakeholders that Lake Michigan's alewife population may be heading towards a collapse, similar to what was experienced in Lake Huron in the early 2000s.

Decisions for stocking are currently made with the aid of a model known as the predator-prey ratio, which allows managers to understand whether the biomass of predators in the system is in balance with the biomass of available prey. This ratio is currently calculated based on estimates of Chinook salmon (predator) and alewife (prey) from stock assessment models. Given that the other salmonine predators also consume alewife, fishery managers have suggested that this ratio should include all stocked salmonines, not just Chinook salmon. In addition, the Lake Michigan food web has undergone important changes, the most notable of which is the expansion of invasive round goby (*Neogobius melanostomus*) throughout the lake, which has become an important prey source for species like lake trout. Finally, there have been changes to the contribution of other species to total stocking effort in Lake Michigan, as well as changes in the movement patterns of Chinook salmon between Lakes Michigan and Huron, such that Chinook salmon in Lake Huron are moving to Lake Michigan to feed.

Based on changes in the decision-making approach, the ecosystem, and likely, the stakeholders in the region, we conducted an updated decision analysis process with managers and stakeholders. The updated process included engagement with decision makers and stakeholders, and updated models and associated parameters used as decision-making tools. Decision makers included all members of the Lake Michigan Committee (i.e., each jurisdiction with fisheries management authority: Michigan, Wisconsin, Illinois, Indiana, and the Chippewa Ottawa Resource Authority [CORA]). Stakeholders represented recreational anglers, charter boat captains and associations, and multiple sport fishing clubs and associations. Our aim was to determine the composition and total number of salmonines to stock in Lake Michigan that would be most likely to achieve shared objectives of the fishery stakeholders.

The specific objectives of our project were:

1. To engage managers and stakeholders in a Lake Michigan salmonine stocking decision analysis;
2. To incorporate new information, particularly on predator diets, salmonine wild production, and Chinook salmon movements from Lake Huron, into both forecasting and assessment models;

3. To forecast risks associated with alternative stocking strategies that consider effects of all salmonine predators using updated information in the forecasting model;
4. To engage managers and stakeholders in discussions about future management procedures for Lake Michigan salmonine stocking, informed by our analysis.

We used the process of structured decision making (SDM) to evaluate potential stocking strategies for salmonines in Lake Michigan by integrating stakeholder values and perspectives, ecological knowledge of the system, and technical modeling. The SDM framework allows groups to work together to collaboratively identify the components of the problem, describe a set of shared objectives to be achieved, identify a set of alternative actions that could be taken to achieve the objectives, predict the consequences of each action on each objective, and collaboratively make tradeoffs and assess risk. We conducted a series of workshops in a virtual format, from 2020 to 2022, culminating with an in-person final workshop in September 2022.

During the first few workshops, the group completed the first three steps of the SDM process (problem, objectives, alternative actions). The group crafted a problem statement after identifying affected parties, spatial and temporal considerations, uncertainties and constraints, and discussing the decision at hand. The final problem statement was,

The goal of this project is to determine a stocking strategy that accounts for stakeholder desires regarding a productive [recreational salmonine] fishery now and in the future for all of Lake Michigan, including Green Bay and Grand Traverse Bay, and includes consideration of the ecology and fish dynamics in Lakes Michigan and Huron, and that considers the needs of the economic sector (e.g., tourism, tackle, port communities) in all states that surround the lake.

The objectives were determined by the group based on a brainstorming session in which they discussed their various values and goals for the salmonine fishery in Lake Michigan. The group created an objectives hierarchy, in which the fundamental objectives (i.e., those objectives that the group fundamentally cared about and wanted to achieve) included concerns about the fishery itself (maintain or improve the world-class fishery for salmonines in Lake Michigan), the industry surrounding this fishery (maximize economic return for the tourism sector), effects of stocking on other fisheries (minimize negative effects on recruitment of other valuable species), and costs of implementation (minimize costs of stocking). Means objectives (i.e., the means to achieving the fundamental objectives) for the salmonine fishery included return rates on stocked Chinook salmon, catch of large fish, and catch of a desired proportion of each of the stocked species. These objectives would be achieved through maintaining forage, including alewife. The group acknowledged that the maintenance of the salmonine fishery was affected by stocking, natural reproduction, and forage availability.

The alternatives consisted of a suite of ideas that fell into the categories of stocking actions, methods to increase survival of stocked fish, and triggers that would mean that the stocking strategy should change. The full list of strategies contains many ideas that could be considered by the Lake Michigan Committee when making stocking decisions. The group acknowledged that for this exercise, the main lever that we could implement was changes in the number and species of fish stocked into the system.

Overall, information about the fishery and the ecosystem has been gained from a number of sources in recent years. During the consequences step, we gathered these new data and models and updated models as needed. Stock assessment models, which have been updated by members of the Lake Michigan Technical Committee, provided new information on the abundance and biomass of predators and prey. We also had better information about the movement of Chinook salmon between Lakes Huron and Michigan, and about predator diets, including changes associated with the increase in round goby abundance. Updated information was incorporated into the improved forecasting model to evaluate consequences of stocking changes.

We used these models to forecast the effects of different stocking scenarios on the abundance of alewife in the system. We presented the results of these modeling efforts in the in-person workshop in September 2022. The results for our policy simulations were unexpected. Overall, the forecasting model indicated that there was a high probability of a crash of the alewife population in Lake Michigan under a status quo stocking scenario (i.e., the stocking strategy that was implemented in the most recent year). Further examination of stocking strategies did not reveal a large reduction in risk even with large reductions in stocking for all species. Strategies that focused on one or a few species (e.g., Chinook salmon, lake trout) likewise did not reveal approaches that substantially lowered the risk of alewife crashes without large overall stocking cuts. We determined that the reason for the surprisingly high risk of future alewife crashes was due to the way recent observations of alewife recruitment are interpreted by the assessment model. Briefly, a series of comparatively low recruitments in the past decade resulted in changes to the model parameters that, in effect, indicate the population is less productive than previously believed. This lower productivity means the population is less able to recover from weak year-classes in the presence of high predation rates.

We discussed potential reasons for the deviation of the forecasts from expectations. The alewife assessment model is complex, requiring both survey data from trawl and hydroacoustic programs, and estimates of predator consumption of alewife, to derive estimates of recruitment. Thus, the alewife assessment model has a high degree of uncertainty in its predictions, which carries over as uncertainty in our risk results. The alewife assessment model has not been reviewed for several years, and our findings suggest a need for the models used to estimate alewife recruitment to be revisited. In particular, it would be valuable to examine whether there is evidence in the data for temporal trends in productivity, something the current model is not designed to assess.

