PROJECT ABSTRACT

Title: Forecasting biological and economic impacts of aquatic invasive species in Lake Michigan

Abstract Body: A computable general equilibrium (CGE) model is developed to assess the current threat in Lake Michigan of bigheaded carp, non-indigenous aquatic invasive species (AIS) projected to have spatially explicit and species-specific impacts on the environment and the economy. The CGE model is designed to link spatial biomass data from the Atlantis ecosystem model of Lake Michigan with recreational fishing behavior and the broader economy. Forecasted effects from the AIS on biomass levels of sport-fishing species across time and space are heterogenous and impact households' decisions regarding when, where, and what species to fish. Decisions are modeled using a spatially explicit, zone-level application of a modified household production function approach. After generating the welfare implications from the explicit space and species model, the results are compared to other simulated versions of the model, with the intention of uncovering biases that may exist in welfare estimates when space or species level information is ignored. Results indicate that aggregating over one or both can under- or over-estimate welfare impacts by failing to account for important tradeoffs between ecological and economic systems. The welfare discrepancies are most pronounced for the models that ignore households' species-specific preferences.

FINAL NARRATIVE

Project Title: Forecasting biological and economic impacts of aquatic invasive species in Lake Michigan

Grantee Organization: Great Lakes Fisheries Trust

Project Team:

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Key Search Words: bighead and silver carp, aquatic invasive species, coupled systems, ecosystem modeling, computable general equilibrium modeling, recreation demand, Lake Michigan

BACKGROUD/OVERVIEW

1. Briefly summarize the project description as outlined in the original proposal

Fisheries in the Great Lakes are estimated to contribute $5 billion annually to the local and regional economies (NOAA, 2016), yet these valuable industries are continually invaded and damaged by non-indigenous aquatic invasive species (AIS) (Vander Zanden et al., 2010; Zhang et al., 2016). AIS threaten the ecosystem and the economy by altering food webs, energy flows, species biomass levels, and commercial and recreational activities (Snyder et al., 2014; Pejchar and Mooney, 2009). Often, complex tradeoffs exist between ecological and economic impacts, making it difficult to assess human and ecological implications and treatment options. For example, Alewives reduced reproduction of native species, like lake trout and yellow perch, by feeding on their larvae (Kornis and Janssen, 2011), but provided additional prey for economically valuable salmonines (Madenjian et al., 2008; Jacobs et al., 2013). Similarly, Dreissena mussels negatively impacted power plant operations (Pejchar and Mooney, 2009), yet increased water clarity and light penetration (Mayer et al., 2001; Vanderploeg et al., 2012).

Identifying these biological and economic tradeoffs and their implications on human and ecological welfare is key to making informed management decisions regarding prevention or control of the AIS. The intent of this research project was to produce estimates of welfare for cost-benefit analysis of management options, by developing models that do not neglect key relationships between the natural and economic systems, and generate more accurate estimates and policy analysis. Building such models, however, are difficult as wild species (e.g. fish) inherently move across time and space, invasive species heterogeneously impact wild species, individual consumer behaviors change based on ecosystem services, and the general flows of goods and services shift within the local or regional economy to account for the invasion. While each of these difficulties has been addressed individually, recent attempts to bring them together have failed to fully merge the different spatial and temporal scales of the economic and environmental systems. The purpose then of this project is to fill the void, to enhance and improve bioeconomic modeling frameworks to inform fisheries management and policy response to invasive species.

A computable general equilibrium (CGE) model is built to account for spatially explicit, species-level impacts from the current threat of invasion and establishment in Lake Michigan of bigheaded carp, an AIS projected to have detrimental impacts on food webs in the Great Lakes (Zhang et al., 2016; Wittmann et al., 2015; Chick and Pegg, 2001). Using the results of the Atlantis ecosystem model of Lake Michigan, developed by Fulton et al. (2011), simulations of the invasion impacts on biomass levels of each fish species are produced. The forecasted biomass effects are then used to project changes in recreational fishing behavior. A model of recreational demand is developed within the CGE where it is assumed that fishermen demand species biomass, a measure of environmental quality, to reach desired levels of overall quality or enjoyment from fishing; the treatment of which is borrowed from Carbone and Smith (2013). Because the invasion will affect different parts of the lake in different ways, recreational demanders can substitute across zones (change fishing locations) in Lake Michigan. These choices are modeled as a spatially explicit, zone-level application of a modified household production function decision process. Space or location and species preferences are reflected in fisherman decisions and incorporated into a CGE model making it spatially explicit and species-specific. The model construction and implementation fulfills five project objectives:

1. Develop an Atlantis model for Lake Michigan and adapt it for invasion scenario simulations.

2. Develop a computable general equilibrium (CGE) model of the regional economy and extend it through an aggregation methodology to couple recreational demand modeling with the broader scale, non-spatially explicit CGE model.

3. Couple the ecological and economic models.

4. Use the coupled models to evaluate the ecological and economic consequences of invasions of Bighead Carp.

5. Use the coupled models to evaluate the ecological and economic consequences of invasion control scenarios to allow managers and agencies to weigh the potential value of policies.

2. Briefly summarize any significant changes to the work performed in comparison to the originally proposed and funded plan of work. If changes were made, describe how they affected your ability to achieve the intended outcomes for the work.

Due to the spatial delineation decided on by the team for the Atlantis ecosystem model, the seamless use and reconciliation of empirical recreational demand estimation was not possible. Though fishing demand was unable to be empirically derived at a finer scale, we built our own model of recreation demand that was compatible with the CGE model; the model allowed for substitutions between species and fishing sites, which occurred in response to both price and incomes effects. Clear price and income effects would not have been possible with the empirical approach originally proposed.

We ran simulation scenarios for bigheaded carp invasion at the current level of Dreissena mussel biomass in Lake Michigan. In a related project, we used the Atlantis model to evaluate the relative effects of quagga mussels and nutrient loads on the Lake Michigan food web, which was the basis for Nicholas Boucher's masters thesis at the University of Michigan. For Boucher's thesis, he ran simulation scenarios with and without quagga mussels at three different nutrient levels (double, half, and current phosphorus loadings to Lake Michigan). Boucher's analysis informed us about the effect of quagga mussels on the Lake Michigan food web. In the future, we plan to use the Atlantis model to simulate bigheaded carp invasion on the food web without quagga mussels to see if the presence of quaggas has influenced the potential for bigheaded carp to grow and affect the food web and the regional economy. We hope to present this work at the Lake Michigan Technical Committee, the annual meeting of the Great Lakes Fishery Commission, and the Asian Carp Regional Coordinating Committee.

OUTCOMES

3. To what extent and how (if at all) did this research project advance scientific knowledge of the issue?

Scientific knowledge of the issue was advanced in several ways due to this research. From the ecological standpoint, this is the first adaption of the Atlantis Ecosystem model to fit Lake Michigan. The calibration of the Atlantis model can now be used for assessment of invasive species impacts and other exogenous shocks to the Lake ecosystem.

We can use the Atlantis model to evaluate climate change effects on the phenology of the lake's production cycle, and spatial distributions of organisms. Also, we can evaluate the interactive effects of multiple stressors including nutrient loads, invasive species and climate change. The calibrated Lake Michigan Atlantis model can now be used to project spatio-temporal impacts of bigheaded carp, and thereby guide management surveillance efforts.

We also can use output from the Atlantis model, along with output from prior Ecopath with Ecosim modeling efforts on bigheaded carp impacts on Lake Michigan to assess potential areas of uncertainty about bigheaded carp impacts. In contrast to the Atlantis model, the Ecopath model is not spatially explicit, has a coarse time step, and does not incorporate lake temperature or hydrodynamics as model inputs.

Contributions to the economic literature include (1) expanding the ecological representation in a computable general equilibrium (CGE) framework, (2) modeling spatial recreational demand within the CGE, and (3) integrating spatially explicit ecological details with non-market values in recreational demand. By coupling the ecological and economic systems through spatial recreation demand and analyzing the model, we identify the importance including space and species-specific information when estimating welfare impacts from an invasive species. In particular, the comparative analysis suggests that biases may result in welfare estimates if the modeling approach aggregates out spatial or ecological detail.

4. To what extent and how (if at all) did this project contribute to the education and advancement of graduate or undergraduate students focused on Great Lakes fishery issues?

Through this grant and collaborative work, Stephanie Brockmann (a University of Wyoming graduate student) was able to complete her dissertation research. Her dissertation work was directly related to this project and expanded on the models used in this report. The research has provided her with the potential for peer-reviewed publications and has generated several opportunities for her to present at conferences and symposiums.

Nicholas Boucher used the Lake Michigan Atlantis model developed on this project to explore the relative effects of nutrients and quagga mussels on the lake's food web and fisheries. This experience provided him with a thorough understanding of ecosystem models and modeling, Great Lakes fisheries management, and food web dynamics. He also gained valuable experiences from presenting his work at regional and international meetings and getting feedback from university and agency scientists, and fisheries experts.

