

The Impact of Chronic Diseases on Patient Participation and Healthcare Value: Potential Future Trends

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Abstract

The impacts of aquatic invasive species (AIS) on the recreational fishery in the Laurentian Great Lakes are of concern to managers and policy makers. Some AIS have the potential to depress sportfish populations, reducing recreational fishing opportunities and damaging local economies. Alternatives that could reduce the threat of AIS could be costly. Assessments of how AIS could affect recreational fishing participation and the economic value derived from it would contribute to the evaluation of these alternatives. We assessed best-case and worst-case scenarios for how a range of AIS could affect recreational fishing participation and economic value. We utilized previously developed scenarios for how AIS could affect sportfish populations as input for a recreational fishing model developed by Ready et al. (2018). Their model estimated changes in fishing participation and economic value from such scenarios. Given uncertainty in how AIS could affect sportfish, projected effects of AIS on economic value varied widely, with some scenarios likely to have minimal effects and others leading to losses of over \$100 million annually. None of the scenarios would lead to a large percentage decrease in recreational fishing in the eight Great Lake states, largely because anglers have numerous inland fishing opportunities. Nevertheless, lakeshore communities dependent on Great Lakes fishing could still suffer considerable economic loss. Collectively the economic valuation of the range of scenarios narrows down the possible impacts on fishing and the economy that decision makers need to consider.

Keywords: invasive species, recreational fishing, economic value.

Introduction

Together, the Laurentian Great Lakes represent the largest freshwater system in the world and provide a range of benefits to people including water supply, recreational and commercial fisheries, transportation, and recreation. Aquatic invasive species (AIS) put these benefits at risk and are considered major threats to the Laurentian Great Lakes (Mills et al., 1993; White House Council on Environmental Quality et al., 2010).

The potential impacts of invasive species on the Great Lakes recreational fishery have been of concern to managers and policy makers. Some invasive species have the potential to depress sportfish populations, reducing recreational fishing opportunities. Because recreational fishing makes an important contribution to the economy of the Great Lakes region, many stakeholders have concerns about how changes to the fishery could affect the regional economy.

Policies to address this concern continue to be debated. For years, people have advocated a variety of approaches to reduce or prevent the movement of invasive species into the Great Lakes. These measures, ranging from requirements for lake-going ships to treat their ballast

water to hydrological separation of the Great Lakes and Mississippi River basins, could be costly. Some approaches to separating the Great Lakes and Mississippi River basins discussed in recent years were estimated to cost up to \$14 billion (U.S. Army Corps of Engineers, 2014).

Assessments of how invasive species could affect the economic value of the Great Lakes recreational fishery could help policy makers evaluate these alternatives. Such assessments require both ecological and social components; estimates of the potential effects of AIS on sportfish populations need to be paired with assessments of how changes in fish populations may affect fishing participation and the economic value of fishing.

The literature includes numerous examples of studies to assess the ecological impacts of invasive species. Authors approach this task in a variety of ways. Some have utilized findings from other invasions in other contexts (Kulhanek et al., 2011; Ricciardi and Rasmussen, 1998) or developed empirical models (Rinella and Luschei, 2007). Others have approached this task using theory-driven assessments and models based on understanding how invasive species impacts are influenced by community structure (Parker et al., 1999), population dynamics (Love and Newhard, 2012), niche overlap with native species (Thum and Lennon, 2009), and the comparative functional responses of invasive and native species (Dick et al., 2014; Dodd et al., 2014).

Regardless of the approach, however, it is difficult to predict the ecological effects of invasive species with a high degree of certainty (Ricciardi and Rasmussen, 1998) as the data need to predict effects are often lacking (Kulhanek et al., 2011; Leung et al., 2012). Further, it is difficult to predict the effects of invasive species in new contexts in which their effects may differ from locations where they are currently present (Kulhanek et al., 2011).

In response, some scientists have utilized expert opinion to assess the possible impacts of invasions (Hardin and Hill, 2012; Hill and Lawson, 2015; Lauber et al., 2016; Wittmann et al., 2015, 2014). In Lauber et al. (2016), we described our approach of using an expert panel to assess impacts. We tasked the panel with developing a range of scenarios for how invasive species with diverse ecological functions (pelagic and benthic planktivores, piscivore, herbivore, and macrophyte) could affect sportfish populations in the Great Lakes. Rather than attempting to develop a single best estimate of invasive species effects, we produced a range of plausible, internally consistent scenarios that would encompass the full range of effects that invasive species might have on these populations. These estimates were intended to establish the bounds within which the effects of invasive species on Great Lakes sportfish populations were likely to fall.

Our next step was to develop and apply an economic model (Ready et al. [2018]) to assess how the predicted changes in sportfish population in the Great Lakes would affect recreational fishing participation and the net economic value of recreational fishing. As Ready et al. (2018, p. 306) explained the concept of net economic value in this context (p. 306):

When an angler goes on a fishing trip, he or she gets enjoyment out of that experience and places some value on that enjoyment. The angler must pay some expenditures (on gasoline, bait, charter services, etc.) for the trip, but the anticipated value of the trip to the angler exceeds the cost to the angler. This must be true, or the angler would not go on the trip. The difference between the value to the angler of the trip and the cost to the angler is called the angler's consumer surplus from the trip. The net economic value of the

recreational fishery is the sum over all trips and over all anglers of these per-trip consumer surplus values.

