Using decision analysis to collaboratively respond to invasive species threats: a case study of Lake Erie grass carp (*Ctenopharyngodon idella*)

Kelly F. Robinson[1,*], Mark DuFour[2,] Michael Jones[3], Seth Herbst[4], Tammy Newcomb[5], James Boase[6], Travis Brenden[7], Duane Chapman[8], John Dettmers[9], James Francis[10], Travis Hartman[11], Patrick Kočovský[12], Brian Locke[13], Christine Mayer[14], Jeff Tyson[15]

[1] Quantitative Fisheries Center, Department of Fisheries and Wildlife, Michigan State University, 480 Wilson Road, East Lansing, MI, 48824, USA, kfrobins@msu.edu, telephone: (517) 884-8872, fax: (517) 432-1699

[2] Quantitative Fisheries Center, Department of Fisheries and Wildlife, Michigan State University, 480 Wilson Road, East Lansing, MI, 48824; Present address: Ohio Department of Natural Resources, Division of Wildlife, Sandusky Fisheries Research Station, 305 East Shoreline Drive, Sandusky, OH, 44870, USA, mark.dufour@dnr.state.oh.us

[3] Quantitative Fisheries Center, Department of Fisheries and Wildlife, Michigan State University, 480 Wilson Road, East Lansing, MI, 48824, USA, jonesm30@msu.edu

[4] Michigan Department of Natural Resources, Fisheries Division, Lansing, MI, USA, HerbstS1@michigan.gov

[5] Michigan Department of Natural Resources, Lansing, MI, USA, newcombt@michigan.gov

[6] United States Fish and Wildlife Service, Alpena Fish and Wildlife Conservation Office, 9311 Groh Road, Grosse Ille, MI, 48138, USA, james_boase@fws.gov

[7] Quantitative Fisheries Center, Department of Fisheries and Wildlife, Michigan State University, 480 Wilson Road, East Lansing, MI, 48824, USA, brenden@msu.edu

[8] Columbia Environmental Research Center, United States Geological Survey, Columbia, MO, 65201, USA, dchapman@usgs.gov

[9] Great Lakes Fishery Commission, 2100 Commonwealth Blvd., Suite 100, Ann Arbor, MI, 48105, USA, jdettmers@glfc.org

[10] Michigan Department of Natural Resources, Fisheries Division, Waterford Field Office, Waterford, MI, USA, francisj@michigan.gov

[11] Ohio Department of Natural Resources, Division of Wildlife, Sandusky Fisheries Research Station, 305 East Shoreline Drive, Sandusky, OH, 44870, USA, travis.hartman@dnr.state.oh.us

[12] Lake Erie Biological Station, United States Geological Survey, 6100 Columbus Avenue, Sandusky, OH, 44870, USA, pkocovsky@usgs.gov

[13] Ontario Ministry of Natural Resources and Forestry, Lake Erie Management Unit, Wheatley, Ontario, Canada, brian.locke@ontario.ca

[14] Department of Environmental Sciences, Lake Erie Center, University of Toledo, 6200 Bay Shore Rd., Oregon, OH, 43616, USA, christine.mayer@utoledo.edu

[15] Great Lakes Fishery Commission, 2100 Commonwealth Blvd., Suite 100, Ann Arbor, MI, 48105, USA, jtyson@glfc.org

Abstract

Decisions about invasive species control and eradication can be difficult because of uncertainty in population demographics, movement ecology, and effectiveness of potential response actions. These decisions often include multiple stakeholders and management entities with potentially different objectives, management priorities, and jurisdictional authority. We provide a case study of using multi-party, collaborative decision analysis to aid decision makers in determining objectives and control actions for invasive grass carp (*Ctenopharyngodon idella*) in Lake Erie. Creating this process required binational (Fisheries and Oceans Canada, United States Fish and Wildlife Service, U. S. Geological Survey) and multi-state/provincial collaboration to craft a shared problem statement, establish objectives related to ecological, economic, and social concerns, determine potential response actions, and evaluate consequences and tradeoffs of these actions. We used participatory modeling and expert elicitation to evaluate the effectiveness of control scenarios that varied in action type (i.e., removal efforts and spawning barriers) and the temporal and spatial application of these actions. We found that removal efforts concentrated in areas of high catchability, when paired with a spawning barrier on the Sandusky River, Ohio, USA, could effectively control grass carp in Lake Erie, if all assumptions are met. We determined a set of key uncertainties regarding gear catchability and current population size that have led to the transition to an adaptive management process. In addition, our work formed the basis for grass carp management plans for the states of Michigan and Ohio and has provided a means for collaboration among agencies for effective application of control efforts.

Keywords: structured decision making, uncertainty, grass carp, Great Lakes, fishery management

Introduction

Uncertainty is common in natural resources management but can be particularly challenging when making decisions about how to control or eradicate an invasive species. Invasive species' ecology and demographics often are considerably different in invaded systems than in native regions (Johnson et al. 2017), which can result in uncertainties regarding species' effects in these systems and effective control methods. These uncertainties can be more problematic when species invasions occur in a large, multi-jurisdictional aquatic ecosystem like the Laurentian Great Lakes, because agency coordination related to objectives for eradication, as well as data collection and analysis, might be minimal or difficult. Decisions about how to control or eradicate a species, therefore, often are made under extreme uncertainty (Runge et al. 2011b), social indeterminism (Tyre and Michaels 2011, Michaels and Tyre 2012), and multi-jurisdictional complexity. Uncoordinated management actions and ecological uncertainties can lead to confusion when making decisions and prioritizing for control and eradication efforts, as well as to the inefficient use of often limited financial and personnel resources. In addition, if jurisdictions do not typically work together in making management decisions, management turbulence could lead to uncertainty in the outcome, as authorities might not share a common set of values (Tyre and Michaels 2011).

Multi-party collaborative decision making processes provide a framework to collectively provide guidance for invasive species response efforts (Blomquist et al. 2010; Johnson et al. 2017). A multi-party collaboration combined with the framework of decision analysis (i.e., structured decision making and adaptive management) can allow groups to work cooperatively to define the problem, an agreed-upon set of objectives, and a series of potential control actions (Failing et al. 2013; Hammond et al. 1999). The group can then use methods of participatory modeling to predict the consequences of actions on each objective (Robinson and Fuller 2017) and carefully consider tradeoffs among objectives for arriving at a common set of goals and actions for invasive species response efforts. Critically, the decision analytic process requires the explicit articulation of uncertainties that could affect decisions (Failing et al. 2013; Haeseker et al. 2007; Hammond et al. 1999; Runge et al. 2011b). Through decision analysis, the group can determine which uncertainties are key for decision making (i.e., would affect the decision being made), and therefore should be resolved through an adaptive management process (Runge et al. 2011a).

We present a framework for collaboratively responding to aquatic invasive species in the Laurentian Great Lakes. This region necessitates concerted collaborative efforts because of both the multi-jurisdictional nature of fisheries management in the lakes and the tremendous social and economic value of the resources. In addition, it provides a unique example of a shared governance structure, the Joint Strategic Plan for Management of Great Lakes Fisheries (GLFC 2007), which helped reduce the socially generated indeterminism that can plague the management of social ecological systems (Michaels and Tyre 2012). Here, we provide a case study of using structured decision making in a multi-party, collaborative process for the enactment of control actions to suppress grass carp (*Ctenopharyngodon idella*) in Lake Erie; the ultimate goal being eradication of the species. This collaborative effort included representatives from three federal agencies, five state agencies, one provincial agency, four academic institutions, and one binational commission, all of whom formed the formal working group for this process. Although our case study is specific to grass carp in Lake Erie, the methods that we describe are directly applicable to other aquatic invaders in the Great Lakes ecosystem, or to other multi-jurisdictional systems where uncertainty and lack of coordination can undermine invasive species response efforts.

Establishment of the four major Chinese carps (i.e., black carp [*Mylopharyngodon piceus*], silver carp [*Hypophthalmichthys molitrix*], bighead carp [*H. nobilis*], and grass carp) poses great risks to the Great Lakes ecosystem, including damage to the lakes' ecosystems and important recreational and commercial fisheries (Clapp et al. 2012; Cudmore et al. 2012; Cudmore et al. 2017). Grass carp, in particular, pose an immediate threat to Lake Erie's coastal wetlands and shorelines, as well as the Great Lakes as a whole, because grass carp have been collected from four of the lakes (Cudmore et al. 2017). In addition, reproductively viable grass carp have been captured in lakes Erie and Ontario, and naturalized spawning has been observed in two Lake Erie tributaries (Chapman et al. 2013; ACRCC 2016; Wieringa et al. 2016; USGS 2019). The pathways for introduction of grass carp into Lake Erie are unknown, but likely stem from human-mediated release (Cudmore et al. 2017). Possession of grass carp is illegal in Minnesota, Wisconsin, Michigan, and Ontario; whereas, various state-level regulations allow either culture or possession of triploid (i.e., sterile) individuals in other states that border the Great Lakes (MICRA 2015). Despite these regulations on the possession of diploid individuals, grass carp are spawning in the Sandusky and Maumee rivers in Ohio (Embke et al. 2016; USGS 2019).

The threat of grass carp establishment and spread in the Great Lakes poses both ecological and economic risks (Cudmore et al. 2017). Grass carp consume vegetation, including submerged aquatic macrophytes, necessary for native fish spawning and recruitment (Chapman et al. 2013; Wittman et al. 2014). Removal of vegetation can also alter nesting habitat for waterfowl (Chapman et al. 2013; McKnight and Hepp 1995) and cause declines in biological productivity, energy flow through ecosystems, and supply of detritus (Chapman et al. 2013; Herdendorf 1987), as well as increases in turbidity (Cudmore et al. 2017). From an economic perspective, large-bodied grass carp can damage commercial and recreational fishing gear and the spawning grounds of ecologically and economically valuable species (Chapman et al. 2013). The ability of grass carp to remove vegetation can cause economic damages stemming from shoreline erosion, water management, accumulation of sediments (Herdendorf 1987), and nonpoint source pollution (Mitsch 1992). Given these ecological and economic concerns, effective response efforts for grass carp in Lake Erie are needed. However, uncertainties about the population dynamics of this species and the effectiveness of control actions, as well as the complexities of invasive species response efforts in Lake Erie, creates a difficult landscape for successfully making decisions for grass carp control.

The objectives of our study were to 1) use the structured decision making framework to aid decision makers in agencies around Lake Erie to determine effective strategies for grass carp suppression, 2) identify key uncertainties in the system that would affect grass carp control decisions, and 3) provide a framework for managers and biologists from Lake Erie to collaborate effectively for the control of an invasive species.

Methods

Study Area

Although grass carp have been captured throughout Lake Erie, the majority of captures have been in the lake’s western basin (Cudmore et al. 2017), where reproduction has been detected. As such, the working group agreed that the decision analysis would focus on western Lake Erie (Figure 1), with consideration given to the possibility that fish might migrate out of the western basin.