5. To what extent and how (if at all) did this work help you or others on your team build new relationships with others in the research or management communities?

Invitations and acceptances to conferences have allowed for communication and new collaborations with scientific and research communities. Additionally, the research team collaborated closely to design the models and identify data sources for use in calibration.

Work on this project encouraged development of a proposal to NSFs Coupled Natural and Human Systems initiative, and expanded our collaborations with scientists and managers from varied disciplines and areas. We developed ideas and had discussions with members of the Great Lakes Fishery Commission, with ecologists at the Nature Conservancy (Lindsay Chadderton), social scientists at University of Michigan (Victoria Campbell-Arvai) and Michigan State University (Ken Frank), and fisheries scientists working on the Illinois River (Kevin Irons) and the Mississippi River (Jim Garvey, Duane Chapman, Quinton Phelps).

6. To what extent and how (if at all) do the findings have action implications for fishery managers? If the research has direct management implications, do you have any knowledge of use of the findings by managers? If the research does not have direct management implications at this stage, to what extent did the research advance the process of identifying management responses to critical issues?

This work on bighead and silver carp explicitly outlines the need for fishery managers to invest in prevention and control, because the integrated ecosystem and economic model generates welfare losses in the wake of an invasion. Our findings suggest that consumers substitute across locations, specifically to areas that are less impacted ecologically and are therefore less expensive to fish in. Direct management actions then inherently depend on the ecological and economic characteristics of each spatial location. Through a limited policy analysis, we show that controlling in the least-impacted and least-costly areas can lead to worse welfare outcomes because of the invasion's heterogenous impact on specific species.

In general, our work identifies critical modeling decisions that matter as a first step toward making management decisions and assessing whether responses by management agencies are warranted. As work continues, decisions of managers will be explicitly included in the modeling framework.

7. Considering the above or other factors not listed, what do you consider to be the most important benefits or outcomes of the project?

We find that the spatially-explicit and species-specific model results provide support for modeling economic and ecological relationships that reflect preferences and tradeoffs. The model suggests that the portfolio of species in each zone, fisher preferences, and the biological impacts on certain species matter for estimating welfare. The invasion causes trips, quality production, and overall fishing to become more expensive. Consumers substitute to cheaper species and cheaper zones when they can, but the cost of the invasion is significant. Economy-wide redistributions of labor/capital and reduced demand for both recreational and non-recreational fishing goods contract the economy. Households earn less income and welfare falls.

In considering models that exclude or aggregate out space, species-specifics, or both, we find welfare estimates will likely be biased. When only species specifics are included the impacts from the invasion are overestimated due to inefficient constraints on cost minimization. When space remains but the portfolio of species is condensed to one, non species-specific value, the model only captures a small part of the story: the ability to substitute across fishing locations. Assuming that fisherman value each species the same in this analysis produced the greatest discrepancy in welfare estimates. The model that neglected space and species specifics created a net effect on welfare that fell between the species-only and space-only models. Regardless, each of the three alternative aggregations produced welfare estimates that differed from one another.

When designing a model to assess welfare estimates in cost-benefit analysis of prevention or control strategies, it is important that the researcher identify and understand the economic and ecological tradeoffs and preferences in space and amongst affected species when there is an invasive species threat. Biased welfare estimates can lead to improper policy suggestions. The final outcome of importance for our analysis is the identification of how ecological characteristics matter for effective policy making.

RELATED EFFORTS

8. Was this project a standalone effort, or was there a broader effort beyond the part funded by the GLFT? Have other funders been involved, either during the time of your GLFT grant or subsequently?

No.

9. Has there been any spinoff work or follow-up work related to this project? Did this work inspire subsequent, related research involving you or others?

Yes, Stephanie Brockmann's dissertation research was closely related to this project. Her work refined the spatial resolution from the economic perspective using geographic information system (GIS) data and tools to place recreational fishers' locations in space. Additionally, she performed a simplified policy analysis to highlight the importance of knowing how the ecological characteristics influence consumers' responses to policies.

Further future research includes explicitly modeling policy levers in the consumer and producer problems to assess commercial fisheries contracts, subsidy payments, and other market-based instruments. Additionally, it would be desirable to fully combine and construct the Atlantis ecosystem model within the CGE model. This would allow for a wider variety of management options to be considered because all ecological and economic feedbacks would be present in the model. As a final extension, the team has discussed the need for finer data from the economic perspective to derive more specific and empirically relevant fishing demand.

For his masters thesis at the University of Michigan, Nick Boucher used the Lake Michigan Atlantis model developed for this project to evaluate the relative effects of nutrient loads and quagga mussels on the Lake Michigan food web.

The development of a coupled bioeconomic modeling framework through funding from the GLFT inspired us to develop a proposal to NSFs Coupled Natural and Human Systems initiative, to explore current and potential social, economic, ecosystem and management changes generated by Bighead and Silver Carp to the Illinois and Great Lakes ecosystems. The proposal was titled "Risk, perception and resilience of coupled natural and human systems to aquatic invasive species", and received good reviews, but unfortunately was not funded.

COMMUNICATION/PUBLICATION OF FINDINGS

10. List publications, presentations, websites, and other forms of formal dissemination of the project deliverables, tools, or results, including those that are planned or in process.

<u>We anticipate submitting the following manuscripts for publication:</u>

- Revised work from Stephanie Brockmann's dissertation essay: "Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species."

- Zhang, H., Rutherford, E.S, Mason, D. M., Ivan, L., Campbell-Arvai, V., Beletsky, D., Hoff, M., and Fulton, E., "Ecosystem and Fisheries Impacts of Asian Carp on Lake Michigan - the Atlantis Ecosystem Model Approach." For submission to Ecosystems.

- Boucher, N., Zhang, H., Rutherford, E.S., Mason, D.M., Bunnell, D., and Hu, H.,"The relative effects of changing nutrient loads and Dreissena species grazing on Lake Michigan's food web." For submission to Ecosphere.

Seminars and presentations

- Drs. Zhang, Mason and Rutherford chaired a symposium at the 2016 annual meeting of American Fisheries Society, titled 'Coupled Interactions between Natural and Human Systems: On the Interplay between Aquatic Ecosystem Health, Human Behavior and Decision-Making, and Aquatic Invasive Species' at Kansas City, MO, August 21-26.
- Zhang, H., Rutherford, E.S, Mason, D. M., Ivan, L., Campbell-Arvai, V., Beletsky, D., Hoff, M., and Fulton, E., "Ecosystem and Fisheries Impacts of Asian Carp on Lake Michigan - the Atlantis Ecosystem Model Approach." The 2016 annual meeting of American Fisheries Society, Kansas City, MO, August 21-26.
- Zhang, H., Mason, D., Ivan, L., and Rutherford, E.S., "Modeling potential effects of bighead and silver carp on Great Lakes food webs." Canada AIS Centre. 2017. Webinar.
- Boucher, N., Zhang, H., Rutherford, E.S., Mason, D.M., Bunnell, D., and Hu, H., "The relative effects of changing nutrient loads and Dreissena spp grazing on Lake Michigan's food web." NOAA's Oceanic and Atmospheric Research Webinar, 2018
- Boucher, N., Zhang, H., Rutherford, E.S., Mason, D.M., Bunnell, D., and Hu, H., "Investigating the effects of climate change in Lake Michigan using the Atlantis Ecosystem Model," The International Association of Great Lakes Research Annual Conference, 2018.
- Boucher, N., Zhang, H., Rutherford, E.S., Mason, D.M., Bunnell, D., Hu, H., and Fadlovich, R., "Simulations of spatial variability in Lake Michigan food web dynamics using the Lake Michigan Atlantis Ecosystem Model," International Association of Great Lakes Research State of Lake Michigan Conference, 2017

- Brockmann, S., “Integrating Spatial Decision-Making and Geographic Information Systems to Assess Welfare Impacts from Invasive Species,” The Tropical Agricultural Research and Higher Education Center (CATIE) and Environment for Development Initiative (EfD) Seminar Cartago, Turrialba, CR, 2018.

- Brockmann, S., “Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species,” World Congress of Environmental and Resource Economists Parallel Session, Gothenburg, SWE, 2018

- Brockmann, S., “Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species,” Colorado State and Wyoming Graduate Student Symposium Fort Collins, CO, 2018

- Brockmann, S., “Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species,” American Economic Association Meetings, Omicron Delta Epsilon Graduate Student Session Philadelphia, PA, 2018

- Brockmann, S., “Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species,” Kalamazoo College, Kalamazoo, MI, 2019

- Brockmann, S., “Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species,” University of New Hampshire, Durham, NH, 2019

- Brockmann, S., “Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species,” Allegheny College, Meadville, PA, 2019

- Brockmann, S., “Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species,” University of Delaware, Newark, DE, 2019

11. Please characterize your efforts to share the findings of this research with state, federal, Tribal, and interjurisdictional (e.g., Great Lakes Fishery Commission) agencies charged with management responsibilities for the Great Lakes fishery. If other audiences were priority for this research, please characterize your outreach efforts to those audiences as well. (Please note: You may wish to consult midterm reports in which specific audiences for the findings, and means of outreach to these audiences, were identified.)