Net economic value is considered the most appropriate economic measure to use when assessing tradeoffs between policy alternatives (such as whether to take action to reduce the threat of AIS) (Buck et al., 2010); it represents the value society gains from a recreational activity compared to a situation in which the recreational activity was unavailable. Other economic measures, such as the expenditures made on recreational activities or regional economic impact (which also considers the ripple effects that expenditures can have on a local economy) are also frequently reported. From the narrow perspective of the benefits to the local community, it is tempting to view these direct and secondary impacts as benefits from recreational activities: this is the amount of additional purchases of goods and services within a community resulting from expenditures by recreational anglers. From the broader social perspective, however, expenditures and secondary effects merely represent a transfer of income from recreationists to regional businesses. If these monies were not expended on fishing, they would be spent on other things, and hence not lost from the economy.

We (Ready et al. 2018) developed a recreational behavior model for the Great Lakes region to estimate how participation in the recreational fishery (days fished) and net economic value of the recreational fishery would change as sportfish populations change. We based this model on a survey of sport anglers in the 12 states of the Great Lakes and Upper Mississippi River basins. We used data on the travel cost of fishing trips taken by anglers and statements about how the anglers would respond to changes in fishing populations to model angler behavior in relation to fishing quality. The model was spatially explicit, so that it could estimate the loss in the net economic value of the recreational fishery under geographically explicit scenarios.

In Ready et al. (2018) we provided a tool for assessing some of the socio-economic effects of AIS in the Great Lakes, but in that paper we applied this tool only to *a single worst-case scenario* for bighead carp *Hypophthalmichthys nobilis* and silver carp *H. molitrix*. Policy makers and managers, however, need to make decisions that are appropriate for addressing the *range* of possible effects that AIS could have—not just the worst-case scenario of a particular species. Informing these decisions requires assessing the range of effects that AIS could have on recreational fishing. The scenarios that Lauber et al. (2016) developed encompass a range of possible ways that five different AIS could affect sportfish populations. We apply Ready et al.'s (2018) model to both the best-case and worst-case scenarios for each of these AIS, as opposed to just a single scenario for one AIS as Ready et al. (2018) did. Our results therefore expand on our previous work by analyzing a wider range of the possible effects of AIS on recreational fishing participation and economic value.

Description of Study Area

The Laurentian Great Lakes cover 244,000 km² and contain one-fifth of the world's surface freshwater supply. The fisheries in four of the lakes—Superior, Michigan, Huron, and Ontario—primarily target coldwater salmonids, although fisheries for coolwater walleye *Sander vitreus* and warmwater smallmouth bass *Micropterus dolomieu* occur in nearshore areas and more productive larger bays. Lake Erie is the most productive and shallowest of the five lakes; its fishery primarily targets walleye, yellow perch *Perca flavescens*, smallmouth bass, and salmonids. The Great Lakes system contains connecting corridors in the Detroit River and Lake St. Clair between Lake Huron and Lake Erie, in the Niagara River between Lake Erie and Lake

Ontario, and in 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

As we reported in Lauber et al. (2016), we engaged an expert panel to build a series of plausible, internally consistent scenarios describing how AIS could affect sportfish populations and angler catch rates in the future. Given the inherent uncertainty involved in projecting the future effects of AIS, we designed our process to develop scenarios that would encompass the range of likely possible outcomes for each AIS considered. We recruited a group of aquatic ecologists and fisheries managers with collective expertise about all five Great Lakes and a wide range of AIS. (For a complete description of the scenario-building process, see Lauber et al. [2016]). We first engaged them through a modified Delphi survey in which they identified the AIS that they thought were most likely to affect recreational fish populations throughout the Great Lakes regions and the mechanisms through which they might affect them.

The survey was followed by a 2-day scenario-building workshop. During the workshop, the expert panel first selected five AIS for which they would develop detailed scenarios describing their effects on recreational fish. In selecting species, they represented a range of taxa and ecological functions, focusing on those species that they believed were most likely to affect recreational fish populations and about which they were knowledgeable. The final species they selected were bighead and silver carp (pelagic planktivores, which were treated as one species because their ecological functions are very similar), northern snakehead *Channa argus* (a piscivore), grass carp *Ctenopharyngodon idella* (an herbivore), hydrilla *Hydrilla verticillata* (a macrophyte), and quagga mussel *Dreissena rostriformis bugensis* (a benthic filter-feeder).

For each AIS, the panel developed multiple scenarios describing the mechanisms by which the species might plausibly affect fish populations and angler catch rates. The scenarios included descriptions of the ecological roles the AIS would play within the system, and the direct and indirect effects they would have. Each scenario was accompanied by quantitative estimates of percentage change in catch rates for particular recreational fish species for specified geographic areas throughout the Great Lakes basin.

Ready et al. (2018) previously developed a recreational fishing model for the 8 Great Lakes states that utilizes ecological scenarios, such as those developed by Lauber et al. (2016) to assess how angler behavior and the net value of the recreational fishery (i.e., the total consumer surplus generated) would change if AIS (or other factors) affected recreational fish catch rates in a spatially explicit way. (For a complete description of this model, see Ready et al. [2018].) This model describes how angler behavior and the net value of the recreational fishery would change if AIS (or other factors) affected recreational fish catch rates. It was developed based on data collected from recreational anglers through a travel cost-contingent behavior survey of 3,539 anglers residing in the Great Lakes and Upper Mississippi River basins.

The survey collected detailed data on all fishing trips taken over the 2011 license year. For each fishing trip, information on the trip origin, destination and primary fishing type was collected. Fishing trips were classified into seven types, according to the stated primary purpose of the trip: Great Lakes coldwater (i.e., salmonids), Great Lakes warmwater (i.e., species other than salmonids, which includes warmwater and coolwater fish), anadromous (salmonid fishing during

spawning runs), inland lakes and ponds for coldwater species, inland lakes and ponds for warmwater species, inland rivers and streams for coldwater species, and inland rivers and streams for warmwater species. Contingent behavior questions asked how the number and types of fishing trips would change if catch rates changed.

