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ARTICLE

Using Scenarios to Assess Possible Future Impacts of Invasive Species in the Laurentian Great Lakes

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Abstract
The expected impacts of invasive species are key considerations in selecting policy responses to potential invasions. But predicting the impacts of invasive species is daunting, particularly in large systems threatened by multiple invasive species, such as North America's Laurentian Great Lakes. We developed and evaluated a scenario-building process that relied on an expert panel to assess possible future impacts of aquatic invasive species on recreational fishing in the Great Lakes. To maximize its usefulness to policy makers, this process was designed to be implemented relatively rapidly and considered a range of species. The expert panel developed plausible, internally consistent invasion scenarios for five aquatic invasive species, along with subjective probabilities of

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those scenarios. We describe these scenarios and evaluate this approach for assessing future invasive species impacts. The panel held diverse opinions about the likelihood of the scenarios, and only one scenario with impacts on sport fish species was considered likely by most of the experts. These outcomes are consistent with the literature on scenario building, which advocates for developing a range of plausible scenarios in decision-making because the uncertainty of future conditions makes the likelihood of any particular scenario low. We believe that this scenario-building approach could contribute to policy decisions about whether and how to address the possible impacts of invasive species. In this case, scenarios could allow policy makers to narrow the range of possible impacts on Great Lakes fisheries they consider and help set a research agenda for further refining invasive species predictions.

Nonnative species often lead to negative ecological and economic consequences (Born et al. 2005; Pimentel et al. 2005; Simberloff 2011), but these consequences can vary considerably from one context to another (Simberloff 2011). It is crucial to develop techniques for assessing when nonnative species will become invasive and the possible future impacts they could have. Estimates of these impacts can allow decision-makers to prioritize species in need of attention and justify policy and management responses.

Anticipating the impacts of invasive species is difficult, however, and quantifying these impacts is particularly difficult (Simberloff 2006). Whether, and the degree to which, a nonnative species will have an impact is influenced by a series of interrelated processes, including the introduction, establishment, proliferation, and spread of that species (Leung et al. 2012). Impacts depend on these processes and on numerous variables that are not well understood and that vary from one context to another (Kulhanek et al. 2011).

Predicting invasive species impacts can be approached in a variety of ways. Past authors have predicted impacts based on observations of other invasions involving the same or similar species (Ricciardi and Rasmussen 1998; Kulhanek et al. 2011), expert opinion about likely impacts (Hardin and Hill 2012; Wittmann et al. 2014, 2015; Hill and Lawson 2015), and empirical models (Rinella and Luschei 2007). They have also been predicted by theory-driven assessments and models informed by an understanding of how invasive species impacts are influenced by community structure (Parker et al. 1999), population dynamics (Love and Newhard 2012), niche overlap between invasive and native species (Thum and Lennon 2009), and the comparative functional effects of invasive and native species (Dick et al. 2014; Dodd et al. 2014).

There are a variety of challenges, however, to predicting the impacts of invasive species. Accurate predictions of invasive species impacts can be hampered by the contextual dependency of invasive species responses (Kulhanek et al. 2011) and a lack of necessary data (Kulhanek et al. 2011; Leung et al. 2012). Decision-makers often need assessments quickly, but the time required for developing models can be substantial (Leung et al. 2012). Even under the best of circumstances, there is often considerable uncertainty about the likely impacts of invasive species (Ricciardi and Rasmussen 1998).

Predicting the impacts of invasive species can be particularly daunting in large systems threatened by multiple invasive species. One such system is North America's Laurentian Great Lakes. The Great Lakes make up the largest freshwater system in the world and are highly valued for a variety of reasons, including water supply, recreational and commercial fisheries, transportation, and recreation. Aquatic invasive species (AIS) are considered one of the chief threats to the Great Lakes—both to the ecosystem itself and to the benefits that people derive from it (Mills et al. 1993; White House Council on Environmental Quality et al. 2010). Currently, more than 180 nonnative species have been documented in the Great Lakes, and considerable management attention is devoted to the question of how to respond to the threat of species that could become invasive entering the system. New AIS have the potential to arrive through a variety of pathways, including the ballast water of ships, canals and waterways, contaminated recreational boats and equipment, and the aquarium trade. Policy makers must decide how many resources to devote to reducing the potential for AIS transfer through these pathways, and making this evaluation requires predicting the potential impacts of the many AIS that might arrive.

In recent years, the Great Lakes and Mississippi River Interbasin Study, led by the U.S. Army Corps of Engineers (USACE) was initiated in response to the threat of two Asian carp species (Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *Hypophthalmichthys molitrix*) moving from the Mississippi River basin into the Great Lakes (USACE 2014). Because of fears that Asian carp would establish themselves in the Great Lakes and harm the region's fisheries, the USACE, under a directive from the U.S. Congress, conducted a study to assess the feasibility of a variety of options for preventing the transfer of AIS between the Great Lakes and Mississippi River basins.

As part of its analysis, the USACE sought to identify how important economic activities would be affected if no action were taken and AIS transfer occurred. If these activities would be substantially affected by AIS transfer, more costly efforts to prevent AIS transfer would be justified. One key activity considered to be at risk from AIS is recreational fishing. The Great Lakes recreational fisheries generate net value to anglers estimated at US$1.2 billion per year (Ready et al. 2012) and angler expenditures generate local economic impacts estimated at $7 billion per year (American Sportfishing Association 2008).

Although USACE identified 10 AIS that had the potential to invade the Great Lakes basin and affect its fisheries, they were unable to develop quantitative estimates of how recreational fish species and recreational fishing might be affected (USACE 2014). This lack of assessments of AIS impacts inhibits the development of policies to address invasive species. The options considered by the USACE to reduce the risk of AIS transfer have total projected costs of between US$7 and $18 billion (USACE 2014). Without some estimate of the potential harm that AIS transfer might cause, it is difficult to determine whether these expenses are justified.

This paper reports on the outcome of a process whereby a group of aquatic ecologists developed AIS invasion scenarios for the Laurentian Great Lakes, along with subjective probabilities of those scenarios. We designed a process that could produce relatively rapid assessments covering a range of possible invaders, such as would be needed to inform policy and management decision-making in large systems, like the Great Lakes. We provide detailed descriptions of the scenarios developed through this process, and based on these scenarios, we evaluate the strengths and weaknesses of this approach to assessing possible future invasive species impacts.

LITERATURE REVIEW

Dick et al. (2014) argued that new methods are needed to predict invasive species impacts and set priorities about which species need to be addressed. To be useful for policy makers, methods need to be widely applicable and usable when time, resources, and information are limited (Leung et al. 2012; Dick et al. 2014). In this section we review the literature on using expert judgment to make predictions under conditions of uncertainty.

Burgman (2005) argued that assessments in such contexts need to be "robust to a range of assumptions and uncertainties." When sufficient data are unavailable to make accurate predictions, the probabilities of possible outcomes are often assessed using subjective estimates based on informed human judgments (Goodwin and Wright 1999; Morgan 2014). These "subjective probabilities" are the "degree of belief a person has that an event will occur, given all the relevant information known to that person" (Gregory et al. 2012). Experts are in a better position than laypeople to assess the probability of various AIS effects. However, even experts exhibit flaws in their reasoning (Burgman 2005). One approach used to improve the reliability of experts' assessments of possible future outcomes is to engage groups of experts in making these projections (Ferrell 1985).

Two basic approaches have typically been used to develop group projections (Ferrell 1985). One approach is mathematical aggregation, where individuals make projections independently, and then these projections are combined using mathematical techniques. The other approach is behavioral aggregation, where members of a group communicate with each other and develop projections together. Hybrid methods involving both mathematical and behavioral aggregation are also possible (Hardin and Hill 2012; Hill and Lawson 2015).