In addition to the uncertainties in the alewife model, stocking was evaluated as the sole management lever for maintaining salmonine populations in Lake Michigan in a balance with alewife. However, our results indicated that perhaps the number of naturalized salmonines (i.e., those fish that were reproduced in the system) might mean that stocking is not as effective as a management lever as it previously was. We found that the relative risk of alewife collapse could be reduced by reducing the stocking of all salmonines, but that there was still a risk of collapse.

Accomplishments

Introduction

Lake Michigan's highly valued salmonine recreational fishery is supported by the stocking of five species: native lake trout (*Salvelinus namaycush*), and introduced Chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), steelhead (*O. mykiss*), and brown trout (*Salmo trutta)*. Variation in stocking practices, differential survival of stocked individuals, and wild production of stocked species from tributaries of Lakes Huron and Michigan have led to variations in abundance and catch rates of these species over time (Claramunt et al. 2012; Muir et al. 2012; Clark et al. 2017). Non-native alewife (*Alosa pseudoharengus*) has historically been the primary prey source for all five species, but alewife biomass has been estimated at relatively low levels since 2000 (Figure 1; Madenjian et al. 2016; Tsehaye et al. 2014a and 2014b; Bunnell et al. 2018). This decline is at least partially due to increased predation by stocked salmonines, which has led to discussions between fishery managers and stakeholders about levels of stocking that would ensure a balance among predator and prey biomass. The collapse of alewife between 2003 and 2005 in Lake Huron (Riley et al. 2008; Tsehaye et al 2014b; Kao et al. 2016) has exacerbated concerns of similar outcomes for Lake Michigan.

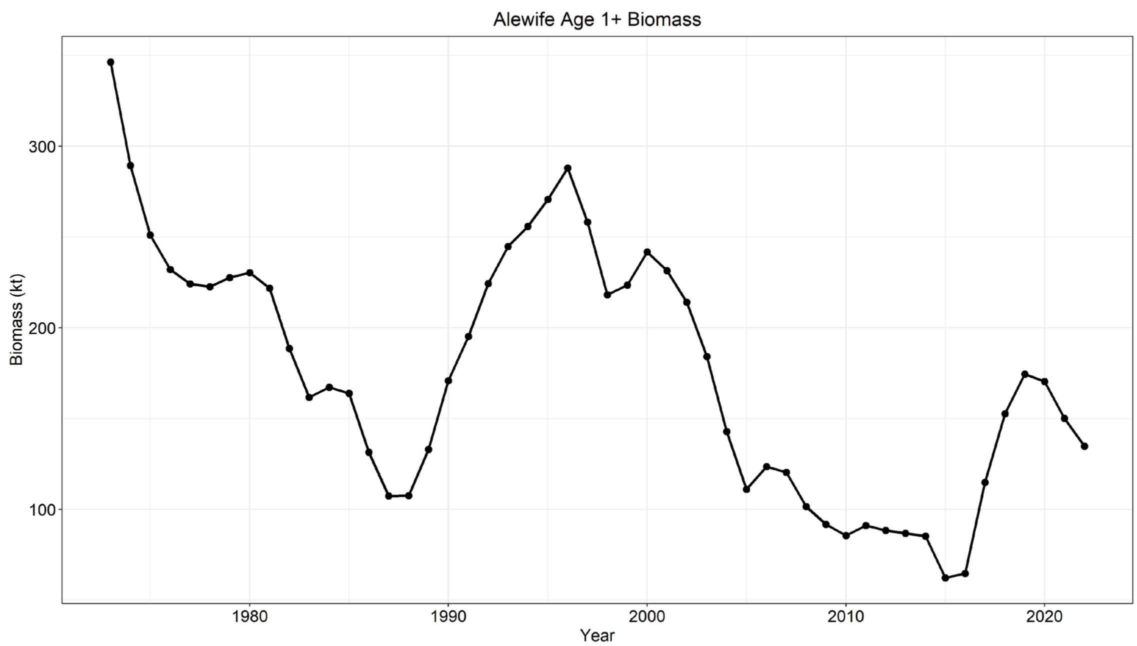

Figure 1: Estimated biomass (from the stock assessment model) of age 1+ alewife in Lake Michigan 1974–2022.

The discussions and debates surrounding salmonine stocking practices have led to both reductions and increases in stocking rates over the years. Reductions were implemented in 1999, 2006, 2013, and 2018, and an increase was implemented in 2020, with these decisions largely informed by analyses of predator (i.e., salmon [largely Chinook salmon]) and prey (i.e., alewife) population dynamics accompanied by estimates of feeding rates on alewife and other prey. Two modeling frameworks have been implemented to analyze the effects of potential stocking strategies: 1) stock assessment models are used to estimate the abundance of each species relative to management targets (Tsehaye et al. 2014b; Jones et al. 2014), and 2) forecasting models, which use the output of the stock assessment models, simulate the effects of stocking strategies into the future (Szalai 2003; Jones et al. 2008).

The basis of the stocking reductions implemented in 2013 and 2018 was a decision analysis (DA) effort that was implemented between 2009 and 2012 that incorporated stock assessment and forecasting models to integrate science and manager / stakeholder preferences to inform stocking decisions. This process led to the decision in 2013 to reduce stocking, largely of Chinook salmon, by 50% in Lake Michigan. The implementation of the decision analytic framework allowed stakeholder involvement, which led to great agreement among all parties (state agencies, managers, stakeholders) about the need for these reductions. One of the results of this DA effort was identification of the need to develop a predator-prey ratio model (PPR) that combined the results from stock assessment models (Tsehaye et al. 2014a and 2014b) to help managers decide whether stocking should be maintained, increased, or reduced to retain the sustainability of the fisheries (Jones et al. 2014; LMC 2018). The PPR calculates the ratio of Chinook salmon biomass to alewife biomass, based on estimates from stock assessment models for these two species. Reference points were determined to identify appropriate levels for maintenance of stocking (target reference point) or reductions in stocking (limit reference point). In 2016, the PPR exceeded the limit reference point, which prompted managers to suggest that Chinook salmon stocking be reduced further. However, unlike in 2013, stakeholders resisted these cuts. Stocking was reduced in 2018 for many species, rather than only for Chinook salmon (LMC 2018).