From this survey data, Ready et al. previously estimated a repeated nested logit random utility model of angler behavior (Morey et al., 1993). This model includes three decisions that must be made for each fishing trip. First, on each day of the year, the angler decides whether to go fishing. Second, each day that a fishing trip is taken, the angler must decide what type of fishing to engage in. Finally, for each fishing trip, a destination must be chosen. The model assumes the angler chooses a destination and fishing type that gives them the highest possible consumer surplus for that day. Destinations that are located closer to the angler's home will tend to generate higher consumer surplus because they require less expenditure on travel expenses. Destinations with better fishing quality (i.e. more availability of water resources, better water quality, and/or higher catch rates) will tend to generate higher consumer surplus. An included random term means that the same angler may visit different destinations or fish for different target species on different days.

From the estimated model parameters, it is possible to calculate how a change in fishing quality (specifically, catch rates) for specific fishing types at specific destinations would change the consumer surplus from a trip for those fishing types to those destinations. It is then possible to predict how fishing behavior would change, including the impact on the types of trips taken, the destinations chosen, and the total number of trips taken. For example, if catch rates decline for some fishing types at some destinations, anglers will react in two ways. They will 1) substitute away from fishing trips whose quality has declined toward fishing trips whose quality has not changed and 2) they will tend to take fewer total trips. The total impact on the consumer surplus enjoyed by anglers will include the consumer surplus loss associated with the lost trips as well as the reduction in consumer surplus from trips that are still taken.

For each AIS scenario, these calculations were done for every angler living in the eight Great Lakes states. Origins and destinations were aggregated at the county level. For each angler, the change in total consumer surplus over the season resulting from the scenario was calculated. These were then averaged for each state and a total change in net economic value was calculated for the scenario. For each destination, the change in total fishing trips to that destination was calculated for each fishing type. These were aggregated by fishing type.

Ready et al. (2018) applied this model to only one of the ecological scenarios developed by Lauber et al. (2016)—the worst case scenario for bighead and silver carp. In the current manuscript, we apply the model to both the best-case *and* worst-case scenarios for *each* of the five AIS considered by Lauber et al. (2016). To generate the necessary input for the recreational fishing model, we had to translate Lauber et al.'s (2016) AIS scenarios, which specified changes in catch rates of particular species, into county-level projections of changes in the catch rates for each of the seven fishing types utilized in the model. We calculated the change in the catch rates of each of the 7 fishing types by weighting the change in the populations of species that were part of that fishing type (with weights based on the importance of each species to the fishing type, as measured by creel surveys). (See the supplementary materials in Ready et al. [2018] for more detailed instructions on how to make these calculations.) Consequently, in a situation in which an AIS had a dramatic effect on some Great Lakes coldwater species, but

minimal effect on others, for example, the overall change in the catch rate of Great Lakes coldwater fishing would be less than for those individual species most affected. We report the best-case and worst-case scenarios (as judged by change in the economic value of the Great Lakes fishery), projecting how the number of fishing days and the net value of fishing (in 2012 dollars) would change in each state of the Great Lakes region. We report the four inland fishing types as a single category in this manuscript. These results provide decision makers with a wide range of possible effects of AIS on recreational fishing participation and value. Note that effects on Canadian recreational fisheries are not included as the Province of Ontario was not included in the surveys that form the basis of the economic model (Ready et al., 2018).

Results

We estimated that anglers in the U.S. Great Lakes region took over 174 million fishing trips in 2011 (Table 1). Wisconsin had the greatest number of trips and Indiana the least. The vast majority of the trips (87%) were inland fishing trips, ranging from a high of 99% of the trips in Minnesota to a low of 75% of the trips in Michigan.

These estimates served as a baseline for our projections of the effects of AIS on recreational fishing trips and the net value of recreational fishing. For each AIS, we summarize the best-case and worst-case scenarios (reported in detail in Lauber et al. [2016]). We then project how the number of fishing days and the net value of fishing would change in each state under these scenarios.

Bighead and Silver Carp

Bighead and silver carp (hereafter referred to as “Asian carp”) are similar in food selection, body size, and potential ecological effects. Asian carp are pelagic filter feeders that consume both phytoplankton and zooplankton and therefore are potential competitors with existing prey species of several important sportfish species (Kolar et al., 2007). They can grow sufficiently large to have a size refuge from predatory fish. To date, Asian carp are not considered to be established in the Great Lakes, though three individual bighead carp have been caught in Lake Erie (Kocovsky et al., 2012).

In developing the scenarios for Asian carp, the expert panel assumed that carp establishment in the Great Lakes would be limited by food availability (Lauber et al., 2016). A central question was whether these species would be limited to high productivity areas (bays near large tributaries and the western and central basins of Lake Erie) or if food concentrations would be high enough for them to also establish offshore populations. The latter scenario was considered less likely, but would lead to more widespread effects, particularly on salmonids. Several independent modeling exercises have been completed on Asian carp effects that largely support the expert panel’s conclusions (Anderson et al., 2015; Currie et al., 2012; Zhang et al., 2016).

The Asian carp scenarios varied widely in their projected impacts (Table 2). Depending on the assumptions made, the establishment of Asian carp could lead to a loss of more than 400,000 fishing trips and nearly \$139 million in value (worst-case scenario) or an increase of more than 11,000 fishing trips and nearly \$4 million in value (best-case scenario).