Mathematical aggregation has the advantage of not requiring a group of experts to be present in the same location (Ferrell 1985). This approach, therefore, is relatively easy to use, and it is easy to avoid having strong personalities or highly regarded individuals dominate a group's conclusions. It has been used in making invasive species predictions (Wittmann et al. 2014, 2015). The approaches used to combine judgments mathematically are often complex, however, and mathematical aggregation misses some of the advantages of having a group of experts engaged in dialogue about a topic.

Behavioral aggregation is an alternative approach. It can allow experts to combine their knowledge and intelligence, increase attention to the task at hand, facilitate creativity, enhance watchfulness for errors, and lead to the resolution of ambiguous and conflicting knowledge (Ferrell 1985; Conroy and Peterson 2013). Behavioral aggregation may be particularly suited to fleshing out the pathways and the decision junctures that have to be addressed and vetted when looking at the impacts of invasive species and considering causal relationships. The benefits of behavioral aggregation are not guaranteed, however, but depend heavily on the particular process through which experts are engaged. Furthermore, behavioral aggregation can be affected by "groupthink" in which strong personalities can disproportionately influence outcomes and individuals may feel pressure to conform to apparent consensus (Janis 1982; Goodwin and Wright 1999; Conroy and Peterson 2013).

The Delphi method (Linstone and Turoff 1975) is a structured process for engaging experts in making a collective judgment that is designed to avoid some of the pitfalls of "groupthink." Rather than meeting face-to-face, experts independently make judgments or projections in an iterative process involving a series of questionnaires. A facilitator aggregates the results at each iteration, keeping individual responses anonymous and then provides those results to the expert panel so that each individual expert can review and revise his or her own estimates in their responses to subsequent iterations. The process continues until sufficient agreement is reached. The anonymity of the Delphi method has been found to reduce the influence of strong personalities on group processes (Conroy and Peterson 2013).

The Delphi method, however, has been criticized for several reasons (Ferrell 1985; Burgman 2005). First, the interactions and information sharing among experts that occur in the Delphi method are minor, minimizing one of the strengths that have been attributed to group processes. Second, the emphasis on reaching consensus encourages uniformity in judgments. Finally, judgments reached through the Delphi method do not adequately portray uncertainty in many contexts.

Indeed, Morgan (2014) has argued that it does not always make sense to try to reach single-estimate forecasts based on expert judgment. When experts can reasonably make different judgments based on different sets of assumptions about the nature of causal mechanisms, combining expert judgments results in estimates that may not be consistent with or logically tied to either set of assumptions. Furthermore, Morgan maintains that minority opinions within a group of experts may ultimately turn out to be correct and single-estimate forecasts may obscure these opinions.

An alternative approach to group decision-making that addresses these concerns is scenario development (Schoemaker 1995). This approach is often used by organizations (such as businesses) trying to develop strategies when future conditions are uncertain. It recognizes that uncertainty is fundamental in planning for the future. Rather than trying to develop a single-estimate forecast to be used in planning for the future, scenario development involves preparing multiple internally consistent descriptions, which represent a range of plausible futures and outcomes. While any individual scenario may have a very low probability, as a set, scenarios can set boundaries around a range of possible futures.

Scenario development can be an especially useful approach when it is difficult to assign probabilities to possible future conditions (Gregory et al. 2012). It can help experts avoid overconfidence and tunnel vision about future projections because it encourages specification of a range of possible future conditions rather than just one (Schoemaker 1995). The process of scenario development also can help to identify key uncertainties affecting future conditions. Gregory et al. (2012) have argued, however, that there is a danger in considering all scenarios as equally likely and that characterizing the degree of agreement or disagreement among experts about the scenarios is important.

Scenario development in environmental and natural resource management contexts has typically been done in the context of planning processes; we are aware of only one instance in which it has been applied to invasive species assessments (Gilioli et al. 2014).

In our research, we applied and evaluated the utility of a modified version of a scenario-building process in which we developed a range of estimates of how AIS could affect Great Lakes recreational fisheries and identified the key uncertainties that could influence which of these futures were most likely. The scenario development was not conducted as part of a planning process, however, as is typical of most scenario building.

We recruited a group of aquatic ecologists to develop a range of plausible, science-based, internally consistent scenarios describing how invasive species might affect Great Lakes fish populations. We engaged these experts through a scenario-building workshop to benefit from the insights emerging from face-to-face dialogue; this workshop was preceded by a modified Delphi survey to avoid “groupthink” at the outset of the process, taking advantage of the relative strengths of these different methods. The scenarios described impacts of AIS on catch rates for recreational fish because changes in catch rates could be used as inputs into economic models to assess the change in net value of recreational fishing and inform policy and management decisions (Ready et al. 2012).

STUDY SYSTEM

The Laurentian Great Lakes cover 244,000 km^2 and contain one-fifth of the world’s surface freshwater supply. The northernmost of the five Great Lakes, and the largest and deepest, is Lake Superior (82,100 km^2, maximum depth 406 m). It is also the most oligotrophic with relatively little human disturbance, and most of the original native fish species are still present. Lake Michigan and Lake Huron are also large, deep, low-productivity lakes. Their trophic state and lower food webs are becoming more similar to Lake Superior in recent decades (Barbiero et al. 2012; Bunnell et al. 2014). Lake Ontario is the smallest of the five lakes and also relatively deep (maximum depth 229 m). The fisheries in these four lakes primarily target coldwater salmonids. Fisheries for coolwater Walleye *Sander vitreus* and warmwater Smallmouth Bass *Micropterus dolomieu* occur in nearshore areas that include smaller embayments and drowned river mouth lakes and more productive larger bays such as Green Bay on Lake Michigan, Saginaw Bay on Lake Huron, and Bay of Quinte on Lake Ontario. Lake Erie is the most productive and shallowest of the five lakes, especially in the western and central basins; its fishery primarily targets coolwater Walleye and Yellow Perch *Perca flavescens*. In addition, this system contains connecting corridors in the Detroit River and Lake St Clair, a shallow expansion of this river, between Lake Huron and Lake Erie, in the Niagara River between Lake Erie and Lake Ontario, and in the outlet river (the St. Lawrence River) between Lake Ontario and the Atlantic Ocean. Allan et al. (2013) recently ranked Lake Superior as the least affected by human disturbance and Lake Ontario and Lake Erie as the most affected.

METHODS

The project team recruited a group of 10 aquatic ecologists and fisheries managers from the Great Lakes region to serve as experts. These 10 individuals and one member of the project team were the participants in the scenario-building process. Six were from universities (Cornell University, The Ohio State University, Purdue University, University of Minnesota-Duluth, and University of Notre Dame). Five were from U.S. or Canadian government agencies (Department of Fisheries and Oceans Canada, National Oceanic and Atmospheric Administration’s Great Lakes Environmental Research Laboratory, Ontario Ministry of Natural Resources, and U.S. Geological Survey’s Great Lakes Science Center). They were selected so that collectively they would provide expertise on all five Great Lakes and a wide range of invasive species taxa.

The scenario-building process (Figure 1) took place in three stages: (1) an initial Delphi survey to identify AIS of concern for the Great Lakes, (2) a 2-d workshop in which scenarios describing the possible effects of five different AIS on recreational fish stocks and catch rates were developed, and (3) an iterative process of review and refinement of these scenarios and assessment of their likelihood.