We shared the preliminary findings of our research with members of the Great Lakes Fishery Commission (Marc Gaden, John Dettmers, Roger Knight and Jeff Tyson). We also shared results with members of the Army Corps of Engineers who are charged with evaluating risk of bioeconomic effects of bigheaded carp in the Great Lakes if the carp move past the Brandon Rd Lock and Dam and enter Lake Michigan.

12. Please identify technical reports and materials attached to this report by name and indicate for each whether you are requesting that GLFT restrict access to the materials while you seek publication. (Please note that the maximum amount of time during which GLFT will restrict access to the results of funded research is 18 months, unless notified that more time is needed.)

Technical Report 1 (No restricted access)

Final Report: Forecasting biological and economic impacts of aquatic invasive species in Lake Michigan

Technical Report 2 (No restricted access)

Nicholas Boucher's Masters Thesis: Examining the relative effects of nutrient loads and invasive Dreissena mussels on Lake Michigan's food web using an ecosystem model. 2019. https://deepblue.lib.umich.edu/handle/2027.42/148814

Technical Report 3 (No restricted access)

Stephanie Brockmann's Dissertation: Economic Implications of Ecological and Economic Spatial Aggregations in Integrated Assessments of Invasive Species. 2019.

13. Manuscripts. Grantees submitting one or more publications or pending publications in lieu of a standalone technical report must submit a cover memo that confirms that all aspects of the funded research are incorporated in the published work, and in cases of multiple publications, identifies or crosswalks the grant-funded objectives to the published article containing results.

N/A

14. Compilation reports. Grantees working on several related subprojects under a single grant may submit a series of subproject reports rather than a single, integrated report. However, grantees must submit a cover sheet or introduction that outlines and crosswalks grant objectives with the location of the results in the compilation document.

N/A

DISCUSSION

The discussion presents the principles, processes, and approaches we took to meet each of our desired objectives. Also included is a section describing our results and a section identifying lessons learned.

Objective 1

The Atlantis Ecosystem Model was developed by scientists with the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) that integrates physical, chemical, ecological, and fisheries dynamics in a three-dimensional, spatially explicit domain, formerly known as the Integrated Generic Bay Ecosystem

Model (IGBEM) ((Fulton, 2001), (Fulton et al., 2003), Fulton et al. (2004a), Fulton et al. (2004b), Fulton et al. (2004c)). The basis of this Atlantis model was a combination of the biological modules of the European Regional Seas Ecosystem Model (ERSEM) (Baretta-Bekker et al., 1997) and the physical processes and spatial layout of the Port Phillip Bay Integrated Model (PPBIM) Murray and Parslow (1999). New modification and improvements of Atlantis can be found in its wiki website (https://wiki.csiro.au/confluence/display/Atlantis/Atlantis+Ecosystem+Model+Home+Page). Atlantis has three submodels including a hydrographic submodel, an ecology submodel and a fisheries submodel Figure (1).

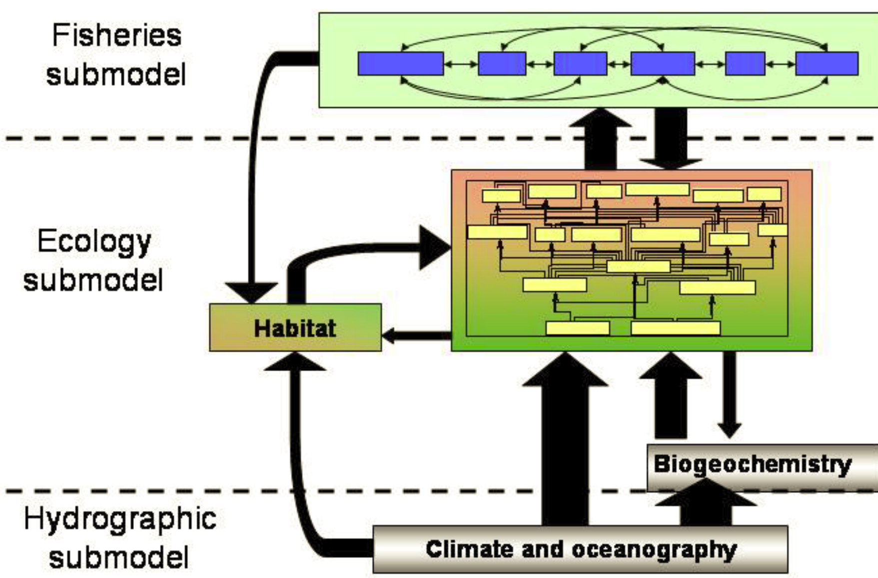

Figure 1: Schematic of Atlantis models for hydrograph, ecology and fishing. This project focuses on the ecology and hydrographic submodels. From Brand et al. (2007).

Configuration to Lake Michigan

Spatial resolutions Many environmental variables were considered in model spatial configuration, including bathymetry, surface water temperature, spring warming rate, substrate, current, fetch, and light. However, we found the most important parameters for configuration were bathymetry, in addition to fishery management units and state borders. To complement the computation time, the model's spatial resolution was mainly based on the bathymetry (30 m and 110 m isoclines) and fishery management boundaries, Figure (2). There are 34 model polygons or boxes and one boundary box located at the Muskegon Lake, a drowned river mouth lake connected to nearshore waters of southeastern Lake Michigan.

Vertically, according to field observation vertical profiles of water temperature and chlorophyll, the water column was divided into 6 layers of different thicknesses, Figure (3).

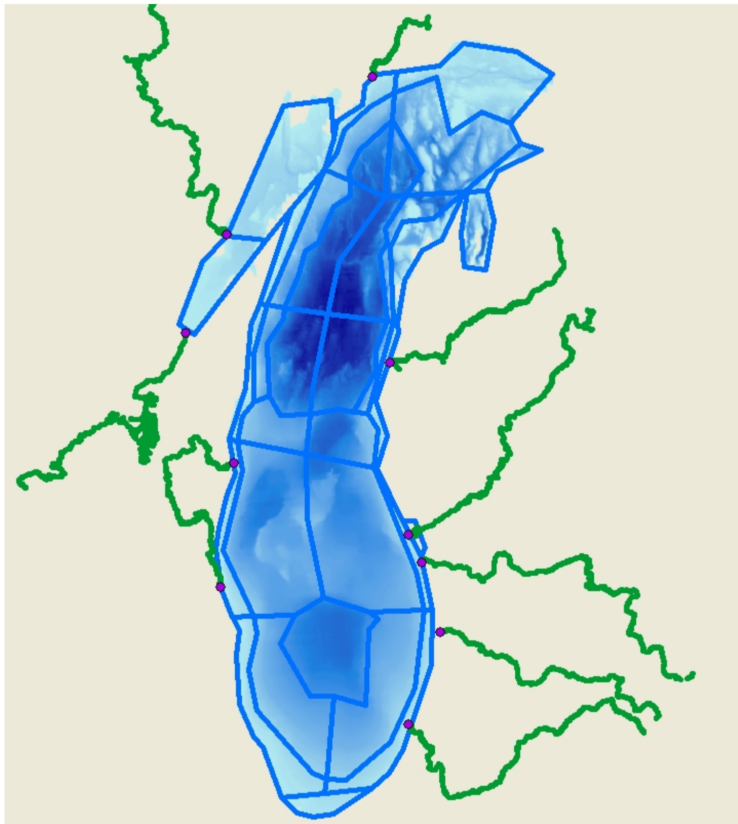

Figure 2: Horizontal spatial resolution for Lake Michigan Atlantis Model. Green lines indicate tributaries to Lake Michigan.

Model groups The dynamics of 38 model groups were simulated, including 18 fish groups (including bigheaded carp); 5 zooplankton, 5 benthic groups, 3 phytoplankton groups Tables (1) and (2). Nitrogen was a common currency between groups. Silica and phosphorus are also simulated dynamically in a very rudimentary fashion.