The best-case scenario assumed that Asian carp would only become established in high productivity areas (Lauber et al., 2016). They would have a small negative effect on salmonids because they would compete with salmonid prey when these prey species were in nearshore areas, reducing their abundance somewhat. The expert panel estimated that Asian carp could lead

to a 5% decrease in Great Lakes salmonids under these conditions. But under this scenario, Asian carp would have both positive and negative effects on warmwater species. While they would compete for food with warmwater species and the prey of warmwater species, they could also serve as a prey resource for some piscivores, increasing their growth rates and releasing other species from predation. Under the best-case scenario, the expert panel assumed that the positive effects would dominate and lead to increases in largemouth bass *Micropterus salmoides*, smallmouth bass, yellow perch, and walleye.

According to the Ready et al. (2018) model, these changes would be more beneficial to recreational fishing in Michigan and Ohio because warmwater species would increase in the western and central basins of Lake Erie, Lake St. Clair, and Saginaw Bay. Anglers living in these states would increase their annual fishing trips by nearly 50,000, and the net economic value of these trips would increase by over \$16 million annually. The biggest negative effects would be felt by anglers in Illinois with a loss of 17,000 fishing trips and nearly \$6 million in value annually. In Illinois, anglers take more than twice as many Great Lakes coldwater trips than Great Lakes warmwater trips and so the small loss in salmonids would have a bigger effect than the increase in warmwater species.

Under the worst-case scenario, the expert panel assumed that Asian carp would become established in the pelagic portions of all lakes except Superior (Lauber et al., 2016). They would compete with alewife *Alosa pseudoharengus* for food, thus contributing to an alewife collapse in Lakes Michigan and Ontario. (The alewife population has already collapsed in Lake Huron.) This collapse would result in an 80% decrease in coho salmon *Oncorhynchus kisutch* and chinook salmon *O. tshawytscha* in Lakes Michigan and Ontario.

Great Lakes coldwater fishing by anglers in the region would decrease by more than 70% under this scenario with a much smaller, but still substantial, decrease in anadromous fishing (more than 10%) (Table 3). Some anglers would switch to Great Lakes warmwater fishing (9% increase in trips) and inland warmwater fishing (3%); these increases would reduce the losses in Great Lakes coldwater trips by more than 90%. The biggest negative effects would be felt by anglers living in the five states that border Lakes Michigan and Ontario with a loss of more than 163,000 trips and \$55 million in value in Illinois alone (Table 2). Minnesota and Pennsylvania would remain relatively unaffected given that the effects of this scenario would be minimal in the Great Lakes that they border (Superior and Erie). Ohio anglers would actually increase their number of fishing trips by over 8,000 and the value of those trips would increase by nearly \$3 million in value as people switched to warmwater fishing in the western and central basins of Lake Erie. The overall effects of this scenario on the net economic value from all fishing would still be negative, however, with a loss of \$139 million annually. Still, the average loss in consumer surplus, per trip taken, is less than \$1.

Northern Snakehead

The 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).

The expert panel reasoned that if northern snakehead became established in the Great Lakes, it would be limited to nearshore areas and shallow, relatively warm waters (Lauber et al., 2016). Ecologically, it would function like other piscivores, particularly largemouth bass. The panel was uncertain, however, about two key questions: whether it would augment or simply replace other predator species in the system; and whether it would itself become a sought-after sportfish. Depending on the assumptions made, the predicted effects on recreational fishing ranged from no change in the status quo to a loss of 140,000 fishing trips and \$48 million in consumer surplus annually (Table 4).

Under the best-case scenario, northern snakehead would partially replace other predator species, but the overall level of predation would not increase in the system (Lauber et al., 2016). In addition, northern snakehead would become a sportfish itself, and so recreational fishing would not be affected.

Under the worst-case scenario, the overall level of predation would increase in the Great Lakes as northern snakehead became established, driving down populations of prey species (Lauber et al., 2016). In addition, northern snakehead would outcompete native predators. Ultimately, populations of smallmouth bass, yellow perch, and largemouth bass would be affected in high-productivity areas and walleye populations would be affected lakewide. In addition, Northern snakehead would have some effects on salmonid populations as it preyed on juvenile salmonids running down streams.

In this worst-case scenario, the most substantial negative effects on recreational fishing would be on anglers living in Michigan, who would lose nearly 55,000 fishing trips and \$19 million in consumer surplus annually. Anglers in Ohio, Illinois, and Wisconsin would also suffer negative effects, as these states border the high productivity areas most affected under this scenario (Green Bay, Saginaw Bay, Lake St. Clair, and the western and central basins of Lake Erie). Anglers in Minnesota and Pennsylvania, which are more distant from these areas, would be much less negatively affected.

Both Great Lakes coldwater fishing (10% decrease) and Great Lakes warmwater fishing (8% decrease) would decline under the worst-case scenario (Table 3). The loss in Great Lakes coldwater fishing would be fairly consistent across the basin with a 9-11% decrease among anglers in each state except for Ohio (7% decrease). The loss in Great Lakes warmwater fishing would be greatest for anglers fishing in Ohio and Michigan with over 790,000 fewer trips (12-14% decrease in these states). Inland fishing trips would increase as anglers switched to inland fishing from Great Lakes fishing. This increase of nearly 1.5 million inland fishing trips would nearly make up for the loss in Great Lakes fishing.

Grass Carp

The grass carp is an herbivore that tolerates 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. Grass carp is now reproducing in Lake Erie (Chapman et al., 2013; Embke et al., 2016), but have not yet become abundant in the Great Lakes basin.