Overview of Decision Analysis

The steps of collaborative decision analysis include working cooperatively to define the problem, identify the relevant objectives and a set of management alternatives to achieve the objectives, predict the consequences of each action on each objective, and evaluate tradeoffs among objectives (Figure 2; Hammond et al. 1999). These steps can be iterative, in that results from a particular step might require the group to revisit previous steps. In addition, the process of decision analysis provides a structured framework for identifying key uncertainties that might hinder management decision making (Hammond et al. 1999; Runge et al. 2011a). In our case study, the team of managers and biologists, facilitated by decision analysts with backgrounds in quantitative fisheries management (hereafter, the "working group"), worked through each of these steps in three 2-day workshops in 2016 and 2017, interspersed with electronic communication. Additionally, because of the multi-jurisdictional nature of the problem, each workshop also included an opportunity for members of the working group to provide updates about their research and control efforts for grass carp in Lake Erie. These updates included grass carp collection efforts at egg, larval, and adult life stages, environmental DNA sampling, targeted capture efforts and rapid response actions, acoustic telemetry investigations into adult movement and spatial ecology (Harris et al. in press), otolith microchemistry, and population genetics.

Here we present the methods associated with each step of the decision analytic process (i.e., problem, objectives, alternatives, consequences, and tradeoffs). We also present the problem statement, the objectives that were elicited from the working group, and the alternatives that were generated. We then describe the methods that we used in the consequences step to predict the ability of each alternative to achieve the stated objectives, as well as in the tradeoffs step to consider differential achievement of objectives under different alternatives.

Problem statement

A clearly defined problem provides the backbone for each subsequent step in a decision analytic framework and ensures that all members of the working group understand the nature of the problem (Hammond et al. 1999). The working group laid out all aspects of the Lake Erie grass carp problem at hand during the first workshop, including the scope of the problem, the triggers for the problem, identification of the stakeholders and decision maker(s), and relevant legal, regulatory, and resource constraints.

State, provincial, and federal agencies around Lake Erie were concerned about the potential detrimental effects of grass carp on the Lake Erie ecosystem and the Great Lakes as a whole. These concerns were related to the increased numbers of reported grass carp captures in recent years, particularly in western Lake Erie, the presence of reproductively viable fish in the region (Wieringa et al. 2016), the presence of fertilized grass carp eggs in the Sandusky and Maumee rivers (Embke et al. 2016; USGS 2019), and recruitment of juveniles from the Sandusky River (Chapman et al. 2013). Based on these concerns, the members of the working group identified stakeholders who could be directly affected by grass carp (e.g., recreational and commercial fishers, stakeholders with waterfowl interests, and conservation groups), contribute to scientific understanding (e.g., managers and researchers), develop and communicate policies (e.g., policy analysts/developers and media), and could be indirectly affected by policy changes (e.g., aquaculture industry, pond management users, live food markets, and shipping industry). The responsibility for addressing this problem falls within the purview of many jurisdictions, as well as multiple governmental and institutional levels, as the extent of potential grass carp invasion is larger than Lake Erie (i.e., the broader Great Lakes and St. Lawrence River). Ultimately, the problem was defined as a need to develop a strategy for controlling grass carp in Lake Erie to socially and environmentally acceptable levels (Figure 2).

Objectives and Measurable Attributes

In a decision analytic process, objectives represent the values of the stakeholders and decision maker(s) (Gregory and Keeney 1994; Hammond et al. 1999). These objectives are often hierarchical in nature, with fundamental objectives that represent the ultimate goals of the group, and means objectives, which describe how to achieve the fundamental objectives (Gregory et al. 2012; Conroy and Peterson 2013). In addition to defining objectives, measurable attributes for each objective must be described so that achievement of each objective can be measured. The working group defined fundamental and means objectives that were relevant to the identified stakeholders in the Lake Erie basin. These objectives were related to ecological, economic, and social values associated with grass carp, including the effects of both the invasive species itself, as well as the effects of potential control actions on the ecosystem and stakeholders (i.e., collateral damage; Blomquist et al. 2010; Johnson et al. 2017).

The objectives hierarchy was comprised of three fundamental and five means objectives (Figure 3). The first fundamental objective was to fulfill public trust responsibility, with means objectives of 1) minimizing the abundance and risk of spread of grass carp within Lake Erie and into other lakes and 2) minimizing the ecosystem engineering effects of grass carp within Lake Erie. Risk of spread was defined as the potential for colonization of areas outside Lake Erie's western basin. Although information is available about grass carp movement within and outside the western basin from ongoing telemetry studies (Harris et al. in press), there nevertheless remains substantial uncertainty about population-level emigration rates of grass carp from and available habitat outside of the western basin. Consequently, the working group decided that a grass carp density of greater than 10 fish per hectare of foraging habitat would lead to a substantial risk of spread. This measure was chosen based on the results of the Binational Grass Carp Risk Assessment, which indicated that ecological effects of the species would be minimal below this density (Cudmore et al. 2017). Foraging habitat was defined as high-quality low-marsh habitat based on Great Lakes Low Marsh Inventory (GLLMI) layers (Gertzen et al. 2017). Likewise, the same metric of 10 fish per hectare of foraging habitat was used as a target threshold for the objective of minimizing abundance of grass carp. Ecosystem engineering effects included food web effects, erosion, and changes in the plant community, which were all related to vegetation biomass. Therefore, ecosystem engineering effects were measured as vegetation biomass consumption (DuFour et al. in review), estimated using established relationships between grass carp biomass and vegetation consumption from bioenergetics models (van der Lee et al. 2017).

We used the four-point method (Speirs-Bridge et al. 2010) and the modified Delphi approach (Kuhnert et al. 2010), a structured approach for expert elicitation, to determine the threshold vegetation loss beyond which experts believed detrimental effects on the ecosystem would arise. Experts from the working group were provided with background information and asked to answer a series of questions via email. Experts were asked four questions:

1) what is the minimum percent vegetation loss from baseline values that would result in negative effects on the ecosystem,
2) what is the maximum percent loss that would result in negative effects,
3) what is your best guess of the percent vegetation loss that would result in negative effects, and

4) how confident are you that the true value falls within your minimum and maximum estimates?

Experts also answered the same four questions related to the frequency of years of exceedance of this threshold that would lead to sustained impairment of the vegetated marsh ecosystem over three different time frames (i.e., 5, 10, and 25 years). Experts discussed the results in a workshop setting and were allowed the opportunity to change their answers if desired. We calculated the mean and 95% confidence intervals for threshold vegetation loss by assuming that the percent confidence provided by each expert was followed a beta distribution with a mean of the "best guess" (Cohen et al. 2016; Robinson et al. 2016). We then drew random samples from each distribution (one distribution per expert) and averaged across random draws to generate an average distribution, weighting equally across participants. Ultimately, the group concluded that a reasonable threshold of vegetation loss was 34% (95% CI = 26–43%).

The second fundamental objective was to minimize the management costs associated with grass carp control (Figure 3). Although members of the working group agreed that invasive species control in general, and grass carp control specifically, will incur costs, all acknowledged that funding and staffing for fishery management agencies can be a limiting factor and therefore should be considered in the decision-making framework, such that funds can be spent as efficiently as possible. Additionally, the group agreed that money spent was a metric that encapsulated a range of costs such as base funding, external grants, staff salaries and fringe benefits, and equipment purchase and maintenance. Therefore, the means objective for minimizing costs was to minimize money spent, measured as the probability and frequency of annually exceeding a set amount of money. However, further discussion indicated that predicting annual grass carp management-related funding would be difficult to impossible. Therefore, we used a relatively small cost metric (US$84,000 per year) based on expert elicitation. Although members recognized this as a low value and that true funding would be more fluid in the future, using a set value allowed us to explore incorporation of a cost metric with established future funding and determine the effect of a low amount of funding on the probability of exceeding the threshold density of grass carp.

The third fundamental objective was to minimize the collateral damage of grass carp control strategies, with means objectives of avoiding economic stress to stakeholders and minimizing the effects on native ecosystems (Figure 3). This fundamental objective was created to acknowledge that control actions for grass carp could have detrimental effects on stakeholders, whether monetarily or in terms of their ability to recreate in desired locations, detrimental effects on other species in the ecosystem, via reduced ability to complete spawning migrations or direct mortality, and could be perceived negatively by stakeholders. For example, walleye (*Sander vitreus*) commercial and recreational harvest is of major socio-economic importance in Lake Erie (2018 harvest in western Lake Erie: 2.65 million individuals; Wills et al. 2019) and would be negatively affected by a physical barrier in the study rivers during their spawning migrations. We measured each attribute on a scale that ranged from a major negative effect (-2) to a major positive effect (2). The attributes for economic stress were effects on commercial (e.g., shipping traffic, bait harvesters, grass carp aquaculture facilities) and recreational (e.g., boaters, fishers) stakeholders. Effects on native ecosystems were measured as effects on migratory species whose life history would be negatively affected by a management action and potential non-target mortality to threatened and endangered species, as well as public sentiment (e.g., piscicide use would be viewed negatively).

Alternatives

The goal of the alternatives step is to describe the set of possible actions, or combinations of actions, that could be implemented to achieve the stated objectives (Hammond et al. 1999). In decision analysis, working groups are asked to be creative and determine all possible actions before limiting themselves to feasibility or uncertainty. For the grass carp case study, the working group identified 20 different potential actions, which ranged from currently used strategies (e.g., incentives for commercial fishers to harvest and report grass carp) to strategies that were not yet feasible and with greater uncertainty in effectiveness (e.g., genetic control). Because of the large number of alternatives and the uncertainty regarding their effectiveness and feasibility, we grouped the actions into categories and focused on actions that were feasible in the near-term. The final list of actions included removal (e.g., direct capture, harvest incentives, chemical control), physical or behavioral barriers, flow modifications, and elimination of grass carp sources (Table 1).

Discussion among working group members during the alternatives phase highlighted the depth and breadth of uncertainty inherent in grass carp control, and aquatic invasive species response efforts more generally. When describing potential control actions, members of the group often articulated uncertainties related to an action, as well as the specific research areas that should be addressed. Based on these uncertainties, we evaluated four hypothetical scenarios for the consequences stage, rather than formally evaluating each of the management actions in Table 1 individually (DuFour et al. in review). These scenarios were chosen to represent actions that were likely to be implemented in the near future, or that would provide the working group with an understanding of how actions could be combined to potentially increase effectiveness. Scenario 1 (“Take No Management Action”), provided a baseline set of predictions for grass carp population growth without implementation of control actions. Importantly, Scenario 1 was not the same as a "status quo" scenario, because control actions were ongoing in Lake Erie. Scenario 2 was to distribute efforts for removal of grass carp equally across seasons and habitats in western Lake Erie based on current best available information ("Distributed Removal"). Scenario 3 consisted of more concentrated removal efforts in river/wetland habitats during seasons that were predicted by experts to have greater catchability ("Concentrated Removal"). Scenarios 2 and 3, therefore, differed in spatial and temporal allocation of actions, but not in total effort implemented (DuFour et al. in review). Scenario 4 combined the capture techniques of Scenario 3 with a moderately efficient hypothetical barrier ("Removal + Barrier"), which would reduce the movement of fish upstream for spawning by 50%. All of these scenarios assumed that actions targeted age-3 and older individuals, which was the minimum age class that was typically encountered in the field. It is important to note, we did not change any demographic parameters within the population model (see below) between scenarios, but rather where and when effort was applied. Effort (*f*) was more or less efficient depending on whether it was applied in a high catchability area (nearshore/tributary habitat; q_{high}) or a low catchability area (open lake/offshore habitats; q_{low}), following Bayley and Austen (2002). The annual survival was affected by adding fishing mortality ($F = q_j * f$) to natural mortality in targeted regions and seasons. To mimic a barrier, we changed the migration rate into the Sandusky during spring to summer to allow only half (50%) of potential spawners to reproduce.