More recently, managers have proposed that future stocking decisions should incorporate a multi-species approach (LMC 2018). Currently, that approach includes evaluating the effects of salmonines other than Chinook salmon on alewife by converting these species' numbers to "Chinook equivalents", based on the number of each species that would be equivalent to one Chinook salmon in terms of lifetime consumption rates. Although this approach is reasonable, it has not been fully vetted and lacks measures of uncertainty. In addition, the Lake Michigan food web has undergone important changes (Kornis et al. 2012; Madenjian et al. 2016) since the 2013 decision analysis was implemented, the most notable of which is the expansion of invasive round goby (*Neogobius melanostomus*) throughout the lake, which has become an important prey source for species like lake trout (Happel et al. 2020; Leonhardt et al. 2020; Kornis et al. 2020; Turschak et al. 2022). In addition, there have been changes to the contribution of other species to total stocking effort in Lake Michigan, as well as changes in the movement patterns of Chinook salmon between Lakes Michigan and Huron (Clark et al. 2017; Kornis et al. 2017).

Based on changes in the decision-making approach, the ecosystem, and likely, the stakeholders in the region, we conducted an updated decision analysis process with managers and stakeholders. The updated process included engagement with decision makers and stakeholders, and updated models and associated parameters used as decision-making tools in the previous (2009–2012) effort. Decision makers included all members of the Lake Michigan Committee (representatives from Michigan, Wisconsin, Illinois, Indiana, and the Chippewa Ottawa Resource Authority [CORA]). Stakeholders represented recreational anglers, charter boat captains and associations, and multiple sport fishing clubs and associations. Our ultimate goal was to determine the mix of salmonines to stock in Lake Michigan that would be most likely to achieve shared objectives of the fishery stakeholders.

Objectives

1. To engage managers and stakeholders to inform the structure and scope of an updated Lake Michigan salmonine stocking decision analysis;
2. To incorporate new information, particularly on predator diets, salmonine wild production, and Chinook salmon movements from Lake Huron, into both forecasting and assessment models;
3. To forecast risks associated with alternative stocking strategies that consider effects of all salmonine predators on a multi-species PPR, and to update the previous forecasting model to allow evaluation of stocking policies in the context of a multi-species PPR;
4. To engage managers and stakeholders in discussions about future management procedures for Lake Michigan salmonine stocking, informed by our analysis.

Project Narrative

Methods and Results

We used a decision analysis (DA) framework known as structured decision making (SDM) to evaluate potential stocking strategies for salmonines in Lake Michigan by integrating stakeholder values and perspectives, ecological knowledge of the system, and technical modeling. Below we describe each of the objectives in detail. Based on the strategies that we used, describing the methods and the results together provides a clearer picture of the process, rather than separating these two sections out.

Objective 1: Engagement of stakeholders in a decision analysis process
We used SDM to engage fishery managers, stakeholders, and researchers throughout the decision process. Structured decision making is a transparent, defensible framework for decomposing a problem into its component parts (Hammond et al. 1999; Gregory et al. 2012). This values-based process (Keeney 1992) allows groups to walk through the steps of defining the problem, describing a set of objectives that represent stakeholder values, identifying potential management actions that could be implemented, projecting the consequences of implementing actions in terms of objective achievement, and evaluating the tradeoffs among objectives (Figure 2; Hammond et al. 1999). In particular, SDM is useful for integrating ecological and social sciences (Robinson et al. 2019), as well as difficult group dynamics, especially when highly technical models, like multi-species stock assessment and forecasting, are needed (Gregory et al. 2012; Jones et al. 2016; Robinson and Fuller 2017; Robinson et al. 2021).

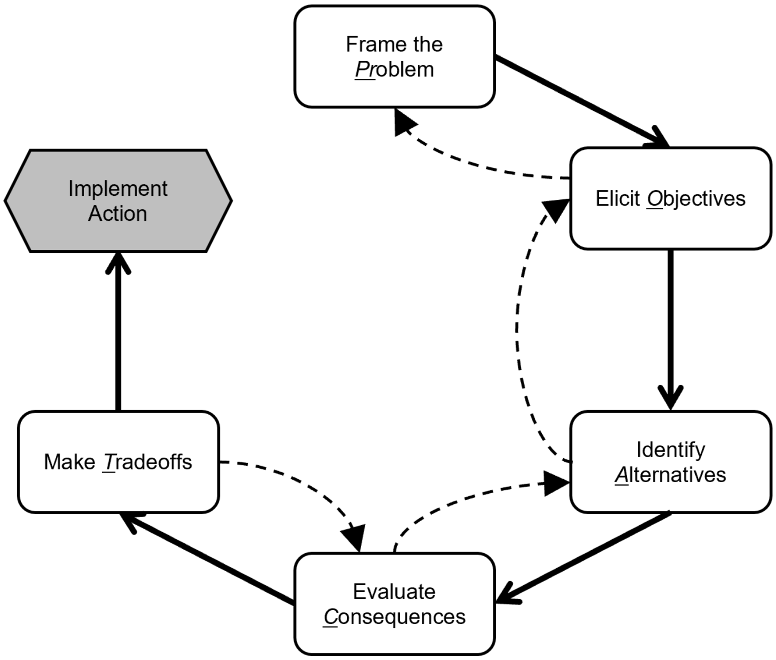

Figure 2: The steps of the structured decision-making framework ("PrOACT") that was implemented for decisions about stocking strategies for salmonines in Lake Michigan. Modified from Runge et al. (2013).

Before beginning the SDM steps, we first identified a group of key stakeholders to participate in the process. We consulted with the members of the Lake Michigan Committee for guidance. In addition, we collaborated with Michigan (Dr. Dan O'Keefe), Indiana / Illinois (Dr. Mitch Zitschke) and Wisconsin (Dr. Titus Seilheimer) Sea Grants to further identify representatives of their states who would be willing to participate. We presented at Sea Grant workshops, including the Ludington Regional Fishery Workshop (Michigan, in-person, February 2020) and the Lake Michigan Regional Fisheries Forum (Wisconsin, virtual, April 2020), describing our project and requesting that stakeholders contact us if interested in participating. Our goal was to identify stakeholders who represent a range of organizations and interests throughout the Lake Michigan basin. Ultimately, the stakeholders who participated in our workshops represented sportfishing associations and interests, charter boat associations, charter boat captains, recreational anglers, and Fishery Advisory Committees (Table 1). In addition to stakeholder participation, all members of the Lake Michigan Committee attended our workshops, as well as researchers from state agencies, representatives of Sea Grant from each state, and researchers from Michigan State University.