The expert panel concluded that if grass carp became abundant in the Great Lakes, it would have novel impacts because it consumes primarily macrophytes, which is unlike any other Great

Lakes native fish (Lauber et al., 2016). It would reduce and change aquatic vegetation leading to increased predation on juvenile fish. These changes to vegetation in nearshore areas would have negative effects on warmwater and coolwater fishes, including northern pike *Esox lucius*, yellow perch, largemouth bass, and most other centrarchids. The negative effects on largemouth bass and northern pike might be offset to some degree by the benefits these fish would gain by the opportunity to prey on young grass carp.

The key uncertainties about the effects of grass carp are based on how numerous and widespread they would become, which would be influenced in turn by how much northern pike and largemouth bass would prey on young grass carp (Lauber et al., 2016). The expert panel varied assumptions about these factors in the scenarios they generated. The projected effects of grass carp ranged from losses of 29,000-60,000 fishing days annually and \$10-21 million in consumer surplus (Table 5).

Under the best-case scenario, grass carp would become established, but would not become numerous because of predation on young fish by northern pike and largemouth bass (Lauber et al., 2016). Although there would be some decrease in yellow perch and centrarchids other than bass, populations of largemouth bass and northern pike would be unchanged because the benefits of preying on young carp would offset habitat loss.

Under this scenario, the greatest effects would be felt by anglers from Michigan and Ohio and, to a lesser extent, Wisconsin and New York. Collectively, these anglers would lose 22,000 in fishing trips and \$5.5 million in consumer surplus. Anglers from Minnesota and Pennsylvania would be minimally affected. Great Lakes warmwater fishing would decline by more than 3.5% under this scenario (Table 3), but all other fishing types would increase as anglers switched to different forms of fishing. Great Lakes coldwater and anadromous fishing would increase about 0.5% while the percentage increase for inland fishing would be less than half of that. The overall decrease in fishing would be only 0.02%.

Under the worst-case scenario, predation by largemouth bass and northern pike would have no appreciable effects on grass carp populations (Lauber et al., 2016). Grass carp would, therefore, become established and reduce macrophyte habitat in all Great Lakes. Largemouth bass, northern pike, and most other centrarchids would decrease by 50% under this scenario, with a smaller decrease in yellow perch.

The greatest effects would be felt by anglers from Michigan. Anglers from Ohio and Illinois and, to a lesser extent, Wisconsin and New York would also be substantively affected. More than 60,000 fishing trips and nearly \$21 million in consumer surplus would be lost by anglers from these states. As with the best-case scenario, anglers from Pennsylvania and Minnesota would be minimally affected. Great Lakes warmwater fishing would decline by 7.5% (Table 3), more than twice as much as under the best-case scenario. Great Lakes coldwater fishing and anadromous fishing would increase 1% or more as anglers switched away from warmwater fishing. The overall decrease in fishing would only be 0.04%.

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.

The expert panel reasoned that if hydrilla became established in the Great Lakes, it would be able to colonize some areas that do not currently have macrophytes because it can become established in deeper waters (Lauber et al., 2016). Under some conditions, this might benefit fish that depend on macrophytes, but hydrilla can also form dense monocultures that can be unsuitable for fish. The effects of hydrilla on fisheries, whether good or bad, would be confined to specific areas that tend to be important for northern pike and bass (particularly largemouth bass). Salmonids would not be expected to be affected as much. Beyond the effects that hydrilla could have on fish populations, it could also make it harder for anglers to catch fish under some conditions, depressing fishing and the value of fishing.

The key uncertainties about the effects of hydrilla on fisheries are linked to the areas that it would colonize (Lauber et al., 2016). In particular, the expert panel was uncertain about whether hydrilla would simply replace other macrophytes or colonize new areas and whether it would maintain similar vegetative structure or form dense monocultures that reduce habitat quality. Depending on these assumptions, hydrilla could lead to a loss of more than 100,000 fishing days and \$35 million in consumer surplus or could actually increase fishing by more than 85,000 fishing days and add \$30 million in consumer surplus (Table 6).

Under the best-case scenario, hydrilla would colonize only deeper areas of the Great Lakes that do not currently have macrophytes (Lauber et al., 2016). Under this scenario, it would improve habitat and fishing opportunities for yellow perch, largemouth bass, northern pike, and muskellunge *Esox masquinongy*. It could lead to substantial increases in fishing by anglers in a number of Great Lakes states including Michigan (27,000 additional fishing days), Ohio (19,000), Illinois (16,000), and Wisconsin and New York (10,000 each). The economic value of fishing would increase by \$3-9 million in each of these states. Minnesota and Pennsylvania would be minimally affected. Great Lakes warmwater fishing would increase by more than 10% under this scenario, with small decreases in other fishing types as people switched to Great Lakes warmwater fishing to take advantage of the improved opportunities (Table 3). Other types of Great Lakes fishing, coldwater and anadromous, would decrease by 1.4-1.6% as anglers substitute toward warmwater species. Inland fishing would decrease by 0.6%. Overall, fishing in the Great Lakes states would increase by a total of 0.05%.

Under the worst-case scenario, hydrilla would replace other macrophytes and form dense monocultures in shallow, calm embayments, particularly in the most productive areas of the lakes (Lauber et al., 2016). This change would harm habitat quality and lead to lower catch rates for yellow perch, largemouth bass, northern pike, and muskellunge. Anglers would be most affected in Michigan (loss of 40,000 fishing trips), Ohio (20,000), Illinois (17,000), Wisconsin (12,000), and New York (10,000). Minnesota, Pennsylvania, and Indiana would be minimally affected. Great Lakes warmwater fishing would decrease by nearly 13% overall. Great Lakes coldwater and anadromous fishing would increase by 1.6-1.8%. Inland fishing would increase by 0.7% (Table 3). Overall, the number of fishing trips would decrease by just 0.6%.