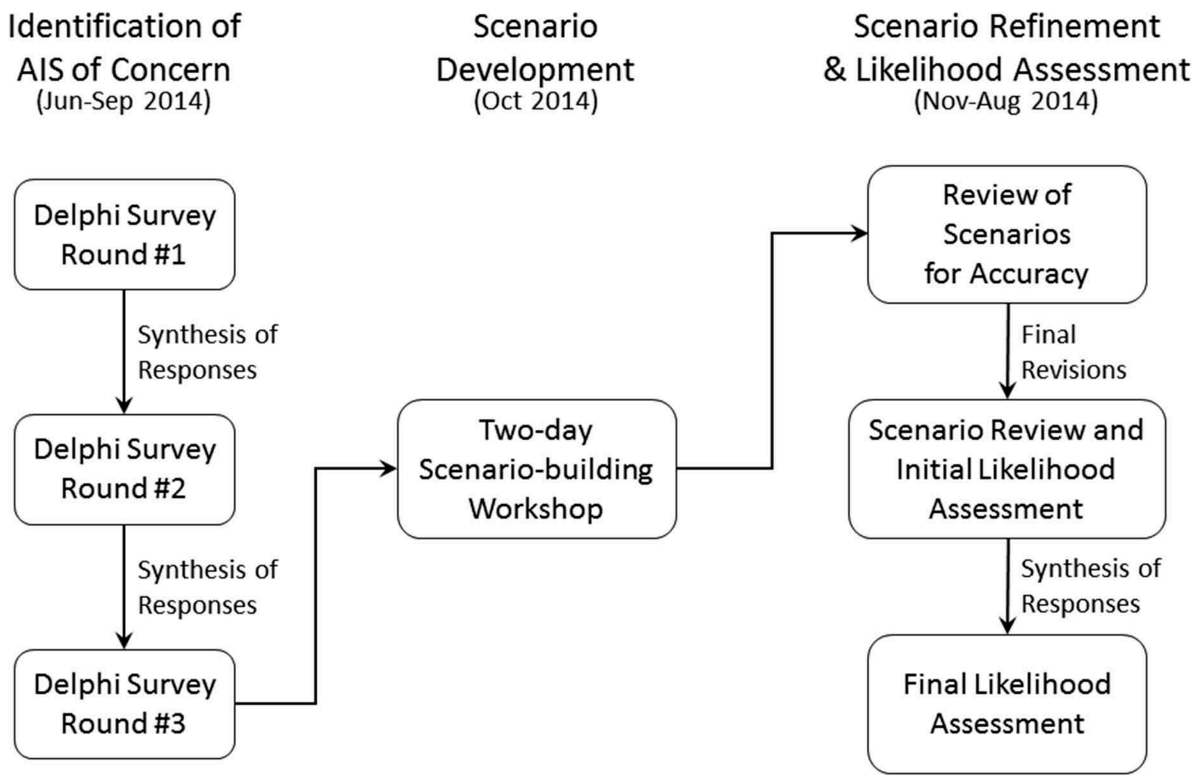

FIGURE 1. Process used to develop aquatic invasive species scenarios.

Initial Delphi survey.—The Delphi survey consisted of a series of three anonymous questionnaires completed by participants. Each round of the survey was implemented by email using a web-based survey instrument. Participants answered the questions independently, rather than in collaboration with each other. In the first iteration, participants were asked to respond to these four open-ended questions designed to identify AIS that are most likely to have new or additional negative impacts on populations of recreationally important fish species in the Great Lakes:

a. What AIS that are not now in the Great Lakes and could conceivably affect populations of recreational fish species do you consider most likely to invade the Great Lakes from other areas?
b. What AIS that are currently in the Great Lakes and that could conceivably have additional effects on populations of recreational fish species do you consider most likely to increase in prevalence or to invade new areas of the Great Lakes?
c. Of the species you identified in questions (a) and (b), which species would you consider most likely to have new negative impacts on the populations of recreational fish species in the Great Lakes?
d. Of the species you identified in questions (a) and (b), which species do you consider most likely to have widespread negative impacts on the populations of recreational fish species in the Great Lakes?

For each question, participants identified one or more AIS and explained, in several brief statements, their reasons for listing each. The project team synthesized these responses by compiling an aggregate list of all AIS listed for each question and a verbatim compilation of the reasons offered by each respondent for listing each species.

In the second questionnaire, distributed approximately 1 month after the distribution of the first questionnaire, participants reviewed the aggregate list of AIS generated in the first iteration of the survey and assessed how likely they thought it was that each AIS would invade the Great Lakes from other areas, invade new areas of the Great Lakes from within the Great Lakes, have new negative impacts on populations of recreational fish species in the Great Lakes, and have widespread negative impacts on the populations of recreational fish species in the Great Lakes. They made these assessments using a standardized four-point scale (not at all likely, possibly, likely, or almost certain). Following the Delphi approach, participants were provided the compilation of the reasons other participants had offered for suggesting each species in the first round of the survey. They were asked to offer any additional reasons for their own answers (those that they did not provide in the initial survey) in a series of brief bullet points. The project team calculated the means, medians, and frequencies of responses to each of the standardized questions and compiled a verbatim record of the reasons offered by each respondent for their answers.

In the final questionnaire, distributed approximately 1 month after the distribution of the second questionnaire, participants responded to the same standardized questions they responded to in the second questionnaire. They were provided with a quantitative summary of how participants responded to these questions in the previous questionnaire and a verbatim compilation of all the reasons offered by respondents for their answers in the previous two rounds of the survey.

The project team compiled the results of this final round of the survey and developed flow diagrams that synthesized participants' thinking about the mechanisms by which each AIS would affect recreational fish stocks. These materials were distributed to the expert panel prior to the workshop. In addition, experts were provided with a list of references, compiled from literature suggested by panel members, that they could review prior to the workshop.

Scenario-building workshop.—The scenario-building participants and project team gathered for a 2-d workshop October 16–17, 2014, at the Cornell Biological Field Station at Shackelton Point in Bridgeport, New York. At the outset of the workshop, the project team reviewed the results of the Delphi survey and participants selected the AIS for which they wanted to develop scenarios from the set of 31 AIS that had been identified during the Delphi survey. In making these selections, participants considered which species were most likely to affect recreational fish stocks in the Great Lakes and how knowledgeable they and the other participants were about each AIS. They made an effort to represent a range of taxa across the set of AIS selected and a range of ecological functions (e.g., piscivore, planktivore, macrophyte).

For each AIS selected, the project team facilitated discussions in which participants developed scenarios projecting the possible effects of the AIS on recreationally important fish if those AIS were to become established in the Great Lakes. Each scenario was allowed to vary geographically from lake to lake and even between regions within a lake, although participants did not focus heavily on parsing out effects across systems. Participants specified the mechanisms by which they expected each AIS to affect recreational fish and identified and discussed key uncertainties that could influence the type and magnitude of these effects. For some potential invaders, multiple scenarios were developed that differed in the assumed extent to which the species would become established. Each AIS was considered individually; possible interaction effects among multiple AIS were not assessed.

Each scenario included quantitative estimates of the possible effects of AIS on recreational fish populations and recreational fishing. These estimates were arrived at through discussion and represent the collective judgment of the group as to how much fish populations might be affected if the AIS interacted within the ecosystem in the manner specified in the scenarios. Although we did not expect any of these individual estimates to represent a likely outcome, collectively the estimates for the set of scenarios for each AIS portrayed a range of plausible outcomes from the perspective of the expert panel. The operating assumption here was that the net value of fishing as an economic activity would be driven primarily by changes in catch rates. For the sake of simplicity, participants assumed that catch rates would be directly correlated with the abundance of recreational fish and, therefore, developed estimates of the impacts of AIS on fish populations. However, in a few cases, participants also considered whether catch rates might be driven by other AIS-induced changes that would make fish more or less vulnerable to angling.

Scenario review and refinement.—Following the workshop, participants engaged in an iterative process of reviewing and refining the scenarios. No substantive changes were made to the quantitative estimates generated during the workshop, but the descriptions of the mechanisms underlying the AIS effects on recreational fish were clarified and minor changes to estimates were made to remove inconsistencies. Participants also individually rated the likelihood of each scenario.