Consequences

The consequences step requires predicting the effects of each potential action on each objective in terms of the measurable attributes. We used a combination of participatory modeling and expert elicitation to make predictions for each of our four scenarios (Figure 2).

We created a spatially-explicit periodic matrix population model to simulate the effects of management actions on grass carp density throughout the western basin of Lake Erie to measure achievement of the public trust fundamental objective (Figure 3; DuFour et al. in review). Our model added seasonal and spatial components to the matrix model created by Jones et al. (2017) for the binational risk assessment of grass carp in the Great Lakes. The model included five age groups: age-1 through age-4 juveniles and age-5+ adults. The matrix model was structured to allow individuals to move among three regions of the western basin, each of which was comprised of both riverine and nearshore lake habitat, as well as a fourth, “unknown” region that represented emigration from western Lake Erie. The three regions represented the three river systems that would most likely provide suitable spawning habitat for grass carp (Kočovský et al. 2012): 1) the Sandusky River and Lake Erie Islands region, 2) the Maumee River and Ohio Lake Region, and 3) the River Raisin and Michigan Lake Region (Figure 1). Each region included two habitat types, river and nearshore, for a total of eight “areas”. The matrix model included four seasons (spring, summer, fall, and winter) that represented three-month time steps, in which fish could move among areas for reproduction and feeding. We chose these seasons to represent the annual feeding and reproductive cycle of grass carp. The initial population abundance for the model was determined via expert elicitation, as the total abundance of grass carp in Lake Erie was unknown (see DuFour et al. in review).

The model allowed adults to move into individual rivers for spawning in the spring, based on the probability of suitable spawning conditions (i.e., ideal temperature and flows) in each river as defined in Kočovský et al. (2012), and back into nearshore areas in the fall to feed. To represent stochastic uncertainty in reproduction in the system, suitable spawning conditions were characterized as a probability (p = 0.68 in the Sandusky River, p = 0.84 in the Maumee

River, and $p = 0.05$ in the River Raisin); therefore, these conditions did not necessarily occur each year in model runs. The model included various statistical distributions (e.g., beta distributions to describe survival rates) to incorporate parametric uncertainty into the decision-making process. The model included population vectors and population projection and movement matrices, which were combined to simulate the regional abundance of grass carp on a seasonal time step. The model used for our case study is described in full in DuFour et al. (in review).

We used the matrix population model to predict grass carp density in foraging habitat after 60 years of implementation of each of the four scenarios, as well as the probability of maintaining population density below 10 fish per hectare under each scenario, defined as the proportion of the distribution of outcomes from 1,000 stochastic runs of the model that fell below the threshold density.

The results of this model were then used, in combination with predicted area of forage habitat (Gertzen et al. 2017), published estimates of vegetation biomass (Duarte and Kalff 1990), and grass carp consumption rates (van der Lee et al. 2017), to predict the proportion of vegetation that would be lost through time via grass carp consumption. We averaged the minimum and maximum values of predicted forage habitat reported in Gertzen et al (2017) to account for uncertainty, with the exception of the model region that included Sandusky Bay. Working group members believed that the maximum estimate from Gertzen et al. (2017) was not realistic, with many participants repeatedly stating that aquatic macrophytes do not cover the entire bay. As a compromise, the working group decided to use an estimate (3,000 ha) that was between the means for the other two regions (1,500 ha each) and the region including Sandusky Bay (~7,000 ha). The biomass estimates included the uncertainty observed in biomass-area relationships from Duarte and Kalff (1990). This study sampled a range of habitats and environmental conditions that included highly productive areas similar to Lake Erie's western basin. Although this study did not include samples from our study area, the working group viewed these samples as representative of biomass fluctuations in this system. By including uncertainty in these data, we buffered our results against error associated with fluctuating environmental conditions over time.

We used expert elicitation to determine the effects of grass carp control activities on the measurable attributes of the collateral damage fundamental objective (Figure 3): effects on recreational and commercial stakeholders, migratory fishes, threatened and endangered species, and public sentiment. Unlike the objectives related to grass carp abundance, we elicited the effects of seven individual activities on each of these attributes: direct capture, harvest incentives for commercial fishers, chemical control, behavioral barrier, physical barrier, flow modifications, and reduction of inputs of grass carp into the system. We asked experts to use the direct rating technique (Goodwin and Wright 2009) to determine the relative effect of each action each attribute. These ratings ranged from a major negative effect (score of -2) to a major positive effect (score of 2) and were elicited for eight combinations of season (spring, summer, winter, and fall) and habitat (river or lake). Experts were initially asked to provide responses via email, through a questionnaire that provided background information and explicit instructions. We then used a modified Delphi approach (Kuhnert et al. 2010), in which experts discussed their responses during a workshop and changed their answers if necessary, to determine the final predictions for each attribute. We averaged the experts' responses to obtain an overall rating for each activity in each habitat and season. The season- and habitat-specific ratings for activities that were included in a given scenario were then averaged to determine a score for the overall scenario. For example, Scenario 3 included direct capture that occurred in the lake in spring, fall, and winter, and in the river in the summer, so the ratings for these four seasons and habitats were averaged (see Table S1 for all ratings).

We used a constraint of US$84,000 per year for the measurable attribute for minimizing management costs. In initial population model simulations, we found that this amount of funding, which assumed that 1 km of shoreline could be sampled one time for US$1000 based on the group's expert knowledge, rendered all scenarios ineffective. Therefore, in our final simulations, we assumed that scenarios would include 500 units of effort to potentially increase effectiveness of actions, similar to DuFour et al. (in review). We also used literature-reported catchability values, for nearshore/tributary habitats (q_{high}) and open lake/offshore habitats (q_{low}), to translate effort to captures (Bayley and Austen 2002).

Tradeoffs

The final step of the decision analysis framework is to evaluate tradeoffs among objectives, because no one management alternative is likely to best achieve all of the stated objectives (Figure 2; Hammond et al. 1999). This step often includes methods like weighted averages, or expected utility scores, which summarize each predicted action into single score for comparison of scores among alternatives. In our case study of Lake Erie grass carp, the decision analysis focused on four hypothetical scenarios that varied in the type of control action and the spatial and temporal application of these actions. We elected to use the results of these scenarios to stimulate discussion about predicted outcomes and potential effects of assigning different weighting schemes to the objectives. We created a consequence table that included the average predicted results, normalized to a 0 – 1 scale, for each combination of objective and action scenario. We polled the working group during the workshop to determine a set of objective weights. We calculated the expected utility score (*E[U]*) for each alternative as:

$$E(U) = w_{Public\ trust}(w_{Spread\ risk} * U_{Spread\ risk} + w_{Vegetation\ loss} * U_{Vegetation\ loss}) + w_{Cost} * U_{Cost} + W_{Collateral\ damage}(w_{Rec.\ users} * U_{Rec.\ users} + w_{Commercial\ users} * U_{Commercial\ users} + w_{Migratory} * U_{Migratory} + w_{T\&E\ species} * U_{T\&E\ species} + w_{Public\ sentiment} * U_{Public\ sentiment}), \quad \text{Equation 1}$$

where *w* is the weight on each fundamental or means objective and *U* is the normalized utility score for an objective, with subscripts describing each objective; T&E is "threatened and endangered", and Rec. is "recreational". The scenario with the greatest expected utility score was the "optimal" scenario. We focused on the 25- and 50-year timeframes for the risk of spread / reduce abundance and risk of vegetation loss means objectives. Results of this process provided a framework for the group to discuss potential tradeoffs among objectives, as well as implications associated with the many uncertainties that were revealed during the decision analytic process.

Uncertainty and Sensitivity

During the course of three workshops, participatory modeling efforts, and analyses of tradeoffs, we found many sources of uncertainty, some of which would affect the decision that is made. These uncertainties were related to potential effectiveness of individual control actions, aspects of grass carp demographics in their non-native habitat like population size, survival rates, and the stock-recruitment relationship (formally evaluated in DuFour et al. in review), as well as estimates of potential funding for control efforts. In particular, fishing mortality and reduction in spawning success, both of which were evaluated in the four scenarios, could be affected by key uncertainties related to gear catchability, barrier effectiveness, and frequency of discharge events that are suitable for grass carp spawning. We explored the implications of these uncertainties through a series of population model simulations that varied the effectiveness of these control actions. We predicted the density of grass carp in western Lake Erie under seven different levels of fishing mortality (F = 0.00, 0.20, 0.30, 0.40, 0.50, 0.60) to mimic concentrated removal efforts (we did not explore this under distributed removal efforts as in scenario 2), 10 passage rates for a barrier on the Sandusky River (P = 20, 25, 30, 35, 40, 50, 60, 70, 80, and 100%), and five different frequencies of suitable spawning discharge events (proportional reductions of suitable spawning discharge events on each of the three rivers of 20, 40, 60, 80, and 100%) to mimic flow modifications.

We also assessed the sensitivity of the decision to changes in thresholds for grass carp density and vegetation loss, as well as the weights assigned to the fundamental objectives. We chose alternative grass carp density thresholds of less than two fish per hectare and less than 16 fish per hectare– the minimum and maximum densities used by Gertzen et al. (2017) when evaluating the ecological consequences of grass carp on low marsh habitat. We used the values from the 95% confidence intervals (26% and 43%) of the expert elicitations for vegetation loss described above. We calculated the expected utility value for each scenario under these alternative thresholds, holding all else constant while changing the predicted outcomes for one objective at a time. To evaluate the effects of different weights on the fundamental objectives, we created a set of indifference curves in which we varied weights on the different objectives and calculated the corresponding expected utility scores. We first varied the weight on the public trust objective from 0.25 to 0.50, in increments of 0.05, while adding or subtracting the weights equally from the costs and collateral damage objectives to maintain the same relative weight on these two objectives. We then varied the weight on the cost and collateral damage objective while holding the public trust weight steady at 0.5.

Results

As with many invasive species decision problems, our case study was a multi-objective problem with a high degree of uncertainty. We present the results (consequences and tradeoffs) from our evaluation of the four case study scenarios and expert elicitation for objectives that were not directly related to grass carp population dynamics, as well as the key uncertainties that were revealed during the decision analytic process.

Consequences

We evaluated the four hypothetical control scenarios in terms of their ability to achieve the fundamental objective of fulfilling the public trust, measured as the probability of exceeding a target density threshold (10 fish/ha) and the probability of meeting the threshold of <34% vegetation loss at 5-, 10-, 25-, and 50-year time steps. Here, we highlight the response scenario outcomes at the 25- and 50-year time steps (Figure 4). This exercise brought to light two key findings related to removal efforts and barrier effects. First, removal-only efforts (Scenarios 2 and 3) reduced population growth rates and terminal density, with concentrated removal (Scenario 3) having a slightly greater effect (Figure 4A). Concentrated removal efforts had a 91% probability of maintaining grass carp densities below the 10 fish/ha target threshold, but that probability was reduced to 8% after 50 years, since the population was projected to continue to grow (Figure 4B). Second, the addition of a barrier to concentrated removal efforts (Scenario 4) resulted in the greatest effect on the population, reducing both growth rate and terminal density (Figure 4B). At the 25-year time-step, there was a 100% probability that grass carp densities would be below the threshold, and at 50 years this probably was 95% (Figure 4B). This exercise demonstrated that removal efforts coupled with a barrier on the Sandusky River could be a useful management strategy moving forward; however, key uncertainties surrounding capture efficiencies and barrier feasibility limited our ability to recommend precise levels of capture and removal effort or specific barrier designs/locations. Moving forward, any increase in removal effort and reduction in spawning success would have a positive effect as the group works to better understand these critical uncertainties.