Quagga Mussel

The quagga mussel is a benthic filter feeder that invaded the Great Lakes in the late 1980s (Mills et al., 1993). 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.

The expert panel evaluated the effects of a possible further increase in quagga mussels coupled with increases in salmon through stocking or increases in wild reproduction (Lauber et al., 2016). Under these circumstances, they considered it possible that alewife populations could collapse, leading to substantial decreases in coho and chinook salmon populations. Such a scenario was considered most likely to occur in Lake Michigan but could also occur in Lake Ontario. Alewife has already collapsed in Lake Huron, attributed by several authors to decreased nutrient loading, quagga mussels, and high wild production of chinook salmon (He et al., 2015; Kao et al., 2016). Note that this worst-case scenario would be mediated if fisheries management agencies take action to reduce salmon stocking to appropriate levels—an action that to date has been unacceptable to some angler groups that wish to maintain high salmonid abundance. The panel compared this possibility with the status quo (which was considered the best-case scenario).

Under the worst-case scenario, 80% of the coho and chinook salmon in Lake Michigan would be lost (Lauber et al., 2016). Only anglers living in states on or near Lake Michigan would be affected, but these effects would be dramatic with more than 375,000 fishing days and \$128 million in consumer surplus being lost (Table 7). Anglers in Illinois would be most affected (162,000 fishing days lost). The other states most affected would include Wisconsin (94,000 fishing days), Michigan (78,000), and Indiana (41,000). The loss of consumer surplus would range from \$14-55 million in each of these states.

The type of fishing most affected under this scenario would be Great Lakes coldwater fishing, which would decrease by nearly 64% (Table 3). Although catch rates for anadromous anglers around Lake Michigan would also decrease sharply, participation in anadromous fishing would be much less affected (8% decrease).

Other fishing types in the region would increase as anglers switched away from Great Lakes coldwater fishing. Great Lakes warmwater fishing would increase by 5% (more than 562,000 days), and inland fishing would increase by 3% (more than 4,600,000 days). The overall decrease in fishing in the 8-state Great Lakes region would be 0.22% because the increase in Great Lakes warmwater and inland fishing would nearly make up for the losses in Great Lakes coldwater fishing.

Discussion

Although there is widespread concern about potential effects of AIS on sportfish and recreational fishing, little work has been done in the Great Lakes to quantify the effects of AIS on recreational fishing participation and the economic value of recreational fishing. We used previously developed scenarios for how AIS might affect sportfish populations in the Great Lakes (Lauber et al., 2016) as input for a model developed by Ready et al. (2018) to determine the possible effects of AIS on fishing participation and value.

We evaluated ecologically plausible impacts of five AIS on recreational fishing participation and economic value. Because of the inherent uncertainties in predicting how AIS will affect sportfish, we considered a range of plausible scenarios for each of the AIS. Consequently, we found a wide range of possible outcomes of how these species could affect the recreational fishery. Most, but not all, of these outcomes were negative, depressing recreational fishing and economic value.

Under some scenarios, particular types of fishing could be dramatically affected by AIS. We predicted that days spent on Great Lakes coldwater fishing trips would decrease by more than 60% under the worst-case scenarios for bighead/silver carp and quagga mussels. Even under these extreme scenarios, however, the overall loss of recreational fishing participation in the 8-state Great Lakes region would be low. The total number of fishing trips never decreased by more than 0.25%, even under these scenarios.

A number of reasons underlie this outcome. To begin with, recreational fishing is dominated by inland fishing, even in the Great Lakes states. More than 85% of the fishing trips taken in the Great Lakes region are to inland fishing locations. Therefore, even when Great Lakes fishing is dramatically affected by AIS, the vast majority of fishing trips are unaffected.

Second, AIS effects differ geographically. For many scenarios, only some of the Great Lakes states are affected. Anglers from Michigan and Illinois would be among the most adversely affected for all AIS scenarios. Anglers from Ohio would be seriously affected by the scenarios impacting warmwater fishing, and Wisconsin anglers would be particularly affected by those scenarios impacting coldwater fishing. Anglers from Pennsylvania and Minnesota, where only 1-3% of the fishing trips are Great Lakes fishing trips, would be relatively unaffected by most scenarios. This geographical specificity moderates the overall effects of some scenarios.

Third, the overall decline in fishing participation is attenuated because the model shows that many anglers may simply switch to different types of fishing if one type declines and to different destinations if only selected areas are affected. In all of the scenarios described above, when one type of fishing was negatively affected, other fishing types increased as anglers switched to fishing for species that were unaffected. This switching behavior often led to substantial increases in days spent fishing for sportfish that were not affected by AIS. These increases were often nearly enough to make up for the losses.

Further, not all anglers fish less when their preferred type of fishing declines in quality (defined as catch rates in this study). Some anglers care less than others about catch rates. Anadromous anglers, in particular, are among the least affected by catch rates. Although catch rates for both Great Lakes coldwater fishing and anadromous fishing are dependent on salmonid populations, when populations of salmonids drop sharply, participation in Great Lakes coldwater fishing decreases much more sharply than participation in anadromous fishing.

For all of these reasons, declines in fishing participation and value are often much less than the corresponding decreases in sportfish populations. Nevertheless, under some conditions the loss of net economic value can be substantial. For all of the AIS we considered, the worst-case scenarios involved economic losses at least in the tens of millions of dollars, and some scenarios involved losses in net economic value of nearly \$140 million. The projected decrease in visits to specific destinations for specific fishing types might have considerable effects on local economies in states and regions that depend on Great Lakes fishing.