We used three specific steps in the post-workshop review and refinement process:

1. In November 2014, participants commented on bulleted summaries of each scenario to ensure that these summaries accurately reflected discussions at the workshop.
2. In March and April 2015, participants reviewed final written descriptions of each scenario and rated the likelihood of each, under the maintained assumption that the AIS would become established in the Great Lakes. Each scenario could describe effects of AIS on multiple fish species, and the likelihood of the entire scenario was rated (as opposed to rating the likelihood of effects on individual species included in the scenario). Likelihood was measured categorically as remote (<1%); highly unlikely (1–10%), unlikely (11–25%), possible but not likely (26–50%), likely (51–75%), highly likely (75–90%), near certain (91–100%). Many participants offered rationales for their ratings.
3. In July 2015, participants were provided with a summary of how all participants rated the likelihood of each scenario and the comments offered to support those ratings, and then they rated the scenarios again. These final ratings are those which are reported in this manuscript.

The entire scenario-development process took place over approximately 15 months. It would have been possible, however, for the process to be conducted within 6 months. Much of the time required is to give members of the expert panel up to 4 weeks to respond to each of the multiple surveys conducted as part of the process. If a group of experts were committed to implementing the process over an even shorter period of time, the process could be completed within as little as 3 months.

RESULTS

Workshop participants developed scenarios for Bighead and Silver carp (pelagic planktivores), hydrilla *Hydrilla verticillata* (macrophyte), Northern Snakehead *Channa argus* (piscivore), Grass Carp *Ctenopharyngodon idella* (herbivore), and quagga mussel *Dreissena rostriformis bugensis* (benthic planktivore). These species were considered among the most likely to affect recreational fish stocks for a variety of reasons, including their proximity to or presence in the Great Lakes, the availability of pathways through which they could invade, their ability to survive and breed in the lakes and their tributaries, and the identification of mechanisms through which they could affect recreational fish. Descriptions of each of the scenarios developed are presented below along with ratings of the likelihood of each scenario by the participants.

Because we were evaluating the utility of a particular approach to assessing possible future invasive species impacts, the scenarios presented below are the product of workshop discussions without any modifications after the fact (other than those minor modifications described in the Methods section). Although members of the expert panel drew on their knowledge of the literature in developing the scenarios (sometimes citing specific facts or figures during discussions), they did not tend to formally reference literature sources during workshop discussions. Consequently, we do not provide literature citations for all aspects of the scenarios, thus emphasizing that they are a product of the group process as it took place during the workshop rather than a product of a review of the ecological literature. The only citations provided are for sources that were explicitly referenced during workshop discussions or factual information that had a direct influence on the scenarios.

Bighead and Silver Carp

Bighead and Silver carp (combined we refer to as Asian carp) are pelagic filter feeders that consume both phytoplankton and zooplankton and therefore are potential competitors with existing prey species of most important sport fish species (Kolar et al. 2007). They can grow sufficiently large to have a size refuge from predatory fish. Because of similarity in food selection and body size, we expect the two species to have similar ecological effects. To date, three individual Bighead Carp have been caught in Lake Erie (Kocovsky et al. 2012). Workshop participants agreed on a number of foundational assumptions that would influence the types of effects that these species would have if they became established in the Great Lakes (Kolar et al. 2007; Kocovsky et al. 2012):

- Asian carp would spawn in Great Lake tributaries. Their distribution could, therefore, be limited by the availability of spawning rivers. However, suitable rivers are available in at least some Great Lakes.
- They would move offshore as adults only in areas with high enough food concentration.
- Asian carp would be unlikely to be temperature-constrained in any of the Great Lakes.
- The primary limitation on their distribution would be food availability.
- It is uncertain how well young carp would survive in clearer waters, given that they reside in turbid, productive waters; predation on young carp could potentially be high. Because of their rapid growth and large size potential, carp would be much less susceptible to predation as they age.

Two broad scenarios (each with subscenarios) describing the possible effects of Asian carp on recreational fish populations were developed that differed in how widely carp become established in the Great Lakes.

- In the first scenario (AC-1), the experts assumed that Asian carp would become established only in high productivity bays in the Great Lakes, near large tributaries, and in the western and central basins of Lake Erie because they currently are abundant in highly productive, turbid river systems in North America and Europe (Kolar et al. 2007).
- In the second scenario (AC-2), the experts assumed that Asian carp also would become established in the pelagic portions of all lakes, except for Lake Superior where pelagic plankton concentrations are too low.

Scenario AC-1.—Under this scenario, Asian carp would become established in the following high productivity areas: Green Bay, Saginaw Bay, Bay of Quinte, Lake St. Clair, and the western and central basins of Lake Erie.

Asian carp would compete with salmonids' prey species (e.g., Alewife *Alosa pseudoharengus*) during the periods in which these prey species were in shallow waters and bays, potentially reducing the abundance of prey for adult salmonids. It is also possible that young salmonids would feed on Asian carp eggs while the salmonids are in rivers, but this beneficial effect for salmonids was expected to be small. Workshop participants agreed that a 5% decrease in salmonids throughout the Great Lakes under this scenario would be a reasonable outcome.

The effects of carp on warmwater and coolwater species (species other than trout and salmon) would be more complicated. Nonsalmonids could possibly be affected by four different processes (Figure 2): (1) Asian carp could compete directly with larval Yellow Perch and Walleye for zooplankton thereby decreasing growth rates and increasing mortality rates of these two species; (2) Asian carp could compete with the prey species of adult Yellow Perch and Walleye (including

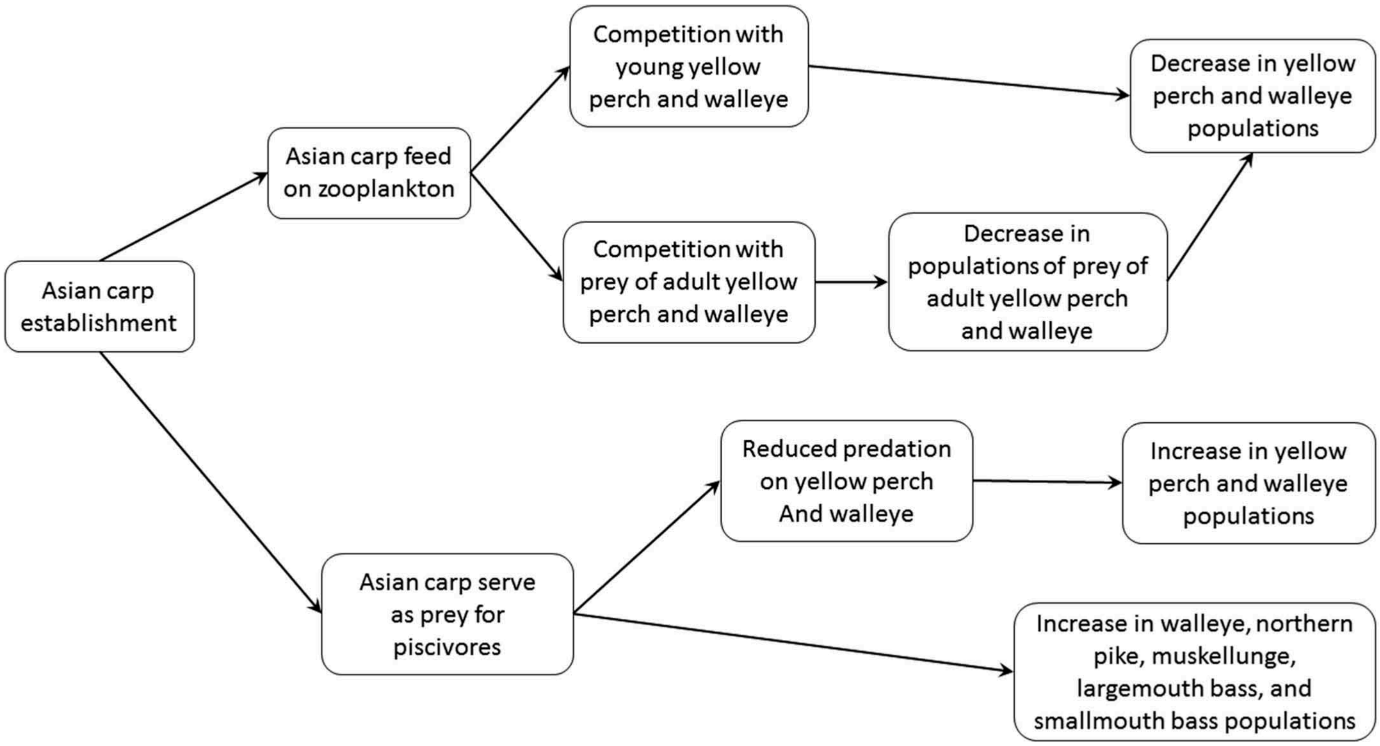

FIGURE 2. Processes through which Bighead Carp and Silver Carp could potentially affect nonsalmonid recreational fish species.