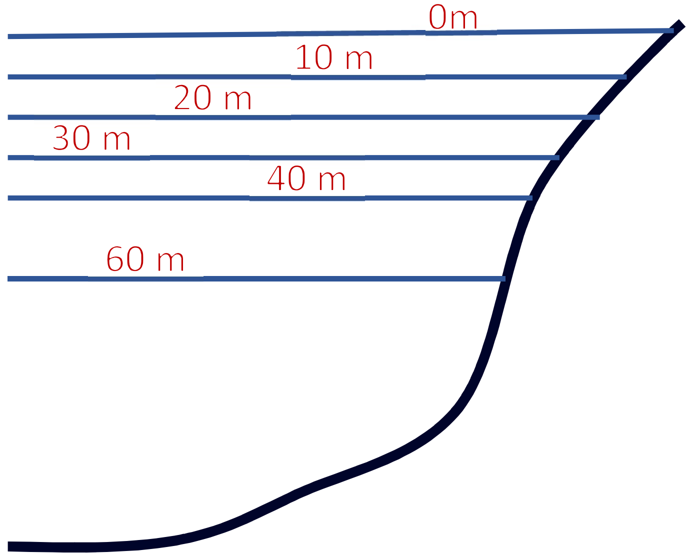

Figure 3: Vertical resolution of the model water column.

Table 1: List of model groups in the Lake Michigan Atlantis Model

Code	**Long Name**	**Type**	**Scientific names**
ALE	Alewife	FISH	Alosa pseudoharengus
BLT	Bloater	FISH	Coregonus hoyi
SSP	Slimy Sculpin	FISH	Cottus cognatus
DSP	Deepwater Sculpin	FISH	Myoxocephalus thompsonii
LWF	Lake Whitefish	FISH	Coregonus clupeaformis
RDG	Round Goby	FISH	Neogobius melanostomus
YPH	Yellow Perch	FISH	Perca flavescens
WAE	Walleye	FISH	Sander vitreus
RSM	Rainbow Smelt	FISH	Osmerus mordax
SLP	Sea Lamprey	FISH	Petromyzon marinus
CHK	Chinook Salmon	FISH	Oncorhynchus tshawytscha
CHO	Coho Salmon	FISH	Oncorhynchus kisutch
STH	Steelhead Trout	FISH	Oncorhynchus mykiss
LKT	Lake Trout	FISH	Salvelinus namaycush
BBT	Burbot	FISH	Lota lota
SLC	Silver Carp	FISH	Hypophthalmichthys molitrix
BHC	Bighead Carp	FISH	Hypophthalmichthys nobilis

Table 2: List of model groups in the Lake Michigan Atlantis Model (continued)

Code	**Long Name**	**Type**
COP	Copepods	MED_ZOO
CLA	Herbivorous Cladocerans	MED_ZOO
BYT	Bythotrephes	MED_ZOO
MYS	Mysis	LG_ZOO
ROT	Rotifers	SM_ZOO
PRO	Protozoa	SM_ZOO
PB	Pelagic Bacteria	PL_BACT
BB	Sediment Bacteria	SED_BACT
AMP	Amphipods	SM_INF
DRE	Dreissenid Mussels	SED_EP_FF
CHI	Chironomids	SM_INF
DIP	Diporeia	SM_INF
OLI	Oligochaetes	SM_INF
GRN	Green Algae	LG_PHY
BLU	Blue Green Algae	LG_PHY
DIA	Diatoms	LG_PHY
MA	Bethic Macroalgae	PHYTOBEN
DL	Labile Detritus	LAB_DET
DR	Refractory Detritus	REF_DET
DC	Carrion	CARRION

Ecological and biological processes, parameter values and data sources

Driving forces Commercial fishery catches were from the US commercial fishery database (Scott Nelson, USGS, personal communication). Water currents, water temperature and surface solar radiation were outputs from a 3-D hydrodynamics model (H. Hu, personal communication). Fish stocking data were from the Great Lakes Fish Stocking Database[1]. Stocked species included chinook salmon, coho salmon, lake trout, rainbow trout, and walleye. Total dissolved phosphorus loads (TDP, 1998-2008) from tributaries were from David Dolan at University of Wisconsin (M. Rowe, NOAA GLERL, personal communication). We assumed the monthly mass ratios between TDP and NH3, NO3, DON, TOP, and Carbon were the same as those of nutrient loads from Muskegon Lake to Lake Michigan, and thereby derived monthly nutrient loads for all tributaries.

Vertebrates All vertebrates in this model are fish species, and modeled with multiple age classes. The number of individuals and their average structural weight (bones and hard parts, in $mg\ N^{-1}$) and reserve weight (soft tissue, in $mg\ N^{-1}$) were tracked for each age class and each spatial model cell through time. Biological and ecological processes that were simulated in the model for fish include growth, consumption, predation, reproduction, movement and migration. See the Atlantis User Guide for equations and parameters.

[1]Great Lakes Fish Stocking Database. U.S. Fish and Wildlife Service, Region 3 Fisheries Program, and Great Lakes Fishery Commission. http://www.glfc.org/fishstocking/index.htm (visited on May 8, 2014)

Invertebrates Invertebrates are simulated as aggregated biomass pools ($mg\ N\ m^{-3}$) in each model cell, with biological processes of growth, predation, and linear and quadratic mortality. The quadratic mortality represents density dependent effects (i.e. predation, disease) that are not explicitly modeled, which may impose a reasonable carrying capacity. See Atlantis User Guide for equations and parameters.

Primary producers Primary producers include phytoplankton and benthic macrophytes. Their growth was simulated as a function of nutrient, light, and temperature. Other biological processes included lysis, grazing loss, linear and quadratic mortality, and space limitation. The initial phytoplankton data were from a Lake Michigan Ecopath with Ecosim model, and values for other parameters were referenced to those from Lake Erie water quality models (Zhang et al. (2008), Bocaniov et al. (2016), Verhamme et al. (2016)). Macrophytes values were from Tomlinson et al. (2010) and studies by H. Bootsma's team at University of Wisconsin Milwaukee (Bootsma (2009), Bootsma et al. (2012)). See Atlantis User Guide for equations and parameters.

Bacteria Bacteria include pelagic bacteria and benthic bacteria. Bacteria biomass is dynamically simulated in the model, which is a function of detritus biomass. The wastes from bacteria were refractory detritus, DON and NH3, which as part of the nitrification-denitrification and remineralization processes. Mortality of bacteria is caused by predation or grazing by different consumers, and other optional conditions (e.g., oxygen limitation, acidification). See Atlantis User Guide for equations and parameters.

Nutrients Nutrients (nitrogen, silicon, phosphorus) were tracked in the Atlantis model, but nitrogen is the common currency. Phosphorous simulation was added for freshwater ecosystems.

Model calibration

We followed the calibration steps suggested by model developers: 1) No species can go extinct, except those whose extinction has been observed in the field during the simulation periods. 2) Simulated vertebrates have reasonable size-at-age. 3) Compare model simulation with historical observations if available. 4) For species with no historical observations, make sure the simulated population dynamics are reasonable. 5) If spatial distributions are available, compare modeled spatial distribution with the observations. Time series of biomass data for calibration included: biomass of zooplankton by taxon groups from Great Lake National Program Office monitoring program; dreissenid mussel biomass from NOAA Great Lakes Environmental Research Lab; fish biomass from the USGS Great Lakes Science Center, and salmonine data from Rogers et al. (2014). Specific data from the Lake Michigan Ecopath with Ecosim model (Rutherford, Zhang, Mason et al. unpublished data) are given in Tables (3), (4) and (5).

Table 3: Initial population biomass (g/m2), growth rates (P/B, per year) and consumption rates (Q/B, per year) of species groups in the Lake Michigan Atlantis model.

Code	**Species**	**Biomass**	**Growth**	**Consumption**
ALE	Alewife YOY	0.598164	3.59	31.8
	Alewife YAO	1.55	1.6	12.43
BLT	Bloater YOY	0.055827	0.944	36.82039
	Bloater YAO	3.9	0.69	9.2
SSP	Slimy Sculpin	0.167	1.51	7.53
DSP	Deepwater Sculpin	0.748	1.13	6.327
LWF	Lake Whitefish YOY	0.025674	0.944	23.41389
	Lake Whitefish Juvenile	0.700357	0.69	8.244582
	Lake Whitefish Adults	0.48	0.7625	5.08
RDG	Round Goby	0.01	0.71	4.7
YPH	Yellow Perch YOY	0.003809	2.66	7.336398
	Yellow Perch Juvenile	0.010279	1.637	4.074439
	Yellow Perch Adults	0.03	0.8	2.207
WAE	Walleye	0.0127	0.214	1.373
RSM	Rainbow Smelt YOY	0.044501	2.26	10.03159
	Rainbow Smelt Adults	0.864	0.529	3.678
SLP	Sea Lamprey	0.000226	0.42	130
LKT	Lake Trout	0.093	0.653	3
BBT	Burbot	0.359	0.25	4.4568

Table 4: Initial population biomass (g/m2), growth rates (P/B, per year) and consumption rates (Q/B, per year) of species groups in the Lake Michigan Atlantis model.