Vegetation loss was closely tied to grass carp densities, because annual vegetation biomass estimates (Duarte and Kalff 1990) and grass carp consumption rates (van der Lee et al. 2017) were fixed across years. As a result, the pattern of meeting our vegetation loss management target mirrored that of meeting our grass carp density target, with increasing probabilities with increased efforts (Scenario 1, year 25 = 0.0%; Scenario 4, year 25 = 93.1%) and decreasing probabilities through time as grass carp abundance increased (Scenario 4, year 50 = 67.0%).

The effects of management actions on the attributes of collateral damage varied greatly. We found that in some instances, a control action was predicted to perform well at improving public sentiment even if it would potentially pose a risk to other aspects of the social or environmental landscape. For example, although direct capture was predicted to result in a minor improvement in public sentiment (0.833–1.000; Table S1), there was a risk of a minor negative effect on recreational and commercial stakeholders, migratory species, and threatened and endangered species (range of scores across measures = -1.056– -0.444; Table S1, Figure 5). For other control techniques, experts predicted a minor to major negative effect for all measurable attributes, especially for chemical control and a physical barrier, the two lowest-scoring control actions (Table S1, Figure 5).

Tradeoffs

Although the four scenarios that we evaluated were not meant to be prescriptive sets of actions that could immediately be implemented to control grass carp abundance, we evaluated these scenarios in a consequence table framework to stimulate discussion about objectives and weights, as well as potential tradeoffs among objectives. The group indicated that fulfilling the public trust was the most important objective, and therefore placed 50% of the weight on this objective, 26% on minimizing collateral damage, and 24% on minimizing management costs. In the cases for which there were multiple means objectives or measures, the weights for the fundamental objective were distributed evenly among the means objectives and attributes. Although we evaluated both a 25- and 50-year timeframe, we present the results for 50 years because the results for 25 years were quite similar, with identical scenario ranks. At year 50, Scenario 4 ("Removal + Barrier") had the greatest expected utility score (0.552), followed by Scenario 1 ("Take No Management Action"; Table 2). The other two scenarios scored much lower. Notably, Scenario 3 ("Concentrated Removal") ranked second at year 25 because the probability of exceeding the grass carp density threshold was still quite high (Figure 4B). Scenario 4 best achieved objectives related to reducing grass carp abundance (public trust), while scoring worst for minimizing costs and for four of the five objectives related to collateral damage (Table 2). Scenario 1 ranked second at year 50 because although it did not achieve objectives related to grass carp population abundance, the other scenarios only performed marginally better than no management action, based upon the weights that were generated through expert elicitation, while costing more and potentially affecting stakeholders and other species.

Uncertainty and Sensitivity

The working group generated a large list of uncertainties, many of which affected the ultimate choice of control actions for grass carp in Lake Erie. We evaluated the effects of uncertainties in the population model through a formal sensitivity analysis (DuFour et al. in review) and found that predicted grass carp population growth rates were most sensitive to uncertainties in survival, the parameters of the stock-recruitment model, and the frequency of suitable spawning events.

In the case of uncertainty in the effects of fishing mortality, we found that $F > 0.40$ would maintain an already low population below the target density of 10 fish per hectare of forage habitat after 60 years (Figure 6). This result suggested that direct capture methods that could achieve these levels of F would be effective control measures. However, a key remaining uncertainty for direct capture is carp catchability (q) with the potential gear types. Fishing mortality is proportional to the product of catchability and effort. Therefore, resolving uncertainty in catchability with specific gear types used for direct capture will provide an estimate of effort required to achieve the target level of F, and allow for a more robust evaluation of the cost objective.

After 60 years of implementation of a hypothetical barrier, we found that the total density of fish was still increasing under the $P = 25\%$ simulation, indicating that potentially reducing passage rates below this threshold could maintain population density below the 10 fish per ha threshold (Figure 7). Similarly, the population density would remain below the threshold if high flow events in western Lake Erie were reduced by more than 80% across the three river systems (Figure 8). Our results indicated that methods to reduce access to spawning habitat by grass carp are hindered by uncertainties in how to construct barriers or modify flow to meet these requirements for effectiveness, as well as how climate change might influence their effectiveness.

When evaluating the sensitivity of the decision to changes in the thresholds for grass carp density or vegetation loss, we found no difference in scenario ranks, with the expected utility scores for Scenario 4 and Scenario 1 remaining the same throughout the sensitivity analyses (Tables S2 – S5). We found that when varying the weight applied to the public trust fundamental objective, Scenario 4 was optimal when the weight on public trust was greater than 0.40, otherwise, Scenario 1 was favored, indicating that decision makers must consider the relative value associated with efforts that could effectively control grass carp but affect other stakeholders or the ecosystem. There was no change in the ranks of the scenarios when varying the weights on the costs and collateral damage objectives, though Scenarios 1 and 4 were equally favored when there was no weight assigned to collateral damage.

Discussion

As with many decisions regarding control of an invasive species, decision-making for grass carp control in Lake Erie was confounded by high uncertainty about population dynamics and effectiveness of potential actions, the existence of multiple decision makers across several jurisdictions at state, provincial, and federal levels, and source and magnitude of external inputs. These common characteristics of difficult problems led biologists, managers, and academics to convene for a series of multi-party collaborative decision analysis workshops. In these workshops, the working group agreed on the nature of the problem, identified a set of ecological, economic, and social objectives that must be achieved, and created a list of potential actions for grass carp control. Through processes of participatory modeling and expert elicitation, we predicted the consequences of a set of control scenarios on the objectives and considered how tradeoffs should be made among these objectives.

Some of the identified actions could be effective at controlling the grass carp population to a threshold level established by the experts in our working group, based on prior risk assessments (Cudmore et al. 2017). However, there were key uncertainties that would impede response efforts and that should be resolved. In particular, our modeling framework allowed us to assess the sensitivity of outcomes of interest to uncertainties in important demographic rates (DuFour et al. in review), as well as evaluate other structural uncertainties related to the level of effectiveness necessary for certain control actions to achieve desired outcomes. These structural uncertainties are a hallmark of invasive species control (Blomquist et al. 2010; Johnson et al. 2017), as managers and biologists are often tasked with making control decisions without clear data about population dynamics of the introduced population or the effectiveness of potential control actions on a new species in the environment. Importantly, sensitivity analyses indicated that the decision among our hypothetical scenarios was robust to different threshold levels of grass carp density and vegetation removed, but that as the amount of weight that stakeholders place on the public trust objective, which encompasses these measures, is decreased, the "Do Nothing" scenario shifted to the highest rank. As the group moves forward with evaluating actual control scenarios, they will need to carefully refine the weights on their fundamental objectives to reflect how the decision makers value the predicted achievement of these objectives. We also acknowledge that uncertainties related to the areal density of macrophytes, as described in Gertzen et al. (2017), could influence the ultimate decision and could be explored in the future.

In addition, the group agreed that the lack of an estimate of current population size for grass carp in Lake Erie was a key uncertainty. Although the population model results indicated that changes in initial population size did not affect the outcome of simulated management scenarios, understanding where the Lake Erie grass carp population is on the invasion curve (Forcella and Harvey 1983) would provide the group with insight into how to adjust or implement management actions. Group members also indicated that an estimate of population size would aid agency personnel in communication with the public about the nature of the problem and the removal capacity relative to population size. This result has encouraged collaboration among researchers (i.e., telemetry and removal efforts and multi-jurisdictional coordination) to begin to develop preliminary population estimates.

Based on these key uncertainties, the working group has transitioned to an adaptive management framework for grass carp control in Lake Erie. Adaptive management is a form of decision analysis in which experimental control or management actions are implemented, and through monitoring efforts, data are collected to update the predictive models from the structured decision-making process (Figure 2; Walters 1986; Williams et al. 2002). In particular, direct capture actions are being implemented in an adaptive framework to reduce uncertainty about catchability estimates, which will be used to estimate the expected gear-specific fishing mortality, F, and update the population model. In addition, we suggest that experimental control actions can be implemented to reduce uncertainty around other aspects of grass carp control, such as effectiveness of physical or behavioral barriers. Although one of our scenarios included a seasonal barrier, this was simply simulated as a decrease in passability of adult grass carp. Members of the working group are now evaluating the feasibility of constructing a seasonal barrier on the Sandusky River (Herbst et al. in review).

Inherent in the adaptive management framework for grass carp is the ability to make predictions with a quantitative model (DuFour et al. in review) that can be updated through the implementation of control actions, rather than as a trial and error approach to control. A similar predictive framework and adaptive management process could be useful for control and eradication of other invasive species, particularly in systems similar to Lake Erie– large, multi-jurisdictional aquatic ecosystems with potential for high social indeterminism, such as a recently-identified potentially reproductive population of grass carp in the Colorado River, USA (Brandenburg et al. 2019). In our case study with grass carp, an added benefit of the iterative nature of decision making under adaptive management is the ability for players within the agencies represented to increase their engagement as the process continues, thereby developing a greater capacity for social adaptation (Tyre and Michaels 2011). Since the inception of the SDM process, the group has grown and remained inclusive to new members that are willing to contribute to the adaptive management process.

Although the evaluation of uncertainty is crucial for decisions related to invasive species control, we also highlight other benefits of the multi-party collaborative effort for this decision problem. The working group was composed of members from many different agencies, institutions, and commissions, all of which had different needs and interests related to grass carp control and eradication. Members of this group were the experts in the control of this species, as well as other aquatic invasive organisms in the Great Lakes and the Mississippi River drainage. The decision analytic process provided a way for all group members to explicitly define the scope of the problem and build a shared set of values and objectives, which had not been discussed previously. Although participants began the process acknowledging that the problem was quite complex, decision analysis allowed for this complexity to be defined and broken down into component parts for analysis. Consequently, the group better understood the complexity at hand and how the decision analytic process helped to make that complexity more manageable.

The participatory model building also led directly to a population model designed to predict the effects of control actions on grass carp, and a framework to inform control actions that could be implemented to reduce critical uncertainties (Herbst et al. in review).

The SDM workshops also served a dual purpose of convening a group to work on the decision analytic process for grass carp and providing a forum for these experts to share the results of their research and control efforts for this species. Through these workshops, the group formed a sense of shared purpose, which has translated to collaborative efforts in the western basin of Lake Erie, including data sharing, a unified calendar of field efforts for all jurisdictions and researchers, and the creation of field teams specific to grass carp control in the Michigan and Ohio Departments of Natural Resources and the United States Fish and Wildlife Service, as well as binational cooperation and assistance of Fisheries and Oceans Canada and the Ontario Ministry of Natural Resources and Forestry. All of these agencies work together on control efforts within and outside of their individual jurisdictions, along with researchers from academic institutions (Herbst et al. in review). Finally, the SDM workshops have resulted in management plans for grass carp in both Michigan and Ohio, an adaptive response strategy document created by the Lake Erie Committee, and extended commitment of time and resources to continue the adaptive management process (Herbst et al. in review).