Table 1: List of organizations represented by the participants in the Lake Michigan Salmonine Stocking Structured Decision Making Working Group

Participant Organizations
Pentwater Sportfishing Association
Michigan Steelheaders
Great Lakes Salmon Initiative
Lake Huron & Lake Michigan Citizens Fishery Advisory Committees
Ludington Charter Boat Association
WI Lakeshore Business Association
Great Lakes Fishing Club of Cheboygan, WI
M&M Great Lakes Sport Fishing Association
Detroit Area Steelheaders
Northwest IN Steelheaders
National Association of Charter Boat Operators
Southeast WI Salmon United
Trout Unlimited
Manitowac Two Rivers Sport Fishing Club
Pentwater Sportfishing Association
Michigan Steelheaders
Great Lakes Salmon Initiative
Lake Michigan Committee
Wisconsin, Illinois/Indiana, Michigan Sea Grant
Michigan State University
USFWS
USGS
Michigan and Wisconsin DNR

We planned to hold at least one in-person workshop with stakeholders where we would work through the first three steps of the SDM process (problem, objectives, alternatives), and a second in-person workshop for objective 4 (see below). However, our project started as the Covid-19 pandemic was just beginning, so we needed to pivot toward holding a series of shorter virtual meetings. In total, 48 people attended at least one of the five workshops throughout the course of this project, with 33 attending more than one workshop. In general, scheduling a meeting that fits the calendars of many people was difficult, and some interested stakeholders were also unable to attend any of the meetings. We recorded all virtual sessions, and sent these recordings, along with detailed notes and power point slides, to all members of the stakeholder group, requesting feedback and questions from those unable to attend.

The goal of the virtual workshops was to identify the problem, objectives, and potential actions for the decision problem of stocking salmonines in Lake Michigan. In the first series of workshops, we walked stakeholders and decision makers through the first three steps of the SDM process. Although there was some iteration involved to ensure that the group agreed with the problem statement and objectives, we present the final versions for this report. Later virtual workshops covered updates on progress related to the stock assessment (conducted by the Lake Michigan Technical Committee) and forecasting models (objectives 2 and 3 below).

Stakeholders and decision makers agreed upon a problem statement that included discussions to identify the decision to be made, affected parties (i.e., stakeholder and rightsholder groups), the spatial and temporal scale of the decision, any constraints to implementation of a decision, and uncertainties that might hinder our ability to make stocking decisions (Table 2). These discussions were centered on the decision of determining salmonine stocking strategies (the management lever available for this decision), which provided the bounds for framing the problem.

Table 2: Topics identified as important aspects of framing the problem of how to decide on stocking strategies for salmonines in Lake Michigan

Category	**Identified Topics**
Affected parties	Charter fishers
	Recreational, Tribal, Commercial, Youth fishers
	Tourism industry / economic impact
	Port communities
	***Important to note that the workshop attendees are not necessarily representing commercial or tribal interests*
Spatial and Temporal Scale	All of Lakes Huron and Michigan, including bays and tributaries
	All states that surround Lake Michigan (economic impacts)
	Consideration of regional differences in the fishery
Constraints (real and perceived)	Concerns about the pending results of the Consent Decree process
	Lack of funds for research
	Time constraints with making stocking decisions
	Objectives of federal restoration programs
	Joint strategic plan- expectation of coordination in actions
Uncertainties	Planting success
	Different perceptions of fishing success
	Prediction of production of wild Chinook salmon
	Uncertainty in how data are collected and used
	Estimates of population parameters (reproduction, mortality, abundance)
	Climate change / future thermal habitat in Lake Michigan
	Changing food availability for juveniles and adults
	Effects of predatory birds

The problem statement was fully defined as:

The goal of this project is to determine a stocking strategy that accounts for stakeholder desires regarding a productive [recreational salmonine] fishery now and in the future for all of Lake Michigan, including Green Bay and Grand Traverse Bay, and includes consideration of the ecology and fish dynamics in Lakes Michigan and Huron, and that considers the needs of the economic sector (e.g., tourism, tackle, port communities) in all states that surround the lake.

After identifying the problem, the group identified a suite of objectives to be achieved. Objectives describe what stakeholders value and ultimately want to achieve with whatever decision is made. An important nuance to consider when defining objectives is that the full set of objectives may include objective statements that conflict with other objectives. The goal of this step was to ensure that all stakeholders' values and objectives are included, regardless of whether there was agreement that the objective was "important". After brainstorming objectives, we began separating objective statements into fundamental and means objectives. Fundamental objectives are those which stakeholders and decision makers fundamentally care about, whereas means objectives are the objectives that describe how to achieve the fundamental objectives (Keeney 2007). Some of the objectives fell into the category of "process objectives". These objectives describe the way the process of making the decision should occur (Keeney 2007). The group began by answering the question "why are we here," and then worked to turn these answers into a set of objectives and a description of potential ways to measure achievement of those objectives. These were all compiled into an objectives hierarchy (Figure 3).