The chief limitation of our projections of economic loss and changes in fishing participation is that considerable uncertainty exists about which of the scenarios is most likely to occur. When Lauber et al. (2016) asked the expert panelists who developed the scenarios to rate the likelihood of each one, the mean ratings of almost all scenarios ranged from “unlikely” to “possible, but not likely.” Panelists also recognized that the establishment of more than one AIS in the same region could lead to additional scenarios that managers might face in the future. Nevertheless, any

method used to project possible future invasive species effects would be similarly uncertain, and fisheries managers and policy makers still have to make decisions in the face of this uncertainty. Under such conditions, scientists have often assessed the likelihood of different outcomes using subjective assessments by experts (Goodwin and Wright, 1999; Morgan, 2014). The scenario-building approach that we used is an expert-judgment approach that is premised on the assumption that the likelihood of any particular scenario accurately describing the future is low (Schoemaker, 1995; Van der Heijden, 1996, 1994). Developing a wide range of scenarios narrows down the range of possible future impacts on fishing and the economy that decision makers need to consider when developing fishery management and local economic development plans. Our projection of potential economic effects of AIS can also be used to help evaluate and justify possible management actions designed to prevent the establishment of new AIS or control existing AIS. Even if none of the individual scenarios develops as described, collectively they help to define the boundaries around a range of possible future conditions that decision makers might face. If any of the AIS we consider do become more widely established in the Great Lakes, additional research could assess how subsequent changes in fishing participation compare to our projections. This work would also provide an opportunity to evaluate methods for making these projections.

Although our model was developed to assess the effects of AIS, it is equally suitable for application to other fishery perturbations that could affect catch rates in the Great Lakes states and, therefore, fishing participation. The model could be used, for example, to assess how other environmental stressors, such as disease or climate change, might influence fishing participation and value in the future.

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Table 1. Fishing trips by state and fishing type in the Great Lakes states in 2011¹.

Destination State	Fishing Trips per Fishing Type (1000s)				Total
	Great Lakes Coldwater	Great Lakes Warmwater	Anadromous	Inland	
Illinois	1,726	810	0	13,869	16,404
Indiana	714	308	614	11,514	13,150
Michigan	1,967	4,113	1,383	21,986	29,450
Minnesota	162	40	19	24,557	24,778
New York	773	1,553	922	15,515	18,764
Ohio	340	2,179	501	11,703	14,723
Pennsylvania	152	374	272	24,637	25,435
Wisconsin	2,359	1,691	358	27,003	31,411
Total	8,193	11,070	4,070	150,783	174,115

¹ The figures in this table were originally reported in Ready et al. (2018).

Table 2. Effects of bighead and silver carp on annual recreational fishing participation (1000s of days) and consumer surplus (CS) (\$1000s) under the worst-case and best-case scenarios.

State of Residence	Worst-case Scenario				Best-case Scenario			
	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)
Illinois	-0.68%	-163.2	-\$91.66	-\$55,515	-0.07%	-17.0	-\$9.55	-\$5,781
Indiana	-0.30%	-41.9	-\$43.13	-\$14,321	-0.03%	-4.5	-\$4.65	-\$1,543
Michigan	-0.28%	-78.1	-\$33.14	-\$26,704	0.09%	26.1	\$11.03	\$8,885
Minnesota	-0.01%	-2.2	-\$0.72	-\$742	-0.01%	-2.0	-\$0.68	-\$695
New York	-0.18%	-33.7	-\$19.57	-\$11,539	-0.03%	-6.3	-\$3.64	-\$2,144
Ohio	0.05%	8.0	\$5.27	\$2,745	0.14%	22.5	\$14.75	\$7,680
Pennsylvania	-0.01%	-1.3	-\$0.71	-\$454	0.00%	-0.6	-\$0.34	-\$219
Wisconsin	-0.39%	-94.3	-\$44.12	-\$32,144	-0.03%	-6.7	-\$3.15	-\$2,297
Totals	-0.23%	-406.6	-\$26.45	-\$138,673	0.01%	11.3	\$0.74	\$3,885

Table 3. Change in number (1000s of days) and percentage of fishing trips by fishing type for the worst-case and best-case scenarios for each AIS.

AIS	Change in Fishing Trips				Total
	Great Lakes Coldwater	Great Lakes Warmwater	Anadromous	Inland	
Bighead and Silver Carp					
Worst case	-5,875.6 -71.72%	946.7 8.55%	-439.5 -10.80%	4,955.0 3.29%	-413.4 -0.24%
Best Case	-891.9 -10.89%	1,022.3 9.24%	-83.8 -2.06%	-34.7 -0.02%	11.9 0.01%
Northern Snakehead					
Worst case	-788.5 -9.62%	-870.4 -7.86%	21.0 0.52%	1,495.3 0.99%	-142.6 -0.08%
Best Case	0.0 0.0%	0.0 0.0%	0.0 0.0%	0.0 0.0%	0.0 0.0%
Grass Carp					
Worst case	82.4 1.01%	-826.6 -7.47%	47.5 1.17%	634.8 0.42%	-61.8 -0.04%
Best Case	39.3 0.48%	-393.0 -3.55%	22.4 0.55%	301.7 0.20%	-29.6 -0.02%
Hydrilla					
Worst case	130.1 1.59%	-1,389.1 -12.55%	75.1 1.84%	1,080.0 0.72%	-104.0 -0.06%
Best Case	-117.5 -1.43%	1,162.0 10.50%	-65.8 -1.62%	-890.0 -0.59%	88.6 0.05%
Quagga Mussel					
Worst Case	-5,225.2 -63.78%	562.3 5.08%	-325.8 -8.01%	4,605.1 3.05%	-383.5 -0.22%
Best Case	0.0 0.0%	0.0 0.0%	0.0 0.0%	0.0 0.0%	0.0 0.0%