Our case study details how decision analysis can be used to guide development of a strategy for controlling an invasive species. Although we provide details about grass carp management, we believe that this framework is equally beneficial to other invasive species control problems in the Great Lakes and other regions where similar epistemic and institutional impediments exist. The decision analytic framework allowed us to bring together experts from throughout the region to work collaboratively on a shared problem. We also determined which uncertainties, of a set of many, should be reduced through adaptive management, ultimately leading to better decisions about the most appropriate response actions in the future, given a well-defined set of objectives. The population model that we created for this project (DuFour et al. in review) can be applied to other species and regions, especially other invasive Chinese carps or species of concern, like northern snakehead (*Channa argus*). Finally, this process has led to new collaborations in control and research for grass carp and other invasive species.

Acknowledgments

We thank all participants in the SDM workshops (A. Bowen, A. Briggs, R. Carter, G. Christie, G. Conover, A. Drake, H. Embke, C. Harris, K. Irons, R. Jackson, S. Keppner, S. Koproski, T. Lewis, A. Mahon, N. Mandrak, E. Monroe, J. Navarro, M. Olfara, K. Pangle, N. Popoff, E. Slavik, S. Thomas, P. Thompson, C. Vandergoot, S. Wagner, T. Widloe, and M. Wilkerson). We also thank E. Irwin and two anonymous reviewers for their valuable input. This project was supported by Great Lakes Restoration Initiative funding provided to the Michigan Department of Natural Resources (grant no. F16AP01094) from the U.S. Fish and Wildlife Service and sub-awarded to Michigan State University. Use of trade, firm, or product names is for descriptive purposes only and is not an endorsement by the federal government. This is publication number XXX of the Quantitative Fisheries Center.

Literature Cited

Asian Carp Regional Coordinating Committee (ACRCC), 2016. Asian carp action plan for fiscal year 2017.

Bayley, P.B., Austen, D.J., 2002. Capture efficiency of a boat electrofisher. Trans. Am. Fish. Soc. 131, 435–451.

Blomquist, S.M., Johnson, T.D., Smith, D.R., Call, G.P., Miller, B.N., Thurman, W.M., McFadden, J.E., Parkin, M.J., Boomer, G.S., 2010. Structured decision-making and rapid prototyping to plan a management response to an invasive species. J. Fish Wildl. Manag. 1, 19–32.

Brandenburg, W.H., Francis, T.A., Snyder, D.E., Bestgen, K.R., Hines, B.A., Wilson, W.D., Bohn, S., Harrison, A.S., Clark Barkalow, S.L., 2019. Discovery of grass carp larvae in the Colorado River arm of Lake Powell. North Am. J. Fish. Manag. 39, 166–171.

Chapman, D.C., Davis, J.J., Jenkins, J.A., Kočovský, P.M., Miner, J.G., Farver, J., Jackson, P.R., 2013. First evidence of grass carp recruitment in the Great Lakes Basin. J. Great Lakes Res. 39, 547–554.

Clapp, D., Mistak, J., Smith, K., Tonello, M., 2012. Proposed 2010 plan for the prevention, detection, assessment, and management of Asian carps in Michigan waters. Michigan Department of Natural Resources, Fisheries Special Report 60, Lansing.

Cohen, J.B., Hecht, A., Robinson, K.F., Osnas, E.E., Tyre, A.J., Davis, C., Kocek, A., Maslo, B., Melvin, S.M., 2016. To exclose nests or not: structured decision making for the conservation of a threatened species. Ecosphere 7(10), e01499.

Conroy, M.J., Peterson, J.T., 2013. Decision making in natural research management: a structured, adaptive approach. John Wiley & Sons, Ltd., West Sussex, United Kingdom.

Cudmore, B., Jones, L.A., Mandrak, N.E., Dettmers, J.M., Chapman, D.C., Kolar, C.S., Conover, G., 2017. Binational ecological risk assessment of grass carp (*Ctenopharyngodon idella*) in the Great Lakes Basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/118 vi. 1–115.

Cudmore, B., Mandrak, N.E., Dettmers, J.M., Chapman, D.C., Kolar, C.S., 2012. Binational ecological risk assessment of bigheaded carps (*Hypophthalmichthys* spp.) for the Great Lakes basin. Dep. Fish. Ocean. Can. Sci. Advis. Sec. Res. Doc. 2011/114 vi, 1–57.

Duarte, C.M., Kalff, J., 1990. Patterns in the submerged macrophyte biomass of lakes and the importance of the scale of analysis in the interpretation. Can. J. Fish. Aquat. Sci. 47, 357–363.

DuFour M., Robinson, K.F., Jones, M.L., Herbst, S. In review. A matrix population model to aid grass carp (*Ctenopharyngodon idella*) management in the Great Lakes Basin – Lake Erie. J. Great Lakes Res.

Embke, H.S., Kočovský, P.M., Richter, C.A., Pritt, J.J., Mayer, C.M., Qian, S.S., 2016. First direct confirmation of grass carp spawning in a Great Lakes tributary. J. Great Lakes Res. 42, 899–903.

Failing, L., Gregory, R., Higgins, P., 2013. Science, uncertainty, and values in ecological restoration: A case study in structured decision-making and adaptive management. Restor. Ecol. 21, 422–430.

Forcella, F., Harvey, S.J., 1983. Relative abundance in an alien weed flora. Oecologia 59, 292–295.

Gertzen, E.L., Midwood, J.D., Wiemann, N., Koops, M.A., 2017. Ecological consequences of grass carp, *Ctenopharyngodon idella*, in the Great Lakes Basin: vegetation, fishes and birds. Ottawa, Canada.

GLFC (Great Lakes Fishery Commission, Editor). 2007. A joint strategic plan for management of Great Lakes fisheries (adopted in 1997 and supersedes 1981 original). Great Lakes Fish. Comm. Misc. Publ. 2007-01. Available at http://www.glfc.org/fishmgmt/jsp97.pdf.

Goodwin, P., Wright, G., 2009. Decision analysis for management judgment. John Wiley & Sons, Ltd., West Sussex, United Kingdom.

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

Gregory, R., Keeney, R.L., 1994. Creating policy alternatives using stakeholder values. Manage. Sci. 40, 1035–1048.

Haeseker, S.L., Jones, M.L., Peterman, R.M., Bence, J.R., Dai, W., Christie, G.C., 2007. Explicit consideration of uncertainty in Great Lakes fisheries management: decision analysis of sea lamprey (*Petromyzon marinus*) control in the St. Marys River. Can. J. Fish. Aquat. Sci. 64, 1456–1468.

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

Harris, C., Brenden, T.O., Vandergoot, C.S., Faust, M.D., Herbst, S.J., Krueger, C.C., In press. Tributary use and large-scale movements of grass carp in Lake Erie. J. Great Lakes Res.

Herbst, S.J., Nathan, L.R., Newcomb, T.J., DuFour, M.R., Tyson, J., Weimer, E., Buszkiewicz, J., Dettmers, J.M., In review. An adaptive management approach for implementing multi-jurisdictional response to grass carp in Lake Erie. J. Great Lakes Res.

Herdendorf, C.E., 1987. The Ecology of the Coastal Marshes of Western Lake Erie: A Community Profile. U.S. Fish Wildl. Serv. Biol. Rep.

Johnson, F.A., Smith, B.J., Bonneau, M., Martin, J., Romagosa, C., Mazzotti, F., Waddle, H., Reed, R.N., Eckles, J.K., Vitt, L.J., 2017. Expert elicitation, uncertainty, and the value of information in controlling invasive species. Ecol. Econ. 137, 83–90.

Jones, L.A., Drake, D.A.R., Mandrak, N.E., Jerde, C.L., Wittmann, M.E., Lodge, D.M., van der Lee, A.S., Johnson, T.B., Koops, M.A., 2017. Modelling survival and establishment of grass carp, *Ctenopharyngodon idella*, in the Great Lakes Basin. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/101. vi + 52 p.

Kočovský, P.M., Chapman, D.C., McKenna, J.E., 2012. Thermal and hydrologic suitability of Lake Erie and its major tributaries for spawning of Asian carps. J. Great Lakes Res. 38, 159–166.

Kuhnert, P.M., Martin, T.G., Griffiths, S.P., 2010. A guide to eliciting and using expert knowledge in Bayesian ecological models. Ecol. Lett. 13, 900–14.

McKnight, S., Hepp, G., 1995. Potential effect of grass carp herbivory on waterfowl foods. J. Wildl. Manage. 59, 720–727.

Michaels, S., Tyre, A.J., 2012. How indeterminism shapes ecologists' contributions to managing socio-ecological systems. Conserv. Lett. 5, 289–295.

Mississippi Interstate Cooperative Resource Association (MICRA). 2015. The use of grass carp (*Ctenopharyngodon idella*) in the United States: Production, triploid certification, shipping, regulation, and stocking recommendations for reducing spread throughout the United States. Report to the U.S. Fish and Wildlife Service from the Mississippi Interstate Cooperative Resource Association. 377 p.

Mitsch, W.J., 1992. Landscape design and the role of created, restored, and natural riparian wetlands in controlling nonpoint source pollution. Ecol. Eng. 1, 27–47.

Robinson, K.F., Fuller, A.K., Hurst, J.E., Swift, B.L., Kirsch, A., Farquhar, J., Decker, D.J., Siemer, W.F., 2016. Structured decision making as a framework for large-scale wildlife harvest management decisions. Ecosphere 7(12), e01613.

Robinson, K.F., Fuller, A.K., 2017. Participatory modeling and structured decision making, in: Gray, S., Paolisso, M., Jordan, R., Gray, S. (Eds.), Environmental Modeling with Stakeholders: Theory, Methods, and Applications. Springer International, Switzerland, pp. 83–101.

Runge, M.C., Bean, E., Smith, D.R., Kokos, S., 2011a. Non-Native Fish Control below Glen Canyon Dam — Report from a Structured Decision-Making Project. Reston, VA.

Runge, M.C., Converse, S.J., Lyons, J.E., 2011b. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. Biol. Conserv. 144, 1214–1223.

Speirs-Bridge, A., Fidler, F., McBride, M., Flander, L., Cumming, G., Burgman, M., 2010. Reducing overconfidence in the interval judgments of experts. Risk Anal. 30, 512–23.

Tyre, A.J., Michaels, S., 2011. Confronting socially generated uncertainty in adaptive management. J. Environ. Manage. 92, 1365–1370.

United States Geological Survey (USGS). 2019. Newly hatched invasive grass carp found in Maumee River, Ohio. https://www.usgs.gov/news/newly-hatched-invasive-grass-carp-found-maumee-river-ohio. Accessed 6/19/19.

van der Lee, A.S., Johnson, T.B., Koops, M.A., 2017. Bioenergetics modelling of grass carp: Estimated individual consumption and population impacts in Great Lakes wetlands. J. Great Lakes Res. 43, 308–318.