Code	Species	Biomass	Growth	Consumption
CHK	Chinook Salmon year 0	0.011228	0.931	13.21298
	Chinook Salmon year 1	0.048398	1.125	7.66106
	Chinook Salmon year 2	0.04128	1.2	5.59
	Chinook Salmon year 3	0.02037	1.2	4.755089
	Chinook Salmon year 4	0.005161	2.558	4.376491
CHO	Coho Salmon year 1-2	0.012	0.74	6.38
STH	Steelhead Trout year 1	0.01549	0.518	4.307736
	Steelhead Trout year 2-5	0.077	0.305	2.9043
	Steelhead Trout year 5+	0.017145	1.48	2.530676
SLC	Silver Carp YOY	0.005527662	2.6747	60.87502
	Silver Carp	0.198	0.631	15.15
BHC	Bighead Carp YOY	0.005389431	2.7028	62.96807
	Bighead Carp	0.198	0.654	15.15
COP	Copepods	5.63	4.9	22.3
CLA	Herbivorous Cladocerans	1.472	18.04	64.42857
BYT	Bythotrephes	0.0528	26.18	96.96296
MYS	Mysis	2.04	4.6	13.7
ROT	Rotifers	0.568	44.9	187.0833
PRO	Protozoa	8.42942	108.7	317.6

Table 5: Initial population biomass (g/m2), growth rates (P/B, per year) and consumption rates (Q/B, per year) of species groups in the Lake Michigan Atlantis model.

Code	**Species**	**Biomass**	**Growth**	**Consumption**
PB	Pelagic Bacteria	17.73281	248	473
DRE	Dreissenid Mussels	2.26	3	11.86
CHI	Chironomids	0.632	7	37.03704
DIP	Diporeia	14.44	5.86	91.5
OLI	Oligochaetes	9.95	4.425	23.4127
GRN	Phytoplankton	23.95705	200	-
PIC	Picoplankton	10.43393	343.8	-

Lake-wide calibration Model simulated biomass for 19 model groups compared to field estimates of lake-wide biomass, shown in Figures (4) and (5).

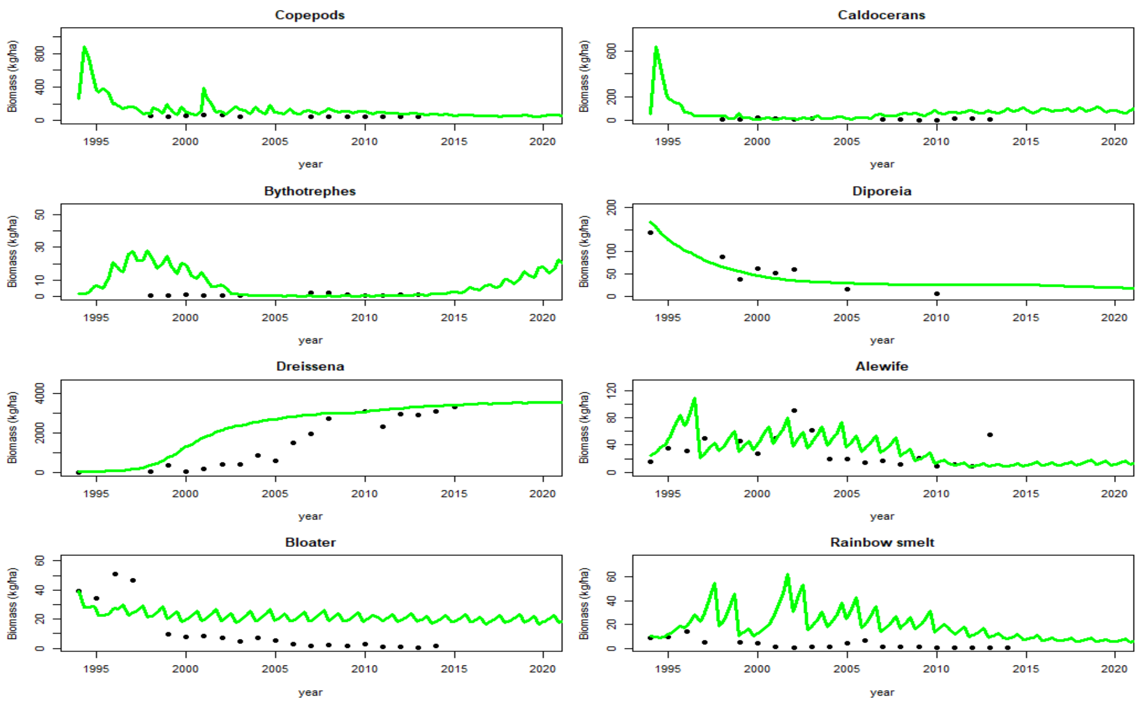

Figure 4: Model calibration on time series of biomass for model groups. Dots indicated observations, lines are for simulation output.

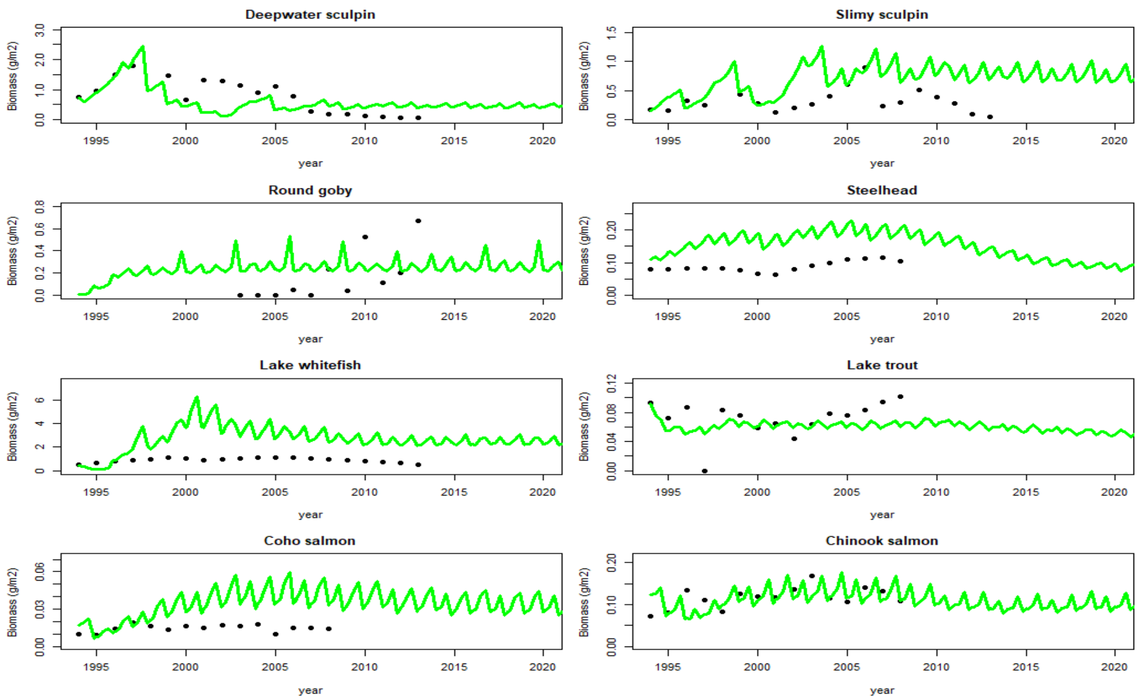

Figure 5: Model calibration on time series of biomass for model groups. Dots indicated observations, lines are for simulation output.

Spatial calibration We calibrated the dreissenid mussel biomass spatial distribution across different depth with observations from Dr. Ashley Elgin at NOAA Great Lakes Environmental Research Lab. Figure (6) presents the calibration data and simulations across depths.