State of Residence	Worst-case Scenario				Best-case Scenario			
	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)
Illinois	-0.10%	-22.9	-\$12.86	-\$7,792	0.0%	0.0	\$0.00	\$0
Indiana	-0.04%	-5.2	-\$5.33	-\$1,771	0.0%	0.0	\$0.00	\$0

Michigan	-0.20%	-54.8	-\$23.23	\$18,722	0.0%	0.0	\$0.00	\$0
Minnesota	-0.01%	-2.7	-\$0.90	-\$920	0.0%	0.0	\$0.00	\$0
New York	-0.04%	-7.1	-\$4.13	-\$2,434	0.0%	0.0	\$0.00	\$0
Ohio	-0.16%	-25.8	-\$16.98	-\$8,841	0.0%	0.0	\$0.00	\$0
Pennsylvania	-0.01%	-2.6	-\$1.42	-\$902	0.0%	0.0	\$0.00	\$0
Wisconsin	-0.08%	-18.5	-\$8.64	-\$6,292	0.0%	0.0	\$0.00	\$0
Totals	-0.08%	-139.5	-\$9.09	\$47,673	0.0%	0.0	\$0.00	\$0

Table 4. Effects of northern snakehead on annual recreational fishing participation (1000s of days) and consumer surplus (CS) (\$1000s) under the worst-case and best-case scenarios.

Table 5. Effects of grass carp on annual recreational fishing participation (1000s of days) and consumer surplus (CS) (\$1000s) under the worst-case and best-case scenarios.

State of Residence	Worst-case Scenario				Best-case Scenario			
	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)
Illinois	-0.04%	-10.6	-\$5.96	-\$3,607	-0.02%	-5.2	-\$2.93	-\$1,773
Indiana	-0.01%	-2.1	-\$2.11	-\$701	-0.01%	-1.0	-\$1.03	-\$341
Michigan	-0.07%	-19.3	-\$8.16	-\$6,575	-0.03%	-9.3	-\$3.92	-\$3,162
Minnesota	0.00%	-0.4	-\$0.13	-\$129	0.00%	-0.1	-\$0.05	-\$47
New York	-0.04%	-7.5	-\$4.36	-\$2,568	-0.02%	-3.2	-\$1.84	-\$1,087
Ohio	-0.08%	-13.0	-\$8.56	-\$4,457	-0.04%	-6.5	-\$4.28	-\$2,228
Pennsylvania	0.00%	-0.8	-\$0.44	-\$279	0.00%	-0.4	-\$0.22	-\$137
Wisconsin	-0.03%	-6.8	-\$3.19	-\$2,324	-0.01%	-3.2	-\$1.50	-\$1,093
Totals	-0.04%	-60.4	-\$3.94	-\$20,640	-0.02%	-28.9	-\$1.88	-\$9,867

Table 6. Effects of hydrilla on annual recreational fishing participation (1000s of days) and consumer surplus (CS) (\$1000s) under the worst-case and best-case scenarios.

State of Residence	Worst-case Scenario				Best-case Scenario			
	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)
Illinois	-0.07%	-16.5	-\$9.31	-\$5,639	0.07%	15.9	\$8.97	\$5,433
Indiana	-0.02%	-2.9	-\$3.02	-\$1,002	0.02%	3.0	\$3.12	\$1,036
Michigan	-0.14%	-39.9	-\$16.88	-\$13,600	0.10%	26.9	\$11.38	\$9,173

Minnesota	0.00%	-0.5	-\$0.15	-\$156	0.00%	0.5	\$0.15	\$154
New York	-0.05%	-9.6	-\$5.56	-\$3,279	0.05%	9.7	\$5.62	\$3,313
Ohio	-0.12%	-19.6	-\$12.85	-\$6,693	0.12%	19.5	\$12.80	\$6,667
Pennsylvania	0.00%	-1.2	-\$0.64	-\$405	0.00%	1.2	\$0.67	\$423
Wisconsin	-0.05%	-11.8	-\$5.54	-\$4,040	0.04%	9.9	\$4.63	\$3,375
Totals	-0.06%	-102.0	-\$6.64	-\$34,814	0.05%	86.6	\$5.64	\$29,574

Table 7. Effects of quagga mussel on annual recreational fishing participation (1000s of days) and consumer surplus (CS) (\$1000s) under the worst-case and best-case scenarios.

State of Residence	Worst-case Scenario				Best-case Scenario			
	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)	Percent Change Fishing Days	Change in Total Fishing Days (1000s)	Average CS Change per Angler (\$)	Total CS Change (\$1000s)
Illinois	-0.68%	-162.4	-\$91.23	-\$55,252	0.0%	0.0	\$0.00	\$0
Indiana	-0.30%	-41.4	-\$42.62	-\$14,154	0.0%	0.0	\$0.00	\$0
Michigan	-0.28%	-78.2	-\$33.18	-\$26,739	0.0%	0.0	\$0.00	\$0
Minnesota	0.00%	-0.1	-\$0.04	-\$37	0.0%	0.0	\$0.00	\$0
New York	0.00%	0.0	\$0.00	\$0	0.0%	0.0	\$0.00	\$0
Ohio	0.00%	0.0	\$0.00	\$0	0.0%	0.0	\$0.00	\$0
Pennsylvania	0.00%	0.0	\$0.00	\$0	0.0%	0.0	\$0.00	\$0
Wisconsin	-0.39%	-94.4	-\$44.16	-\$32,178	0.0%	0.0	\$0.00	\$0
Totals	-0.21%	-376.5	-\$24.49	-\$128,360	0.0%	0.0	\$0.00	\$0