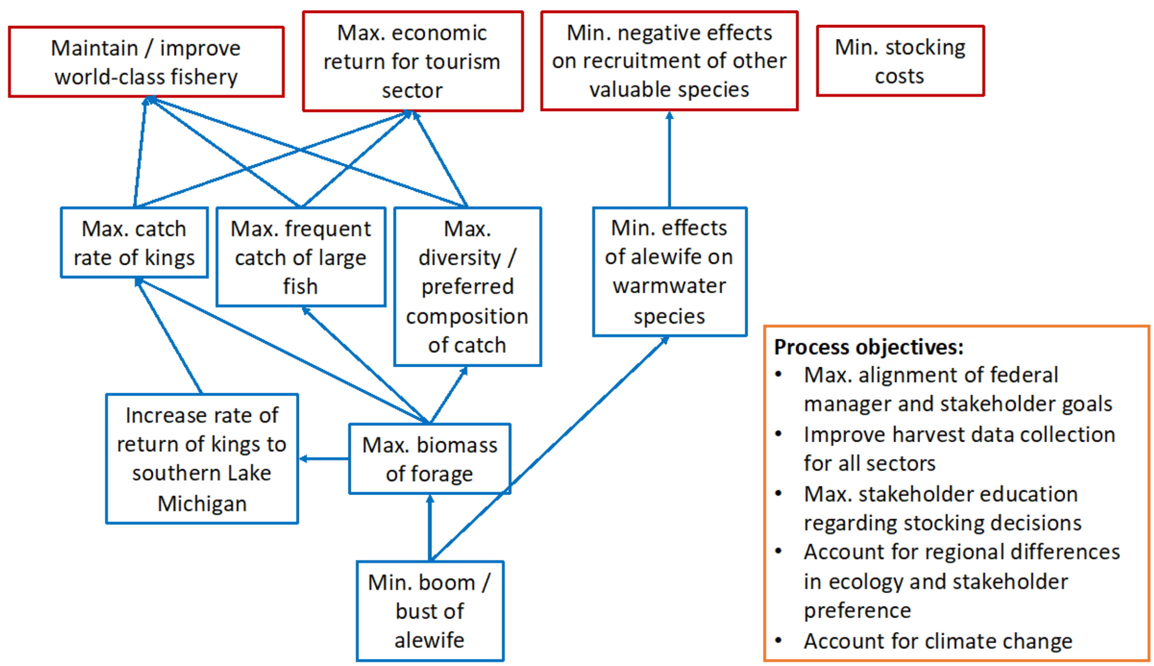

Figure 3: Objectives hierarchy for the decision problem of salmonine stocking in Lake Michigan. Min. = minimize, Max. = maximize, kings = Chinook salmon. Red boxes, blue boxes, and the orange box denote, fundamental objectives, means objectives, and process objectives, respectively.

The fundamental objectives for this decision included concerns about the fishery itself (maintain or improve the world-class fishery for salmonines in Lake Michigan), the industry surrounding this fishery (maximize economic return for the tourism sector), effects of stocking on other fisheries (minimize negative effects on recruitment of other valuable species), and costs of implementation (minimize costs of stocking). Although the tourism sector and the salmonine fishery included different sets of stakeholders and could be affected by many factors, the group agreed that these two fundamental objectives would be similarly affected by stocking of salmonines and share the same means objectives. Therefore, although both of these were represented in the objectives hierarchy, we assumed that achieving the world-class fishery objective would similarly achieve the tourism objective. Means objectives for the salmonine fishery included return rates on stocked Chinook salmon (or "kings"), catch of large fish, and catch of a desired proportion of each of the stocked species. These objectives would be achieved through maintaining forage, including alewife. The group acknowledged that the maintenance of the salmonine fishery was affected by stocking, natural reproduction, and forage availability. As such, we intended to measure achievement of this objective in terms of projected abundance of each salmonine species, as well as projected abundance of alewife, the main forage component for many of these species. Ultimately, the measure of success was reduced to simply projected abundance of alewife, as this became a limiting factor in the results of the forecasting model (see below).

After identifying the objectives, the working group discussed the options available for stocking, and brainstormed new ideas for increasing the efficiency of stocking. In the alternatives step, we asked the group to be creative and bring ideas to light that might not seem feasible, but that could potentially lead to new ideas that could be implemented. The group identified three categories pertaining to stocking decisions which merit consideration by the Lake Michigan Committee when making decisions. Stocking actions (the first category) included, the total number of each species stocked, locations for stocking (e.g., shallow or deep water, northern or southern Lake Michigan), and timing of stocking. The second category described methods to increase survival of stocked individuals, including predator (i.e., predatory birds) control and improvements in stocking methods or timing of release. The third category identified triggers which could signify the need for changes to the stocking plan, which included reference points. Explored scenarios included changes in the number of each species stocked in the system, which included larger fluctuations as well as a status quo option. Scenario response variables were changes in the predicted abundance of predators and prey.

<u>Objectives 2 and 3: Incorporation of new information into and implementation of stock assessment and forecasting models</u>

Overall, since the previous decision analysis process was completed in 2012, more information has been gained from a number of sources. Updated stock assessment models provided new information on the abundance and biomass of predators and prey. We also had better information about the movement of Chinook salmon between Lakes Huron and Michigan, and about predator diets, including changes associated with the increase in round goby abundance. Updated information was incorporated into the improved forecasting model to evaluate consequences of stocking changes. Below we summarize the major improvements implemented in the forecasting model:

- We divided the lake trout population in the model into two separate populations, one for the southern part of the lake and one for the north. This was justified because the population dynamics for these two groups are quite different, with substantially greater natural recruitment in the south, higher mortality rates in the north, and limited mixing between the two populations (Clark et al. 2023).
- Based on empirical evidence for the southern lake trout population, we developed a stock-recruitment relationship to predict future wild recruitment, that included an inverse relationship between alewife biomass and lake trout recruitment.

- We added a relationship between Chinook salmon growth and natural mortality, informed by evidence from Lake Huron, based on observations that substantially reduced Chinook salmon growth leads to sharp increases in mortality.
- We updated the starting values for all predators and alewife to reflect the outputs of the most recent stock assessment models.
- We added round gobies and invertebrates as prey categories in the forecasting model.
- We used recent predator diet data to calibrate the functional response (predator feeding) relationship such that the predicted diets from the forecasting model reflected recent observed diets.
- We added Chinook salmon recruitment from Lake Huron to the model, based on data from tagging studies.
- We updated estimates of wild recruitment for Chinook, steelhead, and lake trout (see above) based on recent assessments of these quantities.
- We added stocking rules to the model that allowed implementation of changes to stocking dictated by either a Chinook-Alewife PPR or an All Salmonines-Alewife PPR.

The forecasting model takes stocking rates and current predator and prey abundances and predicts future abundances over a 25-year period. We compared policy scenarios where stocking rates were fixed at a range of constant levels and scenarios where stocking would be adjusted based on the status of a performance indicator (either Chinook weights or a PPR). Each policy was simulated 100 times, and the distribution of outcomes was summarized for discussion. The primary outcome metric that we used to evaluate policies was the final biomass of alewife at the end of the 25-year forecasting period.

The model updating process was time consuming because of the need to gather the data, update the code, and debug a complex simulation. Although stakeholder input was not directly needed for the model updating process, we wanted to ensure that we maintained engagement with the working group and provided the stakeholders with an opportunity to see our progress and question our assumptions. Therefore, we held two workshops virtually during the modeling process to present our work to date to the working group. We allowed time to describe the data sources that were being used (e.g., the updated diet analysis from PI Roth) and to answer all questions from the group.

<u>Objective 4: Engage managers and stakeholders in risk analysis for stocking strategies</u>
We conducted a hybrid final workshop for the working group (stakeholders and decision makers) that consisted of two half-day sessions, in September, 2022, in Benton Harbor, MI. During this workshop, the Principal Investigators (PIs) summarized the technical work completed for Objectives 2 and 3 and presented the results of a series of policy scenarios from the forecasting model. The group discussed these results and the implication for the fishery and evaluated additional stocking scenarios as requested by the working group.