Gizzard Shad *Dorosoma cepedianum*, Emerald Shiner *Notropis atherinoides*, Alewife, and Rainbow Smelt *Osmerus mordax*) thereby decreasing prey available to adult Walleye and Yellow Perch; (3) Asian carp could release young Yellow Perch and Walleye from predation by serving as an alternate prey for adult Walleye, Yellow Perch, White Perch *Morone americana* and other piscivores; and (4) young Asian carp could serve as a prey resource for large-bodied adult Walleye, Northern Pike *Esox lucius*, Muskellunge *Esox masquinongy*, Largemouth Bass, and Smallmouth Bass.

The magnitude of the effects of Asian carp on nonsalmonid species would depend on which of these processes dominated. Consequently, we developed three sub-scenarios for how warmwater and coolwater species would be affected in high productivity bays and the western and central basins of Lake Erie. Results of past modeling work with which workshop participants were familiar helped to inform alternate scenarios describing how these four processes would interact to affect particular recreational fish species (Currie et al. 2012; Kao et al. 2014; Zhang et al. 2016).

- Scenario AC-1a:. All four processes would occur: direct competition, indirect competition, predation release, and carp as a prey source. Largemouth and Smallmouth bass would increase by 10% as they benefitted from Asian carp as a prey resource. Yellow Perch would increase by 10% because the benefits of release from predation by White Perch would be expected to be larger than the effects of direct and indirect competition with Asian carp. For Walleye, however, the negative effects of competition would be expected to be larger than the positive effects of predation release and a new prey resource. Walleye would be expected to decrease by 10%.
- Scenario AC-1b: Positive effects of the carp on nonsalmonid species (release from predation for Yellow Perch and Walleye and young carp serving as a prey resource for Largemouth and Smallmouth bass) would dominate over the negative effects (direct and indirect competition). Largemouth and Smallmouth bass would increase by 10% (as they did under Scenario 1A). Yellow Perch would increase by 15%. Walleye would increase by 25%.
- Scenario AC-1c: The competition of Asian carp with all nonsalmonid species would be the dominant effect. Under this assumption, we would expect a 10% decrease in Largemouth and Smallmouth bass and a 40% decrease in Yellow Perch and Walleye.

Scenario AC-2.—Under this scenario, Asian carp would also become established in the pelagic portions of all Great Lakes except for Lake Superior, which has too low plankton density. This scenario is considered less likely than Scenario AC-1. The food density in pelagic areas may be too low for large filter feeders, which would need to swim through and filter a large amount of water to maintain themselves and grow. Past modeling has suggested this limitation could prevent the establishment of a large filter feeder off shore (Cooke and Hill 2010). If Asian carp did become established in pelagic areas, their abundance would be limited by the available prey biomass in these areas; in particular, they might not thrive in cold areas where zooplankton production is low.

We considered the effects of Asian carp only on coldwater species (trout and salmon) under this scenario; possible effects on warmwater and coolwater species as specified in scenario AC-1 were not considered for the sake of simplicity and our desire to focus on the most unique impacts of pelagic establishment. The impacts on coldwater species detailed in Scenario AC-2 could therefore be additive to the impacts on nonsalmonid species detailed in Scenario AC-1.

Carp would affect salmonids primarily through indirect competition. In particular, Asian carp would compete with Alewife for food, leading to a reduction in Alewife availability to salmonids. Workshop participants anticipated a threshold effect under this scenario; either Asian carp would have little effect on Alewife and salmonids, or Alewife populations would collapse, and salmonids would follow. Consequently, we developed three sub-scenarios for how salmonids could be affected.

- Scenario AC-2a: Sufficient zooplankton and phytoplankton production would exist offshore to support both Alewives and Asian carp. Asian carp would have no effect on salmonids (beyond the 5% decrease described under Scenario AC-1).
- Scenario AC-2b: The establishment of Asian carp offshore would begin to lead to a decline in Alewives, but fisheries managers would recognize this decline and reduce salmonid stocking to avoid an Alewife collapse. Coho Salmon *Oncorhynchus kisutch* and Chinook Salmon *O. tshawytscha* would decrease by 20% in Lakes Michigan and Ontario. Other salmonids would not be expected to be affected. Lake Trout *Salvelinus namaycush*, Rainbow Trout *O. mykiss*, and Brown Trout *Salmo trutta* would switch from Alewife to Round Goby *Neogobius melanostomus* as a food source, and would be unaffected. In addition, newly hatched Lake Trout would be released from predation by Alewives and released from competition with other salmon and would experience no net negative effects.
- Scenario AC-2c: The establishment of Asian carp offshore would lead to a collapse in the Alewife population. Without this food source, an 80% decrease in Coho and Chinook salmon was identified as possible in Lakes Michigan and Ontario. A similar decrease has already happened in Lake Huron (Bunnell et al. 2014; He et al. 2015), and the expert panel did not predict further declines in that lake. Chinook Salmon is more dependent on Alewives than other predators (He et al. 2015; Yuille et al. 2015).

The mean and median ratings of the likelihood of each scenario (under the maintained assumption that Asian carp were to become established in the Great Lakes) ranged from highly unlikely to possible, but not likely, although some individuals considered four out of the six scenarios to be likely or highly likely (Table 1). Although none of the scenarios were perceived to be likely based on median values, those perceived as most likely were those in which Asian carp would cause (1) a 10% increase in Largemouth Bass *M. salmoides*, Smallmouth Bass, and Yellow Perch in high productivity areas and a 10% decrease in Walleye in these same areas (AC-1a) and no effect on salmonids beyond the 5% decrease specified in all scenarios (AC-2a), and (2) a 20% decrease in Coho and Chinook salmon in Lakes Michigan and Ontario and a 5% decrease in other salmonids in all the Great Lakes (AC-2b).

Northern Snakehead

Northern Snakehead is an obligate air-breather and can therefore survive in poorly oxygenated water such as shallow ponds and swamps (Courtenay and Williams 2004). It feeds almost entirely on fish (Saylor et al. 2012). In the USA, it has spread primarily through intentional or accidental release. It is established in the Potomac River and several other locations on the east coast, and suitable habitats for this species occur across the Great Lakes basin (Herborg et al. 2007). Both parents guard their eggs and newly hatched larvae in a floating nest. Workshop participants agreed on a number of foundational assumptions that would influence the types of effects that this species would have if it were to become established in the Great Lakes (Courtenay and Williams 2004; Herborg et al. 2007; Saylor et al. 2012):

- Based on areas of North America where it has become established, Northern Snakehead would be expected to be limited to river systems and nearshore areas. It is generally restricted to shallow, warmer waters. It would not be expected to establish in pelagic portions of the Great Lakes.
- Northern Snakehead is tolerant of low oxygen conditions and a wide range of temperatures, although a narrower range of temperature is needed for spawning.
- The presence of vegetation helps spawning, but is not a necessary condition for spawning.
- Northern Snakehead would be expected to functionally act like other piscivores, especially Largemouth Bass, but also Northern Pike and Bowfin *Amia calva*.