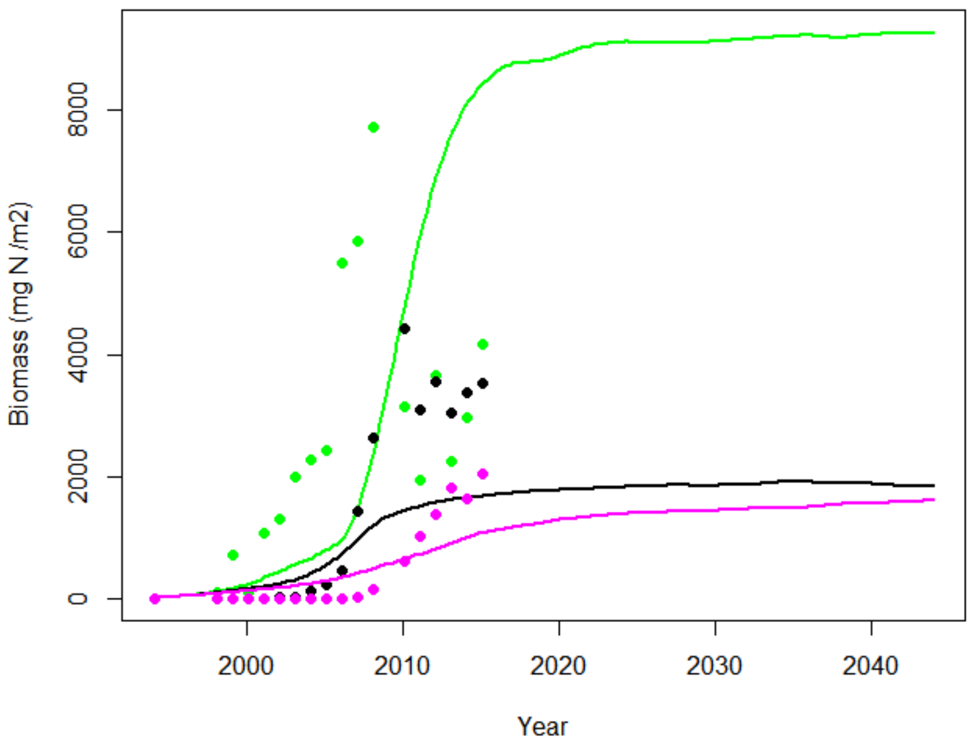

Figure 6: Comparisons of dreissenid mussel biomass between observations and model simulations at different depths (green for 30-50m, black for 50-90m and magenta for > 90m).

Simulation scenarios

Bighead and Silver carp (collectively, bigheaded carp) were added into the Atlantis model, and parameter values were based on Zhang et al. (2016). We ran the model for 50 years, and then output the biomass for different species including bigheaded carp across different habitats, Figure (7). In the figure, zone 1 (in green) is southern Green Bay, zone 2 (in yellow) is northern Green Bay and northern Lake Michigan, zone 3 (in blue) is northwest Lake Michigan, zone 4 (in black) is southwest Lake Michigan, and zone 5 (in light blue) is southeast Lake Michigan. The deep water areas (greater than 110m deep, in red) are not included in the analysis. To evaluate the impacts of bigheaded carp on fish production, we compared the differences of fish biomass between simulations with and without bigheaded carp. We did a sensitivity analysis on bigheaded carp consumption by setting bigheaded carp maximum clearance rates to 125% 75%, 50% and 25% of the baseline clearance rate (100%).

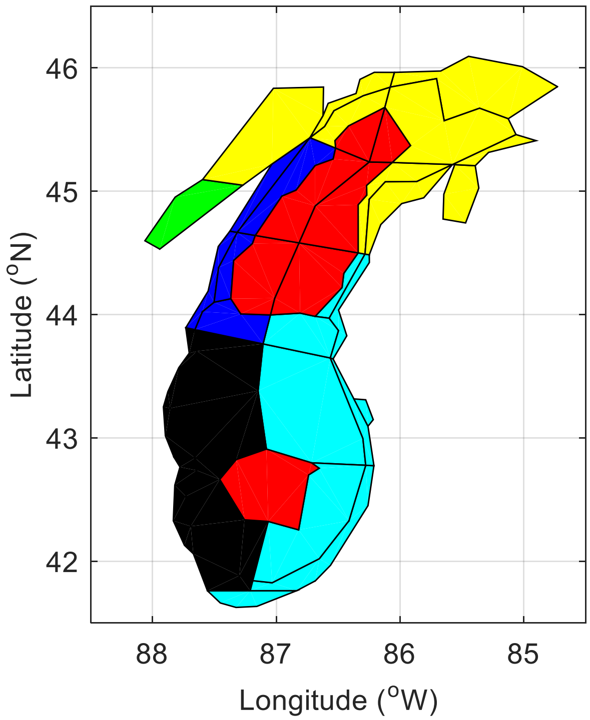

Figure 7: Zones for aggregating Atlantis model output of sport fish biomass and harvest to serve as input to economic model analysis. Different colors represent different zones.

Simulation results

All simulation data are available, including biomass over the simulation period for each model group from each zone. The difference in biomass between bigheaded carp simulation scenarios and the baseline scenario of no bigheaded carp was also presented for each group and each zone. Here we present biomass dynamics of 4 resident fish species (alewife, lake whitefish, chinook salmon, and coho salmon) under different bigheaded carp consumption scenarios over simulation periods.

Simulated bigheaded carp biomass Due to model limitation, we have to introduce bigheaded carp at the beginning of the simulation year 1994. Bigheaded carp biomass increased over time and didn't reach an equilibrium status by the end of 50 simulation years, Figure (8). Bigheaded carp biomass increased with increasing consumption rates. At low consumption rates, silver carp may not survive.

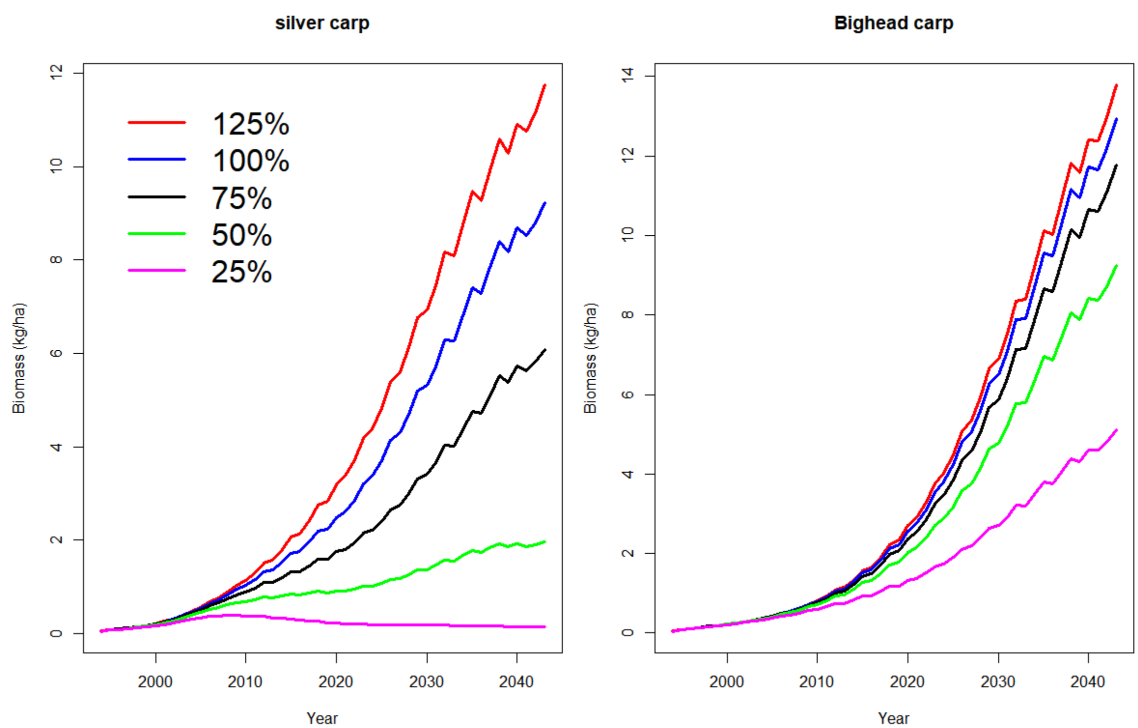

Figure 8: Biomass of silver carp (left) and bigheaded carp (right) from zone 5 under different consumption rates. The number in the legends indicated the consumption of the baseline consumption, e.g., 125% means the consumption in this scenario is 125% of the baseline consumption rate.

Biomass of resident fish species Alewife biomass declined to very low levels after 2010. Lake whitefish biomass was sustained over the simulation period due to the growing food sources from dreissenid mussels and round gobies. Chinook salmon biomass was highly variable over time. Steelhead biomass decreased after 2010 and stayed low. The differences among different bigheaded carp scenarios were smaller than the variation in the fish dynamics due to other factors.