The results for our policy simulations were unexpected. Overall, the forecasting model indicated that there was a high probability of a crash of the alewife population in Lake Michigan under a status quo stocking scenario (Figure 4A). Further examination of stocking strategies did not reveal a large reduction in risk even with large reductions in stocking for all species (Figure 4B). Strategies that focused on one or a few species (e.g., Chinook, lake trout) likewise did not reveal approaches that substantially lowered the risk of alewife crashes even with large (i.e., 50%) reductions in stocking.

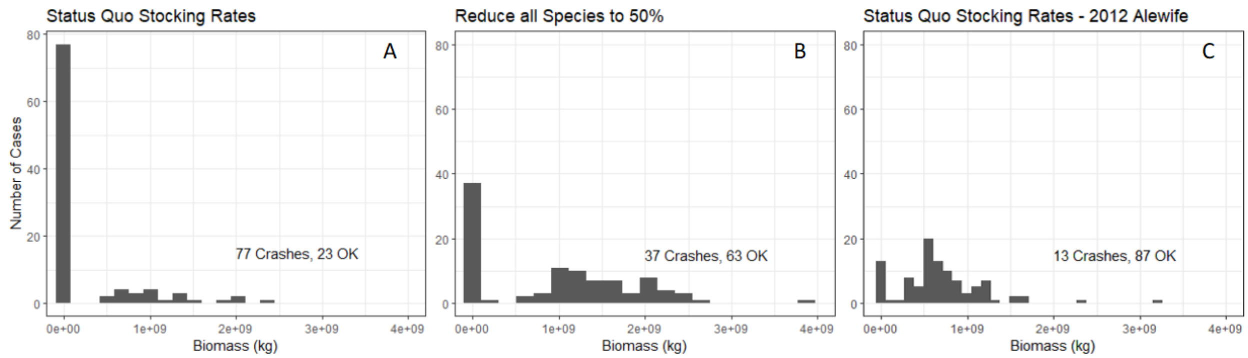

Figure 4: Simulation results of (A) stocking salmonines at status quo rates, (B) reducing the stocking rates of all salmonines to 50% of status quo rates, and (C) stocking salmonines at status quo rates but assuming the 2012 estimates of alewife stock-recruitment parameters. Each graph indicates how many times out of 100 simulations that the alewife population collapsed ("Crashes") or did not collapse ("OK"), with each bar representing the number of simulations that fell within a certain range of alewife biomass (kg).

We determined that the reason for the surprisingly high risk of future alewife crashes was due to the way recent observations of alewife recruitment are interpreted by the assessment model. Briefly, a series of comparatively low recruitments in the past decade resulted in new estimates of the stock-recruitment parameters for alewife that, in effect, indicate the population is less productive than previously believed. This lower productivity means the population is less able to recover from weak year classes in the presence of high predation rates. At the workshop we illustrated this effect by presenting a "counterfactual" simulation wherein we used our prior estimates (from the 2009–2012 DA) of the alewife stock-recruitment parameters to forecast the future with a status quo stocking scenario. The forecasted risk is sensitive to alewife recruitment estimates, as risk in this case was far less than when the current parameter estimates were used (Figure 4C). This indicates high levels of uncertainty in modelled estimates of alewife recruitment must be addressed to improve confidence in risk assessment.

Not surprisingly, these results generated considerable discussion at the workshop. Many participants reported seeing large numbers of alewife in recent years, and catching salmonines in good physiological condition, neither of which are indicative of an alewife population on the verge of collapse. Observations of both fishers and agency biologists seemed to be at odds with the findings of the alewife stock assessment and the forecasting model. It was pointed out that the forecasting model is not an attempt to describe the present situation, but instead to anticipate future conditions resulting from a particular stocking strategy. Nevertheless, participants found it very difficult to reconcile their contemporary observations and the "gut feelings" about the state of the fishery, with the forecasting model results they were seeing.

We discussed potential reasons for the deviation of the forecasts from expectations. The alewife assessment model is very complex, requiring both survey data from trawl and hydroacoustic programs, and estimates of predator consumption of alewife, to derive estimates of recruitment. Thus, the alewife assessment model has a high degree of uncertainty in its predictions, which carries over as uncertainty in our risk results. The alewife assessment model has not been reviewed for several years, and our findings suggest a need for the models used to estimate alewife recruitment to be revisited. In particular, it would be valuable to examine whether there is evidence in the data for temporal trends in productivity, something the current model is not designed to assess.

In addition to the uncertainties in the alewife model, stocking was evaluated as the sole management lever for maintaining salmonine populations in Lake Michigan in a balance with alewife. However, our results indicated that perhaps the number of naturalized salmonines (i.e., those fish that were reproduced in the system) might mean that stocking is not as effective as a management lever as it previously was. We found that the relative risk of alewife collapse could be reduced by reducing the stocking of all salmonines, but that there was still a risk of collapse.

Conclusions and Recommendations

Through this decision analysis project, we were able to work with a stakeholder group to identify a set of objectives that describes their goals for the salmonine fishery in Lake Michigan. We also updated the models that are used to estimate salmonine and alewife abundance in the lake and to project future abundances under different stocking strategies. These updates included new data pertaining to the proportion of each species that is naturally recruiting versus stocked, updates to the consumption of prey items within the lake, and a better understanding of the migratory patterns of Chinook salmon from Lake Huron to Lake Michigan to feed on alewife. We ultimately found that there is a high risk of collapse of alewife, the main prey item for Chinook salmon and an important prey item for other salmonines, under most stocking scenarios that were evaluated. The estimate of the current abundance and future recruitment dynamics of alewife were a key driver in the results observed, and there is high uncertainty about both of these values. Therefore, the working group, which included researchers, managers, and stakeholders, agreed that a better understanding of alewife population dynamics in Lake Michigan would be prudent to pursue. In addition, the group agreed that the LMC may need to consider their approach to risk when deciding on future stocking numbers. Our results indicate that stocking may not be as effective as a management lever as in previous years. We believe that this process greatly benefitted from the diligent participation of the individual stakeholders throughout. We hope that the managers consider continuing to include stakeholders' values as stocking decisions are made.

Outreach Accomplishments

As mentioned above, this project benefitted from the participation of a group of stakeholders from different fishery interests and their willingness to serve as the representative of others who hold their respective values. Decision analysis processes work best when a relatively small group of people can work on the decision at hand, but the process is most transparent and rigorous when the participants keep the stakeholder groups that they represent updated on progress and bring their feedback to the working group. We were able to accomplish this goal throughout our project on salmonine stocking in Lake Michigan.