A key uncertainty about Northern Snakehead is whether it would simply replace other predators already present in the system (with the overall abundance of predator and prey species unchanged) or whether they would increase overall levels of predation and drive

TABLE 1. Scenario-building participants' ratings of the perceived likelihood of scenarios describing how AIS could affect the Great Lakes recreational fisheries.

	Number of participants[a]								
Scenario	Remote (1)	Highly unlikely (2)	Unlikely (3)	Possible, but not likely (4)	Likely (5)	Highly likely (6)	Almost certain (7)	Mean	Median
Bighead and Silver carp									
AC-1a	0	1	2	2	4	0	0	4.0	4.0
AC-1b	0	5	3	1	0	0	0	2.6	2.0
AC-1c	0	4	2	1	2	0	0	3.1	3.0
AC-2a	0	1	4	0	2	2	0	4.0	3.0
AC-2b	0	2	3	2	1	1	0	3.6	3.0
AC-2c	1	2	4	2	0	0	0	2.8	3.0
Northern Snakehead									
NS-1	0	0	2	2	5	0	0	4.3	5.0
NS-2	0	2	2	2	2	1	0	3.8	4.0
Grass Carp									
GC-1	1	2	3	2	0	1	0	3.1	3.0
GC-2	0	2	2	1	4	0	0	3.8	4.0
GC-3	0	0	2	3	3	1	0	4.3	4.0
Hydrilla									
H-1	0	2	2	1	3	1	0	3.9	4.0
H-2	0	3	2	1	3	0	0	3.4	3.0
H-3	0	4	3	0	2	0	0	3.0	3.0
Quagga mussel									
QM-1	0	1	3	2	3	0	0	3.8	4.0

[a]Total number of participants is 9.

down populations of both predator and prey species. Members of the expert panel reported that in the Chesapeake Bay region, models predict that black bass numbers could go down 35% if Northern Snakehead continue to increase in abundance (Love and Newhard 2012), but the impacts on other species are not clear. If Northern Snakehead simply replaces other predators, they may not affect catch rates at all because snakehead could itself become a popular sportfish. If it does impact other species, it would be expected to impact warmwater and coolwater fishes primarily, although they might also feed on young salmonids in river mouths as the salmonids are running down the rivers. Two scenarios were developed reflecting this uncertainty.

- Scenario NS-1: Northern Snakehead would partially replace Largemouth Bass and Northern Pike but not otherwise affect recreational fish abundance. The net effect on the system would be small. Anglers would eventually switch from black bass and Northern Pike to Northern Snakehead, and overall catch rates would not change. (This switch in angler behavior could take time because many anglers place special value on black bass.)
- Scenario NS-2: The presence of Northern Snakehead would increase the levels of overall predation in the Great Lakes and drive down prey populations. They also would out-compete native species for prey, resulting in a decrease in predator populations. They would affect the populations of Smallmouth Bass, Walleye, Yellow Perch, Largemouth Bass, and young salmonids running down streams. Effects on most warmwater and coolwater species would be limited to high-productivity areas such as Green Bay, Saginaw Bay, Bay of Quinte, Lake St. Clair, and the western and central basins of Lake Erie, in which they would decrease by 15%. Walleye numbers would decrease by 15% in all portions of all lakes, however, because they migrate through lakes on an annual basis so that processes in nearshore areas affect the population throughout the lakes. Anadromous coldwater species would decrease by 5% in all Great Lakes.

The mean and median ratings of the likelihoods of each scenario ranged from possible, but not likely to likely (Table 1). The scenario in which Northern Snakehead had a minimal effect on the system (NS-1) was considered more likely than the scenario with negative aggregate impacts on sport fish populations (NS-2).

Grass Carp

Grass Carp is a herbivore. It has tolerance for a wide range of temperatures, but is probably limited by the availability of spawning habitat. It has been introduced to many small water bodies for control of aquatic vegetation. Although introduced fish were supposed to be triploid and sterile, diploids were used by some states and reproducing populations are now established in the Mississippi River basin. Some natural reproduction has occurred in Lake Erie (Chapman et al. 2013), but Grass Carp have not yet become abundant in the Great Lakes basin. Workshop participants agreed on a number of foundational assumptions that would influence the types of effects that this species would have if it were to become more widespread in the Great Lakes:

- Because there are no other native fish in the Great Lakes that consume primarily macrophytes, Grass Carp could have novel impacts if it became abundant. Grass Carp would reduce and alter aquatic vegetation, which could lead to altered wetlands and nearshore habitat, increased bank erosion in protected embayments, and increased predation on age-0 fish by predators because of the reduced cover.
- Grass Carp would live in littoral zones and affect nearshore areas that support warmwater and coolwater fishes. The fish species most likely to be affected by Grass Carp are Largemouth Bass, Northern Pike, Yellow Perch, and most other centrarchids. Smallmouth Bass would be less affected, and Walleye and salmonids would be minimally affected.
- Although certain species might be exposed to increased predation, Largemouth Bass and Northern Pike might also gain certain benefits if they prey on young carp.
- The magnitude of the effects of Grass Carp on sport fish populations would depend on how numerous and widespread they became, which would determine the degree to which they reduce macrophyte habitat. Predation by Northern Pike and Largemouth Bass might influence the degree to which carp become established.

Three primary scenarios were developed:

- Scenario GC-1: Grass Carp would reduce macrophyte habitat in all Great Lakes. Under this scenario, Largemouth Bass (which are most dependent on macrophytes), Northern Pike, and most other centrarchids would all decrease by 50% in all Great Lakes. Yellow Perch would decrease by 10%. Walleye would be unaffected.
- Scenario GC-2: Grass Carp would become established, but not as numerous and widespread as under Scenario 1, so macrophyte habitat would be reduced to a lesser degree. Consequently, warmwater and coolwater species would be less affected. Largemouth Bass, Northern Pike, and most other centrarchids (besides Smallmouth Bass) would decrease by 25%, and Yellow Perch would decrease by 5%.
- Scenario GC-3: As under scenario 2, Grass Carp would become established, but not as numerous and widespread, specifically because of predation by Northern Pike and Largemouth Bass. Centrarchids other than black bass would decrease by 15%, and Yellow Perch would decrease by 5%. Largemouth Bass and Northern Pike would be unaffected because the benefits from preying on carp would roughly balance the negative effects of habitat losses.

The mean and median ratings of the likelihoods of each scenario ranged from unlikely to somewhat more than possible, but not likely, although each scenario was considered likely or highly likely by at least one individual (Table 1). Of the three scenarios, the scenario in which Grass Carp would lead to a 15% decrease in centrarchids other than bass and a 5% decrease in Yellow Perch was considered most likely (GC-3).