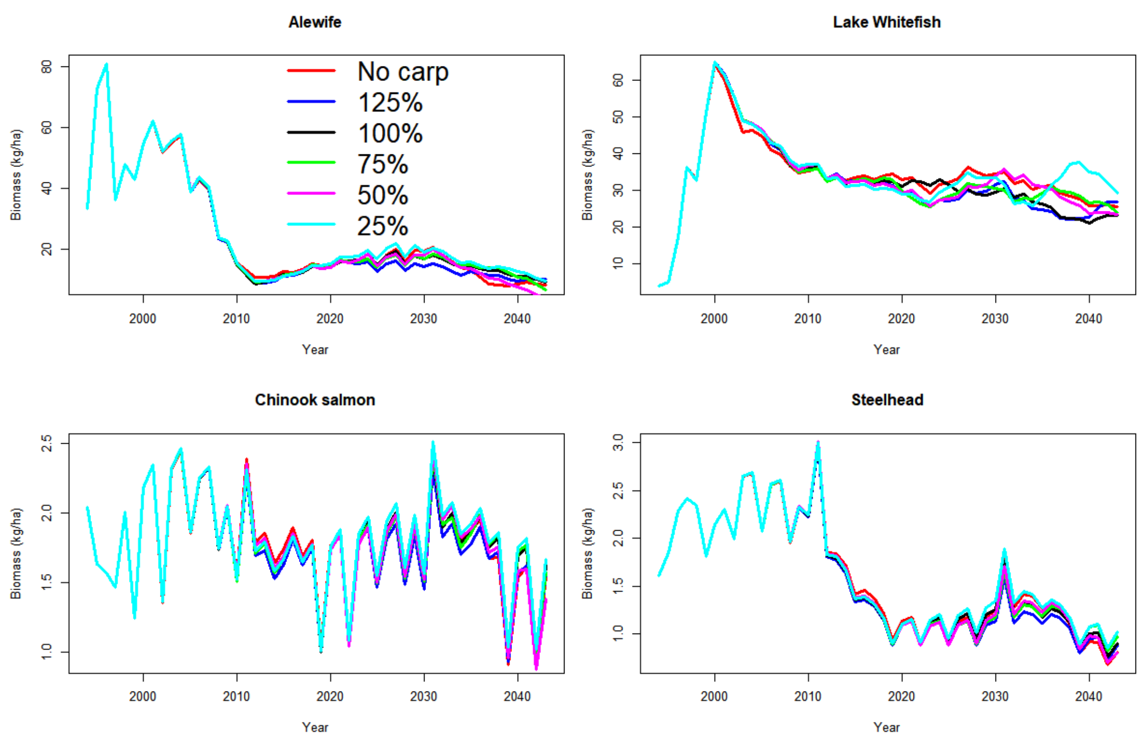

Figure 9: Biomass of resident fish species over simulation periods from zone 5 under different bigheaded carp consumption rates. The number in the legends indicated the percentage increase in carp consumption over the baseline consumption rate, e.g., 125% means the carp consumption in this scenario is 125% of its baseline consumption rate.

Bigheaded carp effects on other fish Bigheaded carp effects on resident species were very small, although higher carp consumption rates tended to result in larger negative effects Figure (10). When bigheaded carp biomass is low (low consumption rates), the effects on other fish species tend to be positive, which may be due to bigheaded carp providing extra food for predators and releasing some of the predation mortality on prey fish.

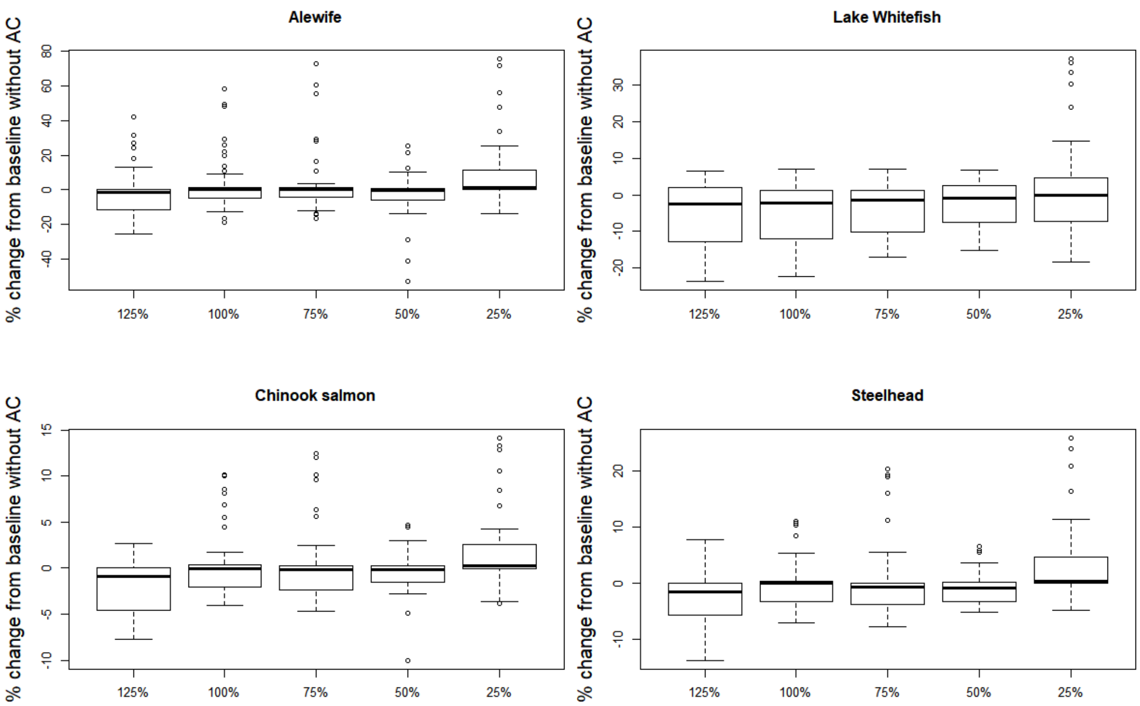

Figure 10: Percent changes in fish biomass under different bigheaded carp scenarios, compared to the baseline without bigheaded carp in the model. The number in the legends indicated the percent increase in bighead carp consumption compared to the baseline carp consumption, e.g., 125 means the consumption in this scenario is 125 % of the baseline consumption rate.

Bigheaded carp effects on sport fishes by Lake Michigan zone The spatial consequences of the invasion on sport fishes have an impact on human behavior in the merged models. Fishes key to the recreational fishery include: bloater, burbot, chinook and coho salmon, lake trout, lake whitefish, rainbow smelt, steelhead, walleye and yellow perch. The economic analysis is based on the 100% carp consumption rate scenario. To document the spatial impact on these species, the percentage differences between species biomass with and without bigheaded carp are presented in Figures (11) and (12).

Figure 11: Percent changes in select fish biomass by Lake Michigan zones for the 25 years used in the economic analysis.

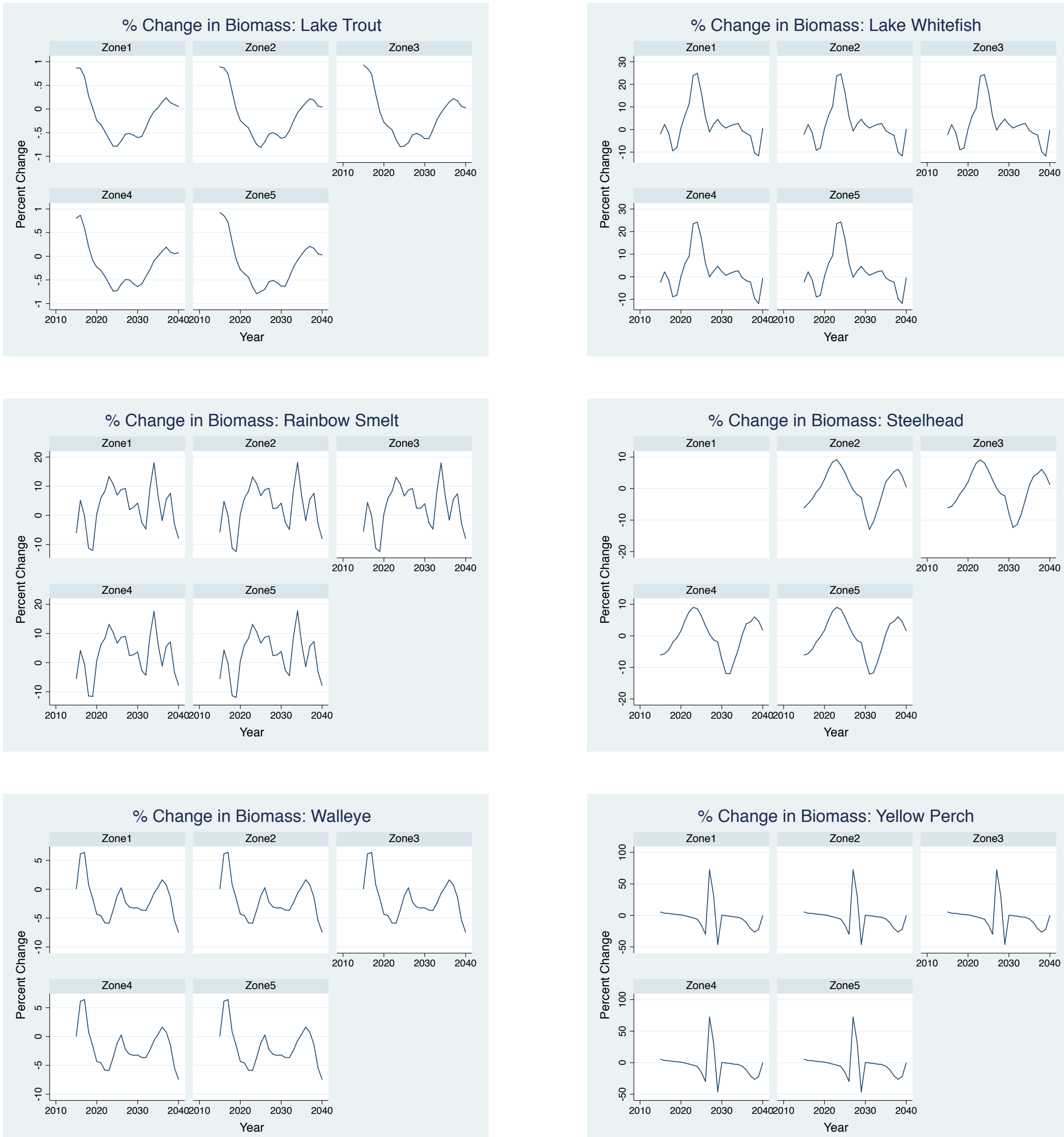

Figure 12: Percent changes in select fish biomass by Lake Michigan zones for the 25 years used in the economic analysis.