In addition to the participation of stakeholders, Sea Grant representatives from each of the states around Lake Michigan participated throughout the process, either as advisors or as part of our core team. Not only did these representatives join the workshops and provide input where needed, they facilitated the process of identifying stakeholders, provided our team with a platform to present project updates and results during the regional fisheries forums, and worked with our core team to ensure that necessary data were available (i.e., angler preferences for species composition) and that our project was promoted appropriately to the public. The accomplishments for outreach for our project were reliant on these individuals.

Management/Research Implications

The results of this DA process were unexpected, as we found that the data and models were indicating that continued stocking of salmonines would lead to a collapse in the prey base (alewife) in almost all scenarios. Ultimately, this meant that the discussions in the final workshop were more about uncertainty and risk than about making tradeoffs and coming to a consensus on a recommendation for stocking decisions for the LMC to consider. Our results highlight the uncertainty that exists around the estimation of alewife population size and recruitment dynamics in Lake Michigan and the profound effect that this uncertainty can have on stocking decisions. Although this project did not result in a recommended or ideal stocking strategy, it did provide information for the LMC to use when assessing the risk of stocking strategies and their risk profile (i.e., risk seeking or risk averse). It also identified a key uncertainty, alewife population abundance and dynamics, that would ideally be resolved in order to provide a more reasonable projection of the effects of salmonine stocking on the ecosystem as a whole, as well as the satisfaction of stakeholders and the economy around the salmonine fishery in Lake Michigan.

In general, the decision analytic framework that was created, in close collaboration with the stakeholders and managers, lays the groundwork for evaluating stocking decisions into the future for this fishery. The objectives identified by the stakeholders will likely continue to remain important and can be used as a benchmark for comparison of stocking or management strategies. The models that were updated for this process can also be further updated as new information becomes available, particularly with respect to resolution of uncertainties around alewife abundance. As this uncertainty is reduced, the decision analysis framework can be used to evaluate stocking decisions and determine how tradeoffs should be made to balance stakeholder desires and ecological realities.

Potential Applications, Benefits, and Impacts

During the course of this project, we were able to provide benefits to fisheries management in Lake Michigan through a number of means. We identified and engaged a group of constituent stakeholders who were willing to work with managers, each other, and fisheries researchers, to make good decisions for the salmonine stocking program. This group collaborated to identify a set of objectives for this fishery that will outlive this project. We expect that managers will be able to continue to engage with this group of stakeholders in the future. Through our work with these stakeholders and the LMC, we created a decision framework that is useful for evaluating how stocking decisions will affect the objectives stakeholders have for the fishery. The obvious short-term benefit of this framework is to provide a decision tool for stocking salmonines in Lake Michigan. However, we anticipate that a long-term benefit of the development of this decision framework is that the working group has seen the benefits of decision analysis, participatory modeling, and stakeholder engagement in the science behind fishery management decisions. We hope that the LMC will continue to use this framework for decisions, and that they will be interested in using the SDM process for other important fishery management decisions. Through this effort we also advanced the scientific understanding of the effects of stocking on the Lake Michigan ecosystem, as well as effects of changes in diet and movement of species. Finally, our process helped to identify areas where additional research is needed (e.g., additional understanding of alewife recruitment dynamics at low lake productivity) to inform management and improve future projection modelling.

Outputs

Category	**Metric**
Outreach	Engagement and sustained working relationship with Lake Michigan fishery stakeholders throughout the project
Outreach	Three presentations about the project at fishery forums in Michigan and Wisconsin
Collaborations	Collaborated with representatives from MI, WI, IL/IN Sea Grants
Collaborations	Collaborators represented Michigan State University, Wisconsin and Michigan DNRs, USFWS, and USGS
Leveraged projects	Ongoing diet work by PI Roth, stock assessment modeling efforts by the Lake Michigan Technical Committee
Products	Two presentations at conferences (IAGLR 2023, AFS 2023)

Disclaimers

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. At the time of publication, data were not publicly available from cooperating organizations, but will be provided upon request to the corresponding author.

Literature cited

Bunnell, D., C. P. Madenjian, T. J. Desorcie, P. Dieter, and J. V. Adams. 2018. Status and trends of prey fish populations in Lake Michigan, 2018. U.S. Geological Survey, Report to Lake Michigan Committee, Ann Arbor, Michigan. 17 p.

Claramunt, R. M., C. P. Madenjian, and D. F. Clapp. 2012. Pacific salmonines in the Great Lakes Basin. Pages 609–650 *in* W. W. Taylor, A. J. Lynch, N. J. Leonard, editors. Great Lakes Fisheries Policy and Management: a binational perspective, 2nd edition. Michigan State University Press, East Lansing, Michigan.

Clark, R. D., Bence, J. R., Claramunt, R. M., Clevenger, J. A., Kornis, M. S., Bronte, C. R., Madenjian, C. P., and Roseman, E. F. 2017. Changes in movements of Chinook Salmon between lakes Huron and Michigan after Alewife population collapse. North American Journal of Fisheries Management. **37**(6):1311–1331.

Clark, R. D., Jr., M. P. Ebener, J. R. Bence, M. S. Kornis, C. R. Bronte, T. J. Treska, J. L. Jonas, C. P. Madenjian, and I. W. Tsehaye. 2023. Estimates of adult Lake Trout mortality from coded-wire tags in a population with developing natural reproduction in southern Lake Michigan. North American Journal of Fisheries Management 43:1035–1051.

Gregory, R. S., L. Failing, M. Harstone, G. Long, T. L. McDaniels, and D. Ohlson. 2012. Structured decision making: a practical guide to environmental management choices. Wiley-Blackwell, West Sussex, United Kingdom.

Hammond, J. S., R. L. Keeney, and H. Raiffa. 1999. Smart choices: a practical guide to making better life decisions. Broadway Books, New York, NY.

Happel, A., Leonhardt, B.S., Hook, T., Bootsma, H., Bronte, C.R., Kornis, M.S., Czesny, S., Turschak, B., Maier, C., Rinchard, J., 2020. Fatty acids reveal salmonine – prey relationships in Lake Michigan. J. Great Lakes Res. 46, 1689–1701. https://doi.org/10.1016/j.jglr.2020.08.005

Jones, M. J., J. R. Bence, E. B. Szalai, and Wenjing Dai. 2008. Assessing stocking policies for Lake Michigan salmonine fisheries using decision analysis. *In*: D. F. Clapp and W. Horns, editors. The State of Lake Michigan in 2005. Great Lakes Fishery Commission Special Publication 08-02. pp 81-88.