Hydrilla

Hydrilla is an aquatic macrophyte that can form dense monocultures in areas it invades. It is spreading northwards from Florida where it was probably introduced through the aquarium trade (Langeland 1996). It is easily spread by recreational boaters when they move their boats from one waterbody to another and it is already present in several locations in New York, Pennsylvania, and Ohio, which are within the Great Lakes watershed. Surface mats usually first occur in July or August and remain through the rest of the growing season. Workshop participants agreed on a number of foundational assumptions that would influence the types of effects that this species would have if it became widespread in the Great Lakes (Wiley et al. 1984; Bettoli et al. 1993; Olson et al. 1998):

- Some plant cover (around 50%) is beneficial to fish by offering a refuge from predation. The problem with hydrilla is that, given the appropriate ecological conditions, it can form dense monocultures, which is a less suitable habitat for growth of young fish. Hydrilla also makes it difficult for fish to navigate in and out of wetland areas.
- Hydrilla has the potential to lead to dissolved oxygen depletion in nursery areas. Oxygen depletion would only be a problem in warm, shallow areas with little water flow. These areas might comprise only a small proportion of shoreline areas, but they are important areas for fish.
- Hydrilla could both colonize areas that do not now have macrophytes and replace macrophytes that are currently in the lake. Hydrilla can colonize deeper areas than some (but not all) other macrophytes. The establishment of Hydrilla will be limited by turbidity.
- Most effects on fish would be confined to wetland areas. These areas are important for Northern Pike and bass,

particularly Largemouth Bass. Workshop participants were uncertain how important wetland areas were to Yellow Perch. Salmonids are not as dependent on wetlands.

- In addition to affecting fish populations, dense beds of hydrilla could make it more difficult for anglers to catch the fish occupying these areas. Therefore, catch rates might decline even more than fish populations.

Given general agreement on the above pathways, three scenarios for the effects of Hydrilla on sportfish populations were developed. These scenarios differ with regard to the areas that Hydrilla colonize.

- Scenario H-1: Under this scenario, hydrilla would replace native plants in the Great Lakes but would not change the habitat structure of enough areas to affect fish populations. The changes in plant species could shift nonsalmonid species composition towards Largemouth Bass and esocids but not affect overall recreational species populations.
- Scenario H-2: Hydrilla would form dense monocultures in shallow, calm embayments, which would reduce habitat quality. These habitat changes would negatively impact warmwater and coolwater fish, leading to a 15% reduction in catch rates for Yellow Perch, Largemouth Bass, Northern Pike, and Muskellunge in all Great Lakes. The reduction would be greater in areas of the lake that are productive; catch rates would be expected to decrease by 25% in Green Bay, Saginaw Bay, and the Bay of Quinte and by 30% in Lake St. Clair. Catch rates might decrease disproportionately vis-a-vis fish abundance because of the difficulty in catching fish in dense stands.
- Scenario H-3: Hydrilla would colonize only deeper areas of the lakes that were not currently colonized by other macrophytes. These newly vegetated areas would provide habitat and attract warmwater and coolwater fish and provide additional habitat and fishing opportunities. Catch rates would increase by 15% for Yellow Perch, Largemouth Bass, Northern Pike, and Muskellunge in all lakes.

The mean and median ratings of the likelihoods of each scenario ranged from unlikely to possible, but not likely, although each of the scenarios was considered likely or highly likely by two to four experts (Table 1). The scenario in which hydrilla did not affect recreational fish catch rates was considered most likely of those considered (H-1).

Quagga Mussel

The quagga mussel is a benthic filter-feeder that invaded the Great Lakes in the late 1980s (Mills et al. 1996). The species is well established in most of the Great Lakes and has replaced zebra mussels *Dreissena polymorpha* in most locations (Karatayev et al. 2014). Quagga mussels consume phytoplankton and may reduce zooplankton through competition. If quagga mussels were to increase further, the reduction in zooplankton productivity coupled with increases in salmon (through stocking, increases in wild reproduction, or immigration) could result in an Alewife collapse and drastically reduce Coho and Chinook salmon.

Scientists have debated whether quagga mussels contributed to the collapse of Alewives in Lake Huron (Nalepa et al. 2007; Barbiero et al. 2011) because densities of quagga mussels are lower in Lake Huron than in lakes Michigan and Ontario (Nalepa et al. 2007). The current densities of quagga mussels in Lakes Michigan and Ontario are an order of magnitude higher than in Lake Huron. It is particularly unlikely that quagga mussels would lead to the collapse of Alewives in Lake Ontario, where the densities of quagga mussels may be decreasing (Birkett et al. 2015). Lake Michigan, which has lower productivity, may be more susceptible.

One developed scenario reflected the possibility that quagga mussels could contribute to an alewife collapse in Lake Michigan. Multiple scenarios were not developed in this case because a second implicit scenario was that quagga mussels would have no effect beyond the current status quo. Under this scenario (QM-1), quagga mussels would increase further in Lake Michigan and lead to an 80% decrease in Coho and Chinook salmon but would not impact other salmonids.

The mean and median rating of the likelihood of this scenario was possible, but not likely with underlying individual responses ranging from highly unlikely to likely (Table 1).

DISCUSSION

We developed five sets of scenarios describing how a range of AIS, were they to become established, could plausibly affect sport fish populations in the Great Lakes. In keeping with the philosophy of scenario building, we did not attempt to develop one single estimate of effects for each species because it would not have been possible to do that with any degree of certainty. Rather, we developed a range of plausible scenarios to facilitate considering a wide range of AIS outcomes. We recognize that additional scenarios could be developed that would be as plausible as our set; we did not attempt to develop an exhaustive set of possibilities. Rather, we sought to develop a set that was sufficiently broad to allow managers and scientists to anticipate most of the range of possible outcomes they might encounter. We think that outcome is valuable, even if none of the AIS scenarios ever develops exactly as articulated by our expert panel.

Although the scenarios we developed were diverse with regard to the types of effects they postulated, several generalizations can be made across the set. First, on average, almost all the scenarios were perceived to be unlikely (11–25%) to possible, but not likely (26–50%), even if the AIS in question were to become established in the Great Lakes. Only one scenario for any of the AIS was perceived to be likely based on the median ratings of all experts on our panel (NS-1), and no scenario was rated as almost certain by any expert. This outcome is consistent with the literature on scenario-building, which recognizes that the likelihood of any particular scenario accurately describing the future is low because of the uncertainty of future conditions (Van Der Heijden 1994, 1996; Schoemaker 1995).

For most of the scenarios, the workshop participants varied widely in their likelihood assessments. Although the mean likelihood of the scenarios was consistently low, as described above, all but three of the scenarios were perceived as at least highly unlikely (1–10%) by some and likely (51–75%) by others. While it might be more satisfying to have more consistent perceptions of the likelihood of these scenarios, it is not surprising given the lack of data available for making predictions, the high level of uncertainty about future conditions, and the different types of expertise and experience among members of the group. Furthermore, this diversity of opinion illustrates that this process was able to avoid the drawback of groupthink in which members of a group feel pressure to conform to the perspectives of others (Janis 1982; Goodwin and Wright 1999; Conroy and Peterson 2013). Indeed, although workshop participants accepted the scenarios as plausible, the diversity of likelihood assessments underscores the value of engaging a group of experts with different perspectives in their development and evaluation. A greater diversity of perspectives on the scenarios resulted.

In contradistinction to some of the public dialogue that has taken place about the effects of AIS, few of our scenarios projected devastating effects on the recreational fisheries of the Great Lakes. Considering these five AIS within the context of the Great Lakes, only four of the scenarios developed projected decreases of 40% or more in any particular fish population, and all four were limited in terms of the species and geographic areas they affected. They were also among the scenarios perceived as least likely. Although the scientific literature also establishes the negative effects that AIS can have on fish populations (Mills et al. 1994; Ricciardi and MacIsaac 2000), our conclusions are not inconsistent with some of the most relevant literature addressing the effects of specific AIS within the Great Lakes. (See discussion below.) Nevertheless, the logic of a scenario-building approach requires that all scenarios are important to consider as possible outcomes of invasions, and so those few scenarios projecting dramatic effects on fish populations need to be considered. The sets of assumptions made in these scenarios about how the Great Lakes system functions differ from the assumptions made in the other scenarios. As Morgan (2014) points out, minority opinions reflecting different ideas about how systems function have in fact turned out to be correct many times in the history of science.