Walters, C.J., 1986. Adaptive management of renewable resources. MacMillan Publishing Company, New York.

Wieringa, J.G., Herbst, S.J., Mahon, A.R., 2016. The reproductive viability of grass carp (*Ctenopharyngodon idella*) in the western basin of Lake Erie. J. Great Lakes Res. 43, 405–409.

Williams, B.K., Nichols, J.D., Conroy, M.J., 2002. Analysis and management of animal populations: modeling, estimation, and decision making. Academic Press, San Diego, California.

Wills, T., Robinson, J., Faust, M., DuFour, M.R., Gorman, A.M., Belore, M., Cook, A., Marklevitz, S., MacDougall, T., Zhao, Y., Hosack, M., 2019. Report for 2018 by the Lake Erie walleye task group. Ypsilanti, MI.

Wittmann, M.E., Cooke, R.M., Rothlisberger, J.D., Lodge, D.M., 2014. Using structured expert judgment to assess invasive species prevention: Asian carp and the Mississippi - Great Lakes hydrologic connection. Environ. Sci. Technol. 48.

Figures

Figure 1: Lake Erie’s western basin, including three systems with potential for reproduction of grass carp— the Maumee, Sandusky, and Raisin rivers. Low marsh habitat, as delineated by Gertzen et al. (2017), is represented in green along coastal margins.

Figure 2: The decision analysis process used for making decisions about grass carp control in Lake Erie. Solid arrows indicate the direction of movement through each step. The dotted arrow indicates how results of monitoring can be used to update model predictions in the consequences step when implementing adaptive management to reduce key uncertainties.

Figure 3: Objectives hierarchy depicting the fundamental (black) and means (dark gray) objectives of the decision process for grass carp control in Lake Erie. Light gray boxes indicate potential actions that could be implemented. T & E = threatened and endangered, min. = minimize, max. = maximize, GC = grass carp.

Figure 4: Projections of A) the total density (fish/ha) of grass carp and B) the probability of the density of grass carp exceeding the 10 fish/ha threshold after 25 (squares) and 50 (circles) years under four different hypothetical control scenarios in western Lake Erie. In panel B, light grey bars represent the 50% credible intervals of the population model projections, and dark grey bars represent the 95% credible intervals. The vertical dashed line identifies the 10 fish/ha threshold identified by the working group.

Figure 5: Relative economic effects of each control action type for grass carp in Lake Erie on recreational (A) and commercial (B) stakeholders, and relative effects on native ecosystems for migratory fishes (C), threatened and endangered species (D), and public perception (E) of stakeholders across seasons and habitats.

Figure 6: Grass carp density projections in western Lake Erie under increasing levels of direct capture, represented as fishing mortality (*F*).

Figure 7: Grass carp density projections in western Lake Erie under declining passage rates (*P*) on the Sandusky River, Ohio, USA, during the spawning season, representing increasing barrier effectiveness.

Figure 8: Grass carp density projections in western Lake Erie under decreasing frequency of high-quality discharge events (*HQ*), as defined by Kočovsky et al. (2012), mimicking flow modifications to reduce spawning. The probability of high-quality discharged events in a given year in each river was proportionally reduced from starting values of $p = 0.68$ in the Sandusky River, $p = 0.84$ in the Maumee River, and $p = 0.05$ in the River Raisin for each model run.

Table 1: Examples of the set of alternatives considered by the working group for the control of grass carp in Lake Erie. Alternatives were grouped into management action categories that represented similar outcomes (e.g., removal actions or implementation of a barrier).

Management Action Category	**Action Type**	**Specific Actions**
Removal	Direct capture	Large seines, trammel net + electrofishing, electrofishing only
	Harvest incentives	Commercial reward, increased outreach, bow-fishing tournament
	Chemical control	General toxicant (e.g., rotenone), ingestible toxicant
Barriers	Behavioral	Acoustic, bubbles, CO_2, strobe light (alone or in combination), electric
	Physical	Western and temporary salmon weirs, submerged retractable and inflatable dams
Habitat modifications	Flow modifications	Reduce flows to inhibit reproduction, increase flows to attract to undesirable locations
Eliminate inputs	Reduce inputs	Reduce diploid contamination of triploid shipments, monitoring and enforcement

Table 2: Consequence table with predicted outcomes, scaled from 0 – 1, for each objective under four hypothetical scenarios of grass carp control in Lake Erie after 50 years of implementation. w_{FO} = weight on fundamental objective, w_{MO} = weight on means objective, min = minimize. Bolded numbers represent the scenario that best achieves a given objective, italicized numbers represent the scenario that performs worst at achieving a given objective. *E(U)* = expected utility score.

			Hypothetical Scenarios					
Fundamental Objective	Means Objective	Measure	1	2	3	4	w_{FO}	w_{MO}
Fulfill public trust	Min. risk of spread	Probability meeting threshold (<10 fish/ha)	*0.000*	0.000	0.081	**1.000**	0.50	0.50
	Min. vegetation loss	Probability of meeting threshold (< 34% loss)	*0.000*	0.007	0.061	**1.000**		0.50
Min. Management Costs	Min. money spent	<US$84,000 per year	**1.000**	*0.000*	*0.000*	*0.000*	0.24	1.00
Min. collateral damage	Min. economic stress	Constructed scale for recreational users	**1.000**	0.162	0.161	*0.000*	0.26	0.20
		Constructed scale for commercial users	**1.000**	0.086	0.096	*0.000*		0.20
	Min. effects on native ecosystems	Constructed scale-effects on migratory fishes	**1.000**	0.261	0.252	*0.000*		0.20
		Constructed scale-threatened/endangered	**1.000**	0.183	0.176	*0.000*		0.20
		Constructed scale-public sentiment	*0.000*	**1.000**	0.991	0.991		0.20
E(U)			0.448	*0.090*	0.123	**0.552**		

Figure 1

Click here to download high resolution image

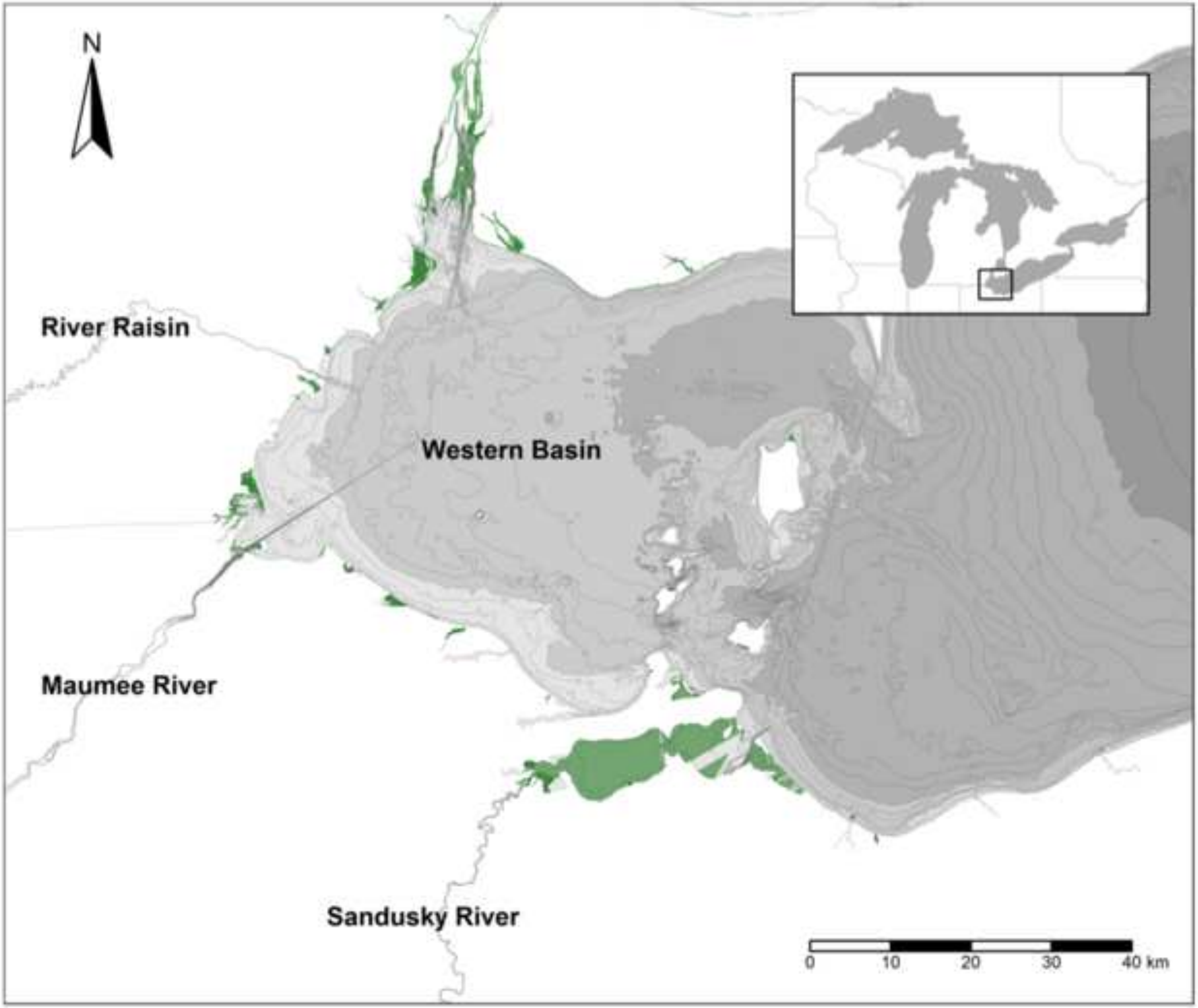
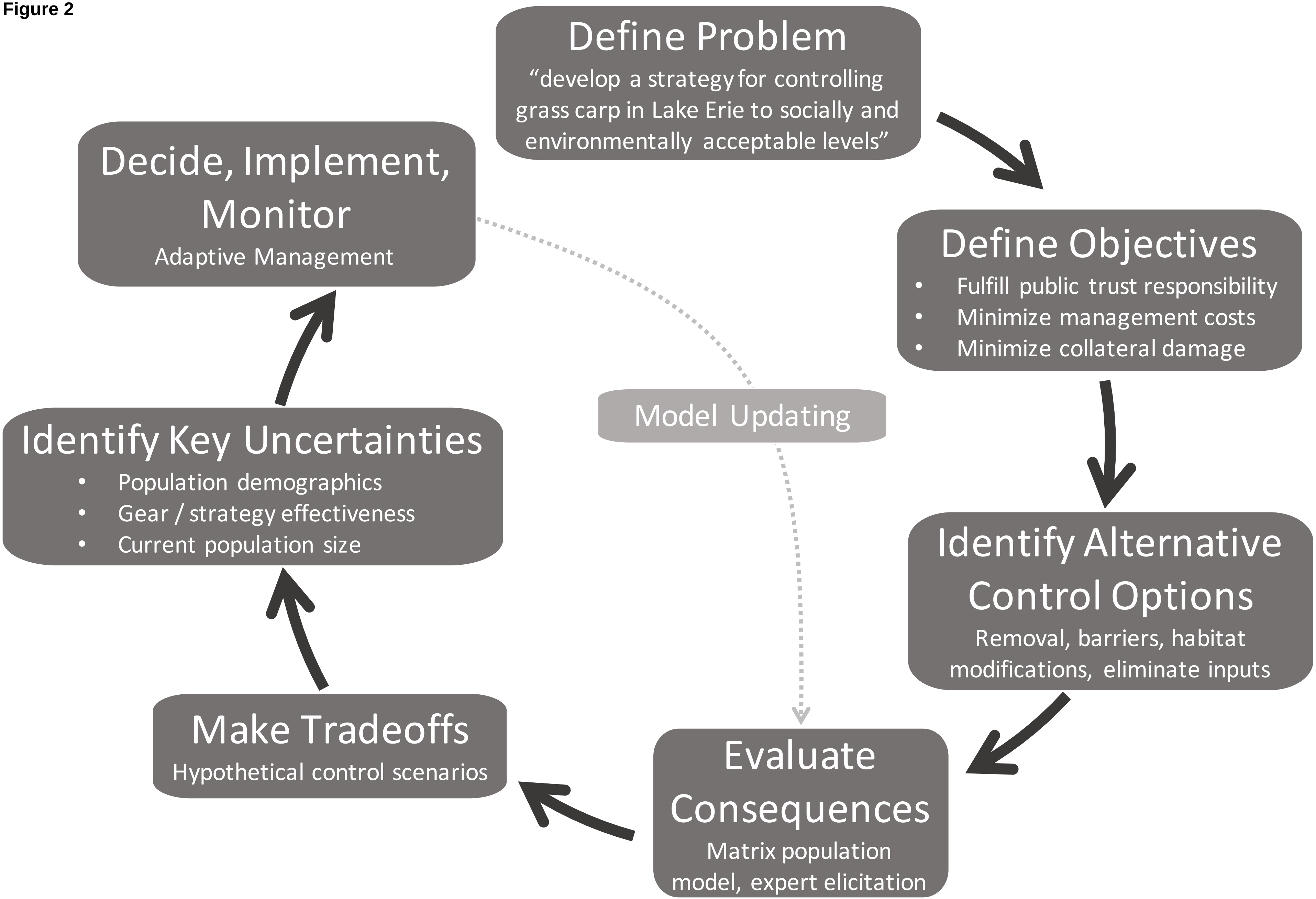