Jones, M.L., Catalano, M.J., Peterson, L.K., Berger, A.M., 2016. Stakeholder-centered development of a harvest control rule for Lake Erie walleye Sander vitreus, in: Edwards, C., Dankel, D. (Eds.), Management Science in Fisheries: An Introduction to Simulation-Based Methods. Routledge, London, pp. 163–183.

Jones, M. J., R. D. Clark, Jr., and I. Tsehaye. 2014. Workshops to revise and improve the Lake Michigan Red Flags Analysis. Project completion report, Great Lakes Fishery Commission.

Kao, Y.C., Adlerstein, S.A., Rutherford, E.S., 2016. Assessment of top-down and bottom-up controls on the collapse of alewives (*Alosa pseudoharengus*) in Lake Huron. Ecosystems 19, 803–831. https://doi.org/10.1007/s10021-016-9969-y

Keeney, R. L. 1992. Value-focused thinking: a path to creative decision making. Harvard University Press, Cambridge, MA.

Keeney, R., 2007. Developing objectives and attributes, in: Edwards, W., Miles Jr., R., von Winterfeldt, D. (Eds.), Advances in Decision Analysis: From Foundations to Applications. Cambridge University Press, New York, pp. 104–128.

Kornis, M.S., Bunnell, D.B., Swanson, H.K., Bronte, C.R., 2020. Spatiotemporal patterns in trophic niche overlap among five salmonines in Lake Michigan, USA. Can. J. Fish. Aquat. Sci. 77, 1059–1075. https://doi.org/10.1139/cjfas-2019-0288

Kornis, M. S., N. Mercado-Silva, and M. J. Vander Zanden. 2012. Twenty years of invasion: A review of round goby *Neogobius melanostomus* biology, spread and ecological implications. Journal of Fish Biology 80:235–285

Kornis, M. S., Webster, J. L., Lane, A. A., Pankow, K. W., Mann, K., Cressman, S. R., and Bronte, C. R. 2017. Recovery rates of stocked and wild Chinook salmon in Lake Michigan, 2011-2015. Report # 2017-07, USFWS-Green Bay Fish and Wildlife Conservation Office. New Franken, WI

Leonhardt, B.S., Happel, A., Bootsma, H., Bronte, C.R., Czesny, S., Feiner, Z., Kornis, M.S., Rinchard, J., Turschak, B., Höök, T., 2020. Diet complexity of Lake Michigan salmonines: 2015–2016. J. Great Lakes Res. 46, 1044–1057. https://doi.org/10.1016/j.jglr.2020.05.010

Lake Michigan Committee (LMC). 2018. Lake Michigan Salmonine Stocking Strategy. http://www.glfc.org/pubs/lake_committees/michigan/LMC%20-%20PPR%20Strategy%20November%202018_Final.pdf , Viewed 03/06/2019.

Madenjian, C. P., D. B. Bunnell, T. J. Desorcie, M. J. Kostich, M. A. Chriscinske, and J. V. Adams. 2016. Status and trends of prey fish populations in Lake Michigan, 2015. U.S. Geological Survey Report to Lake Michigan Committee at Milwaukee, Wisconsin, March 22, 2016.

Muir, A. M., C. C. Krueger, and M. J. Hansen. 2012. Re-establishing lake trout in the Laurentian Great Lakes: past, present, and future. Pages 533–588 *in* W. W. Taylor, A. J. Lynch, N. J. Leonard, editors. Great Lakes Fisheries Policy and Management: a binational perspective, 2nd edition. Michigan State University Press, East Lansing, Michigan.

Riley, S.C., Roseman, E.F., Nichols, S.J., O'Brien, T.P., Kiley, C.S., Schaeffer, J.S., 2008. Deepwater Demersal Fish Community Collapse in Lake Huron. Trans. Am. Fish. Soc. 137, 1879–1890. https://doi.org/10.1577/T07-141.1

Robinson, K.F., DuFour, M., Jones, M., Herbst, S., Newcomb, T., Boase, J., Brenden, T., Chapman, D., Dettmers, J., Francis, J., Hartman, T., Kočovský, P., Locke, B., Mayer, C., Tyson, J., 2021. Using decision analysis to collaboratively respond to invasive species threats: A case study of Lake Erie grass carp (Ctenopharyngodon idella). J. Great Lakes Res. 47, 108–119. https://doi.org/10.1016/j.jglr.2020.03.018

Robinson, K. F., and A. K. Fuller. 2017. Participatory modeling and structured decision making. Pages 83–101 *in* S. Gray, M. Paolisso, R. Jordan, and S. Gray, editors. Environmental modeling with stakeholders: theory, methods, and applications. Springer International, Switzerland.

Robinson, K. F., A. K. Fuller, R. C. Stedman, W. F. Siemer, and D. J. Decker. 2019. Integration of social and ecological sciences for natural resource decision making: challenges and opportunities. Environmental Management 63:565–573.

Runge, M., Grand, J., Mitchell, M.S., 2013. Structured Decision Making, in: Krausman, P., Cain III, J. (Eds.), Wildlife Management and Conservation: Contemporary Principles and Practices. The Johns Hopkins University Press, Baltimore, Maryland, pp. 51–72.

Szalai, E. B. 2003. Uncertainty in the population dynamics of alewife (*Alosa pseudoharengus*) and bloater (*Coregonus hoyi*) and its effects on salmonine stocking strategies in Lake Michigan. Ph.D. thesis. Mich. State Univ., East Lansing, MI.

Tsehaye, I., M. L. Jones, T. O. Brenden, J. R. Bence, and R. M. Claramunt. 2014a. Changes in the Salmonine community of Lake Michigan and their implications for predator–prey balance. Transactions of the American Fisheries Society 143:420–437.

Tsehaye, I., M. L. Jones, J. R. Bence, T. O. Brenden, C. P. Madenjian, and D. M. Warner. 2014b. A multispecies statistical age-structured model to assess predator–prey balance: application to an intensively managed Lake Michigan pelagic fish community. Canadian Journal of Fisheries and Aquatic Sciences 71:1–18.

Turschak, B., Bronte, C.R., Czesny, S., Gerig, B., Happel, A., Höök, T.O., Kornis, M.S., Leonhardt, B.S., Matthias, B.G., Rinchard, J., Bootsma, H., 2022. Temporal variation in the niche partitioning of Lake Michigan salmonines as it relates to alewife abundance and size structure. Can. J. Fish. Aquat. Sci. 79, 487–502. https://doi.org/10.1139/cjfas-2021-0027