These findings must be considered in light of the limitations of this approach. We asked workshop participants to consider the possible effects of a wide range of AIS on all important recreational fish species throughout the entire Great Lakes. Although defining the task broadly was necessary if we wanted our work to be relevant to decision making about higher-level invasive species policy, it is unrealistic to expect any group of aquatic ecologists to have expertise across such a range of species and conditions. Several workshop participants commented on their lack of knowledge about particular species and interactions. It is possible that a different set of participants would have reached different conclusions about the AIS most likely to affect fish populations or how much they would affect them. The experts also argued that the exercise was constrained not only by their own lack of knowledge but also by the state of knowledge within the field, with one arguing that the process “made me realize how little we know about the ecology of these species and their likely impact on the Great Lakes.”

Defining the task broadly also encouraged the expert panel to make simplifying assumptions in the development of the scenarios. The group tended to develop broad scenarios that described Great Lakes basinwide potential effects, and it considered each AIS individually. In reality, the mix of species is different across the lakes, and hence, the effects of any AIS will differ a great deal among subsystems within the Great Lakes and invasions may involve multiple AIS arriving at the same time.

Even with these simplifying assumptions, each of the scenarios developed was complex and multi faceted. The intention was to develop scenarios that were internally consistent, and to trace through all the logical drivers and consequences. This complexity made it more difficult for workshop participants to evaluate the likelihood of the scenarios. Some participants thought some or most aspects of some scenarios were likely, but other aspects were unlikely. In several cases, the perceived unlikeliness of a specific aspect of a scenario may have led participants to consider the entire scenario as unlikely, even if other aspects of the scenario were deemed likely. One workshop participant described it, as follows:

> We have made each of these scenarios so detailed, that even if you agree with one aspect of it (i.e., [W]alleye decrease 10%) another aspect of it may be less believable ([Y]ellow [P]erch increase by 10%). This causes me to rate the overall probability of many events occurring as very low. If we had been asked about the probability of any one species changing by x%, then I think I could rate that probability higher.

Coming to consensus across a group of experts in a process such as this on all aspects of all scenarios may not be a realistic or even a desirable goal. Hardin and Hill (2012) have also noted the impracticality of reaching consensus across a diverse group about the likely impacts of nonnative fishes.

Finally, as might be expected for any complex problem, the perspectives of some of the experts tended to shift over time as discussions proceeded and participants incorporated aspects they had not initially considered. This is a strength of the process we employed, but we had to stop the process at some point. We chose to make that cut-off point the end of the workshop, because that was the point at which face-to-face discussions among workshop participants ended. We did, however, allow minor inconsistencies in the scenarios to be corrected after that time. Several participants rethought aspects of the scenarios in hindsight or questioned how the group reached a particular decision that later struck them as inconsistent. It is likely that the scenarios would have continued to be fine-tuned. We think that it might take time for some of these second thoughts about the scenarios to emerge. One possible refinement to our scenario-building approach in the future might include a conference call with panel members after the workshop to make any necessary adjustments to the scenarios before finalizing them.

It is useful to compare our scenarios to other predictions that have been made about the possible future effects of AIS on recreational fish in the Great Lakes. Unfortunately, few such predictions have been made. While literature on the impacts of AIS on fish sought by anglers in contexts outside the Great Lakes is available (e.g., Colle and Shireman 1980; Saylor et al. 2012), literature that explores the possible effects of AIS in the Great Lakes is less common.

Of the AIS we considered, perhaps Bighead and Silver carp have been the most extensively evaluated with regard to their likely future effects in the Great Lakes. Cooke and Hill (2010) and Kocovsky et al. (2012) both considered the question of whether and where Asian carp could become established in the Great Lakes. Our work was predicated on the assumption that Asian carp would become established but considered the question of where they would become established. These past authors reached conclusions similar to ours with regard to the areas in which Asian carp are likely to become established, and workshop discussions were informed, in part, by this work. Cooke and Hill (2010) considered Asian carp unlikely to colonize most open-water regions in the Great Lakes, but concluded they could become established in productive embayments and wetlands. Kocovsky et al. (2012) determined that the major tributaries of the western and central basins of Lake Erie were suitable for spawning of Asian carp.

Much of our focus, however, was on how much of an effect Asian carp would have on sport fish populations in the areas where it became established. In contexts outside the Great Lakes, Asian carp have been found to have considerable effects on ecosystems, but their demonstrated effects on sport fish have been found to be small; these findings are consistent with most of our Asian carp scenarios. Irons et al. (2007) found declines in the body condition of two native planktivores (Gizzard Shad and Bigmouth Buffalo *Ictiobus cyprinellus*) in the Illinois River, and they attributed this decline to competition with Bighead Carp and Silver Carp. These declines were small (<10%), however. McClelland et al. (2012) reported that the arrival of Asian carp in the Illinois River did not decrease species richness or the abundance of native species. These studies, however, focused on Asian carp impacts in a river system with different characteristics than the Great Lakes, and so the results are probably not comparable.

Because Asian carp are not yet established in the Great Lakes, work to assess their effects there has been based on prospective expert judgment or modeling. Wittmann et al. (2014) and Cooke et al. (2014) used structured expert judgment to predict the effects of Bighead and Silver carp on biomass of recreationally and commercially harvested Yellow Perch, Walleye, and Rainbow Smelt in Lake Erie. Although the approach they described has similarities to ours, because it relies on expert judgement, it differs in that it relied on mathematical rather than behavioral aggregation. In particular, they used a structured expert judgment approach in which experts' individual assessments of the effects of Asian carp were combined mathematically, and weights were based on how well each expert had performed in their predictions of a set of calibration variables. Despite these differences in approach from ours, these authors also concluded that the effects of Asian carp on sport fish populations would be small, and they even predicted an increase in Yellow Perch biomass because they have a wide enough niche to avoid competition with Bighead and Silver carp.

Zhang et al. (2016) reached similar conclusions about the potential impacts of Bighead and Silver carp in Lake Erie, based on a food web model in which they varied assumptions about the Asian's carp diet and about nutrient loads. Large food-web impacts occurred in only 2% of model simulations. Currie et al. (2012) evaluated potential consequences of Asian carp establishment in Lake Ontario. They articulated a range of possible outcomes and considered it quite plausible that they could become established without impact to other trophic levels. However, they also recognized the possibility that Asian carp establishment could lead to an Alewife collapse and devastate the Chinook Salmon population. This more extreme possibility is consistent with one of our scenarios (AC-2c), although our scenario postulated such a collapse only for Lakes Michigan and Ontario. The consistency of our scenarios with the literature is not surprising given that our experts relied in part on their knowledge of the literature in the development of these scenarios, and in fact, some of our experts were authors of these studies.

Based on these results, we suggest that the scenario-building approach utilized in this paper could contribute to management and policy surrounding strategies to address possible ecological impacts of invasive species. Scenarios clearly reflect the uncertainty inherent in trying to predict AIS impacts but still allow managers and policy-makers to narrow the range of possibilities they consider with regard to how AIS could affect Great Lakes fisheries. For example, rather than assuming the total net value of all Great Lakes recreational fisheries is at risk from particular AIS, our scenarios would allow researchers to use existing economic models (Ready et al. 2012) to estimate a range of possible effects on the net value of recreational fishing. This work can thus inform important decisions about the value of measures that could prevent the spread of AIS, although the impact of AIS on recreational fishing is only one of a broader set of impacts that must be considered.

In addition, the scenario-building approach could also contribute to a research agenda related to AIS impacts on fisheries. Given that the set of scenarios developed for each AIS is based on a different set of assumptions about ecological processes, research could help to determine which set of assumptions is correct. The research results could thus help to further refine predictions of invasive species impacts.

A scenario development approach similar to that used here could be used to project future conditions in other complex ecological systems. Such an approach would allow decision makers to anticipate and prepare for a range of possible futures when precise estimates of future conditions are impossible.

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