Figure 2



Define Problem
"develop a strategy for controlling grass carp in Lake Erie to socially and environmentally acceptable levels"
Define Objectives
• Fulfill public trust responsibility
• Minimize management costs
• Minimize collateral damage
Identify Alternative Control Options
Removal, barriers, habitat modifications, eliminate inputs
Evaluate Consequences
Matrix population model, expert elicitation
Make Tradeoffs
Hypothetical control scenarios
Identify Key Uncertainties
• Population demographics
• Gear / strategy effectiveness
• Current population size
Decide, Implement, Monitor
Adaptive Management
Model Updating

Figure 3

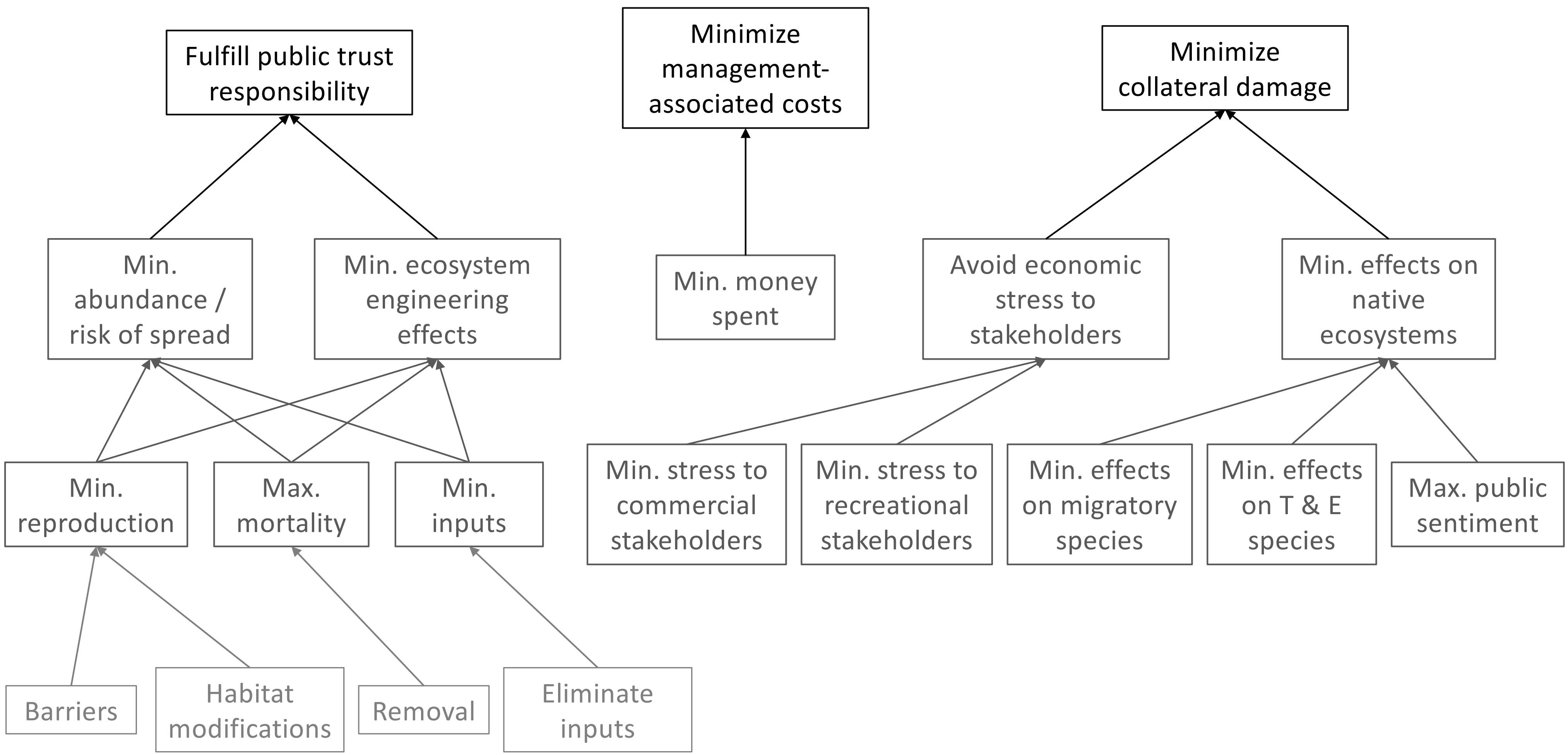

Fulfill public trust responsibility
Minimize management-associated costs
Minimize collateral damage
Min. abundance / risk of spread
Min. ecosystem engineering effects
Min. money spent
Avoid economic stress to stakeholders
Min. effects on native ecosystems
Min. reproduction
Max. mortality
Min. inputs
Min. stress to commercial stakeholders
Min. stress to recreational stakeholders
Min. effects on migratory species
Min. effects on T & E species
Max. public sentiment
Barriers
Habitat modifications
Removal
Eliminate inputs

Figure 4

Click here to download high resolution image

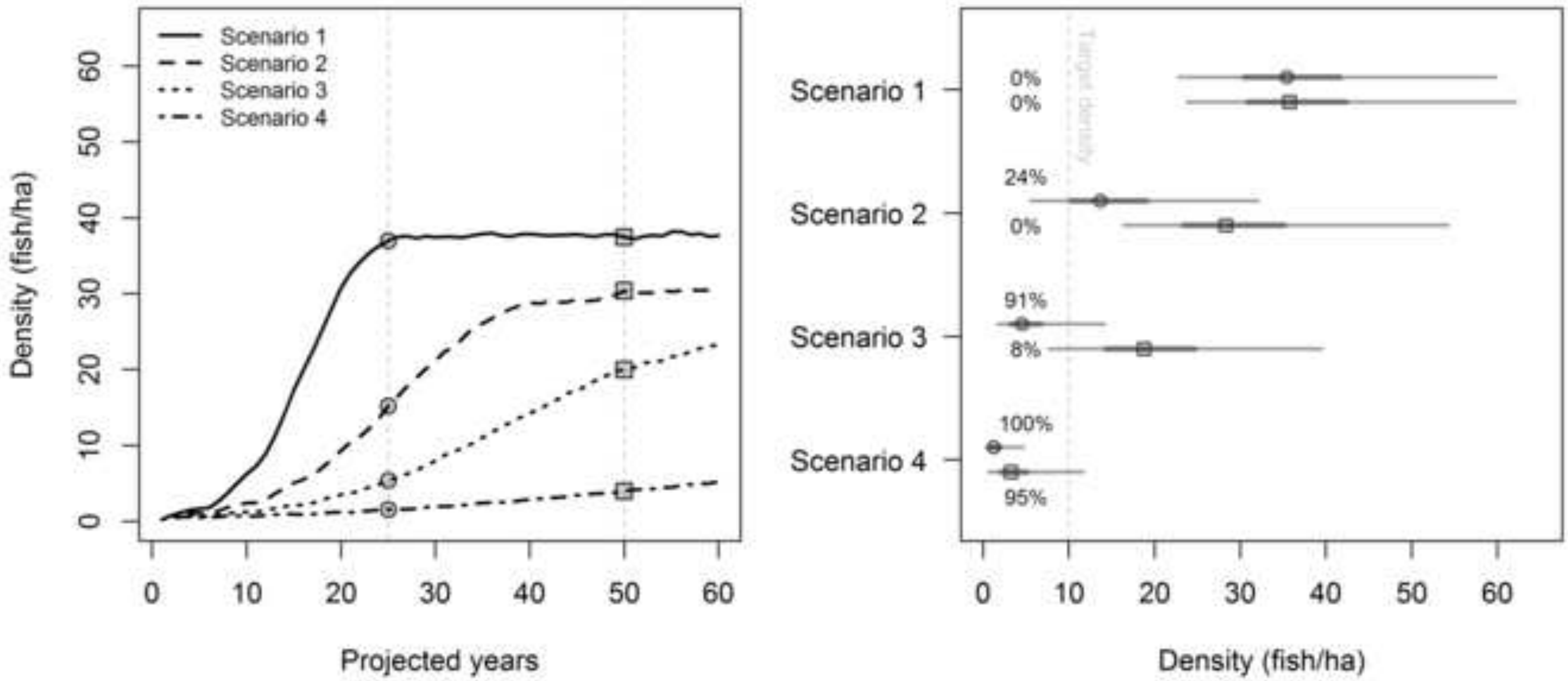


Figure 5

Click here to download high resolution image

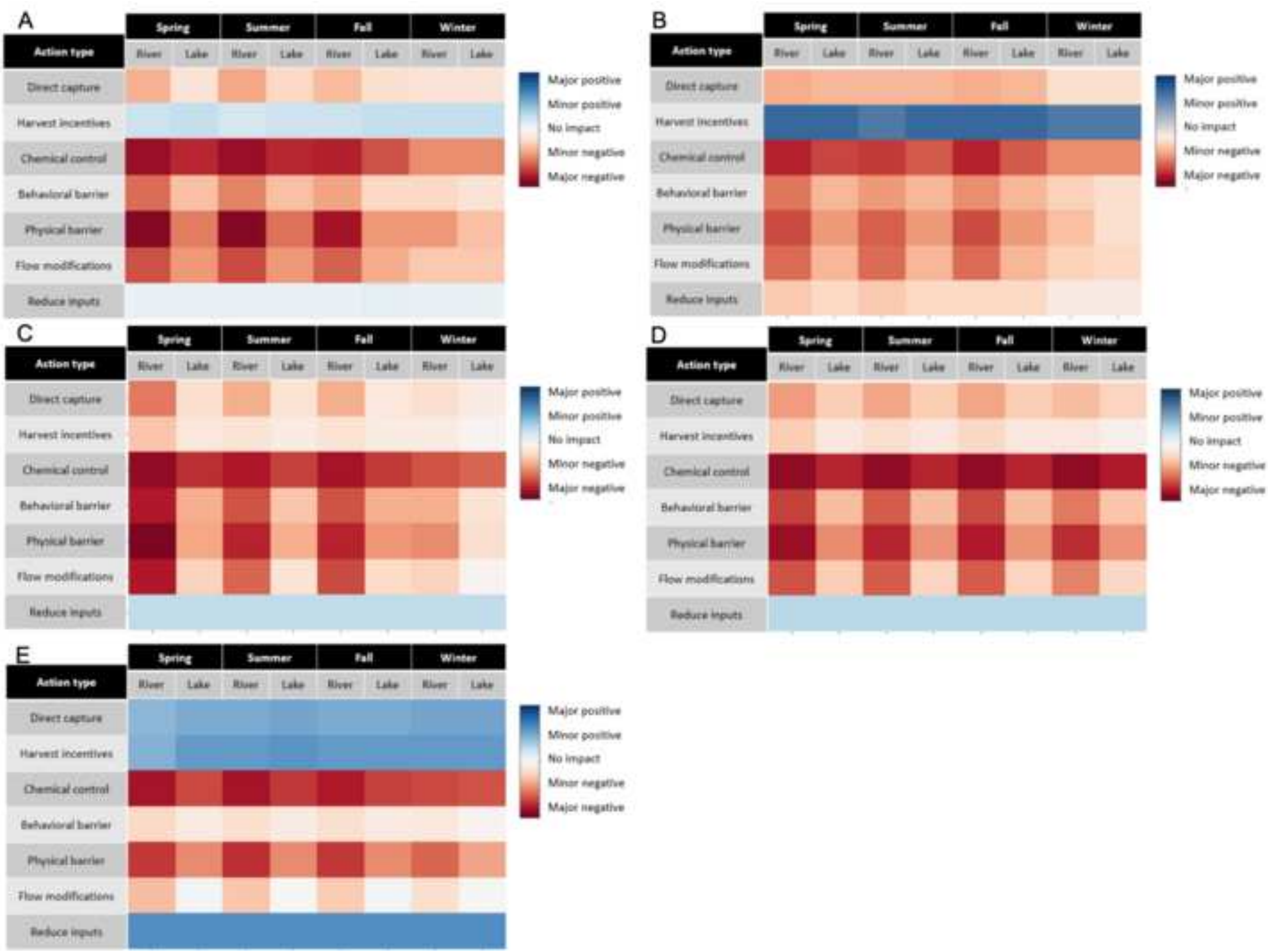


Figure 6

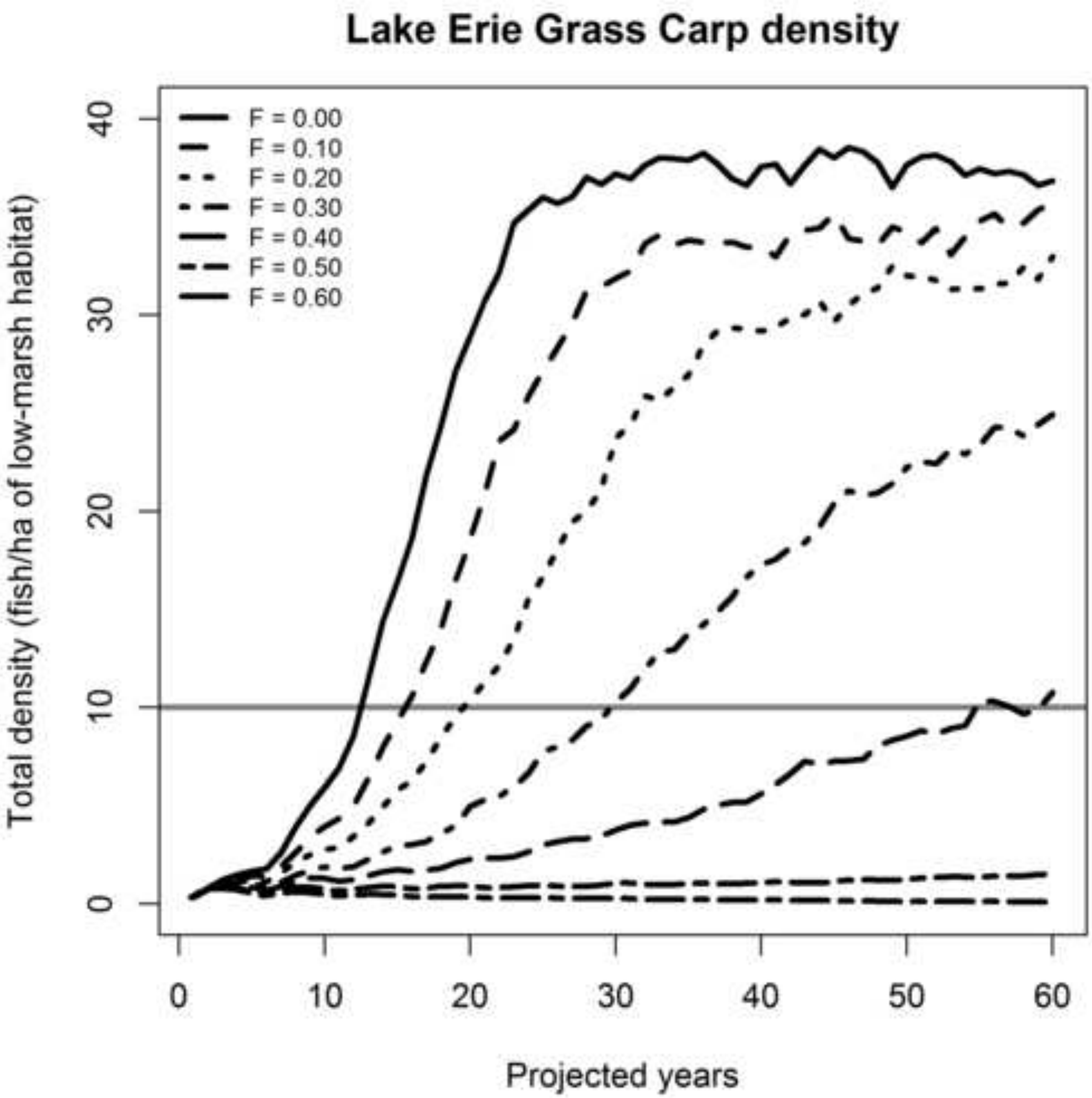

Lake Erie Grass Carp density
F = 0.00
F = 0.10
F = 0.20
F = 0.30
F = 0.40
F = 0.50
F = 0.60
Total density (fish/ha of low-marsh habitat)
0
10
20
30
40
Projected years
0
10
20
30
40
50
60

Figure 7
Click here to download high resolution image

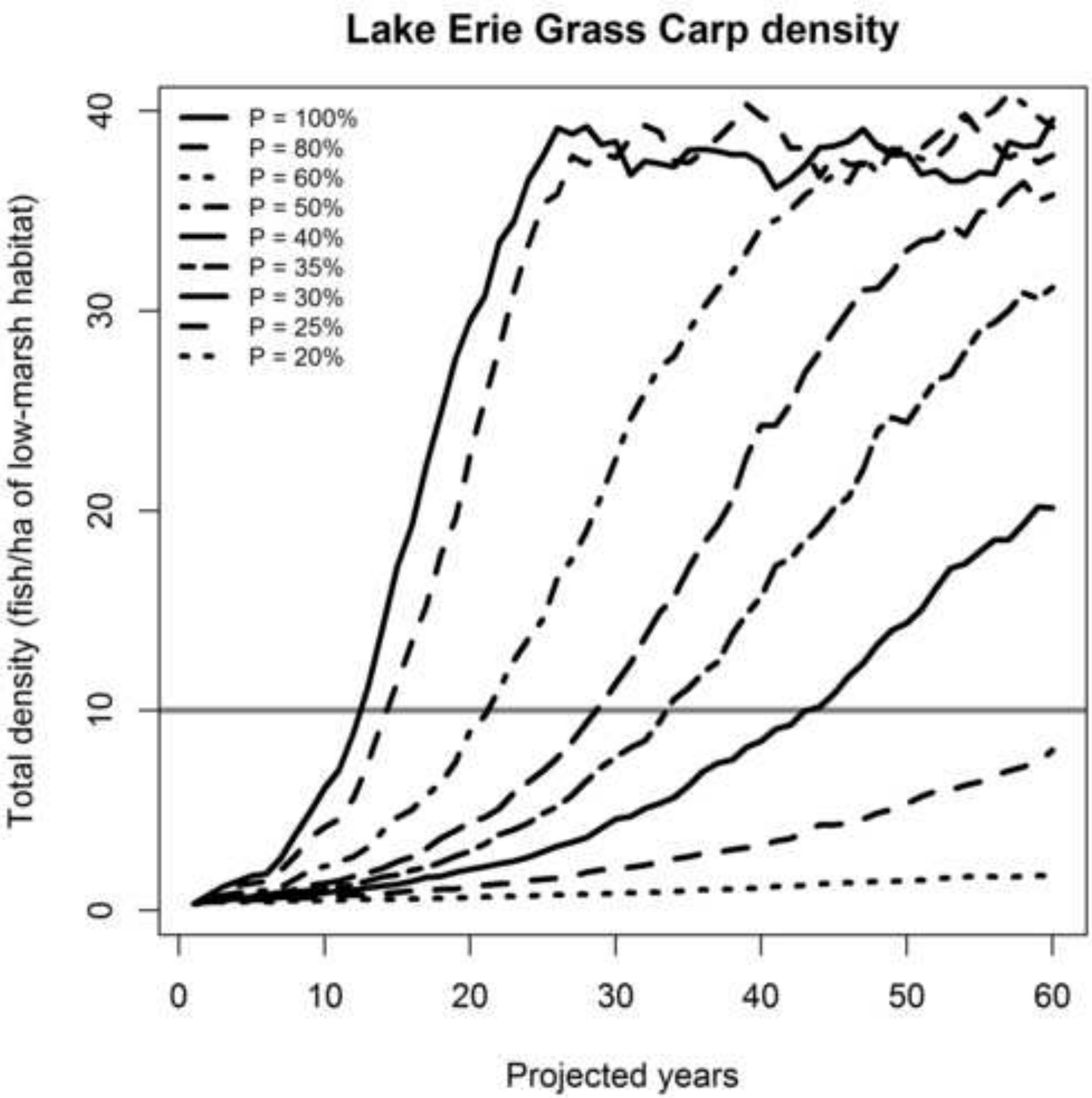


Figure 8
Click here to download high resolution image