A projected invasion of bigheaded carp to Lake Michigan has spatially heterogeneous consequences among and within species and across zones, which has an effect on associated human behaviors. Average annual percentage changes are shown in

Figure (13). With the invasion, all select fishes other than bloater, lake whitefish and rainbow smelt experience declines over the course of the invasion, although the extent and duration of the declines vary by species and zone.

Species	Average % Change in Biomass, by Zone				
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Bloater		+	+	+	+
Burbot	-	-	-	-	-
Chinook		-	-		-
Coho	-	-	-	-	-
Lake Trout	-	-	-	-	-
Lake Whitefish	+	+	+	+	+
Rainbow Smelt	+	+	+	+	+
Steelhead		+	-	-	-
Walleye	-	-	-	-	-
Yellow Perch	-	-	-	-	-

Figure 13: Summary of average annual percentage changes in biomass. "+" signs indicate a positive average annual and "−" signs indicate a negative average annual percentage change.

Objective 2

We assess the economy wide implications of the invasion scenarios by linking the outputs of the Atlantis model with a model of the regional economy. A summary of the process follows Figure (14):

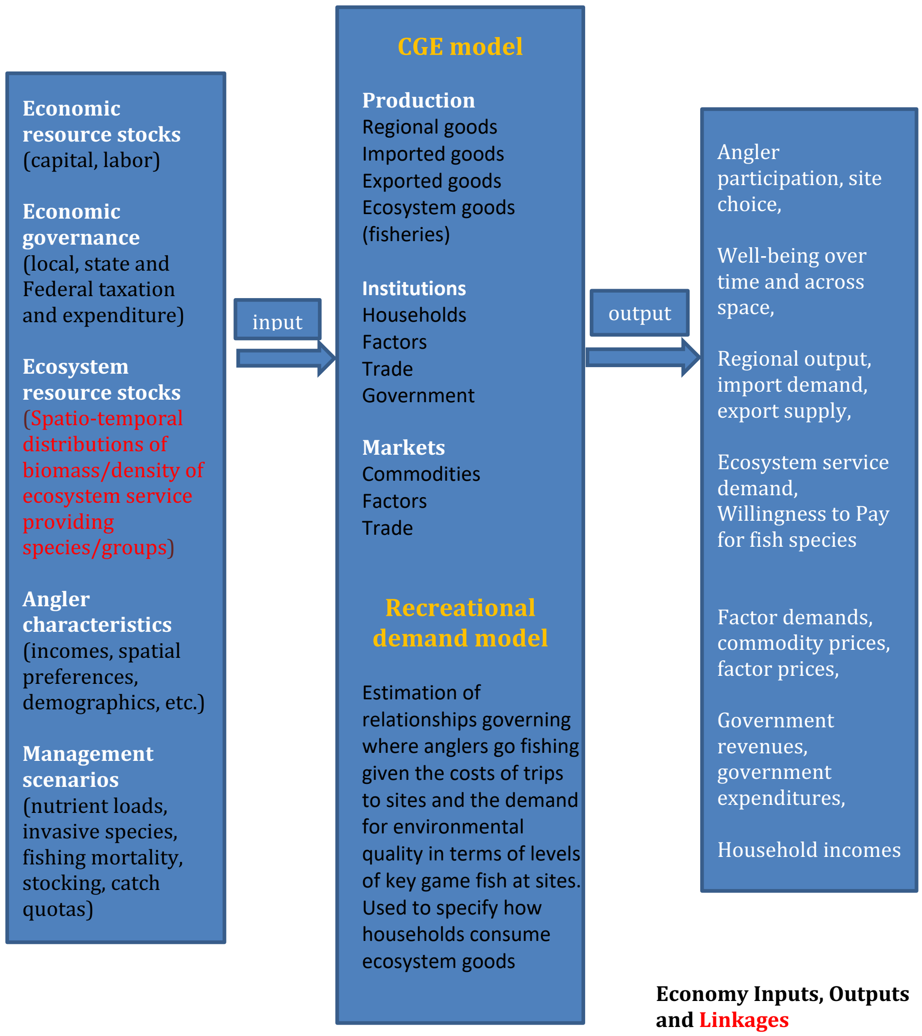

Figure 14: Elements of the CGE model.

The regional economy consists of households and producing sectors, linked to one another and the rest of the world through commodity and factor markets, and linked to the Lake Michigan ecosystem by outputs of the Atlantis model, spatiotemporal distributions of biomass/density of ecosystem service providing species/groups. Households own economic resource stocks (capital and labor) and are differentiated by income (into nine household groups). Producing sectors are aggregated into nine industries which allow a specific focus on the linkages between the economic and ecological models and allow for wide ranging analyses of alternative policies. Table 6 presents the industries.

Table 6: Industries

Agriculture	Commercial fishing
Power generation	Gasoline/Fuel
Air transport	Rail transport
Water transport	Truck transport
Miscellaneous	

The miscellaneous industry is a catch-all for all other production in Michigan. An IMPLAN derived social accounting matrix (SAM) for 2014 provides the bulk of the benchmark dataset. These manipulations to the IMPLAN data are detailed below.

Several species provide inputs to ecosystem services, the focus here being to recreational demand for sport fishing. Incorporating recreational demand that takes place over space and across species requires a significant expansion of household behavior as show in Figure (14). Table 7 lists the ten species identified from the Atlantis model as significant components of recreational demand.

Table 7: Sport fishes

Chinook	Lake Trout
Coho	Burbot
Steelhead	Bloater
Walleye	Lake Whitefish
Yellow Perch	Rainbow Smelt

We briefly outline the economic approach before considering important components in detail. Among the numerous economic CGE models, those pioneered by (Ballard et al., 1985) and (De Melo and Tarr, 1992) provide a basis for the CGE developed in this project. The approach consists of a sequence of static optimizations and resulting equilibria connected through the evolution of the Atlantis model resource stocks.

Labels for the aspatial sectors in the model are given in Table (8). Profit-maximizing, price-taking firms employ capital and labor in all sectors, to produce their outputs in a continuous, nonreversible, and bounded process. Outputs from industries may be used as intermediate goods in production by other sectors, sold in regional markets and exported out of the region to domestic (lower 48 States) or foreign markets, while regional production is differentiated from aggregate imports following Armington (1969). Capital and labor are homogeneous, perfectly mobile within the region, and defined in service units per period. Firms in sector i employ factors of production and intermediate goods to produce their output, which is sold in regional markets and exported out of the region to either domestic markets, or foreign markets. Substitution between regional supply and aggregate exports is given by constant elasticity of transformation (CET) functions as are the substitution possibilities between exports to domestic markets and exports to foreign markets. Firms smoothly substitute over primary factors through constant elasticity of substitution (CES) functions, but employ intermediates in fixed proportions through Leontief functions.

Table 8: Institution labels

Sector	**Label**	**Sector**	**Label**
Agriculture	AGR	Commercial fishing	FISH
Power generation	POW	Gasoline/Fuel	FUEL
Air transport	AIRT	Rail transport	RAILT
Water transport	WTRT	Truck transport	TRKT
Miscellaneous	MISC	Labor	LAB
Capital	CAP	Indirect business taxes	INDT
Household group 1	HHD1	Household group 2	HHD2
Household group 3	HHD3	Household group 4	HHD4
Household group 5	HHD5	Household group 6	HHD6
Household group 7	HHD7	Household group 8	HHD8
Household group 9	HHD9	Federal government	FGOV
State government	SGOV	Inventories	INV
Foreign trade	FT	Domestic trade	DT

Households are differentiated by their income category and demand composites of regionally produced goods and imports, where imperfect substitution possibilities are given by nested CES functions. Household demands are governed by CES functions over aggregated goods, where the price consumers face are indices of aggregate import and domestic prices, with domestic and foreign import prices taken exogenously. Substitution possibilities in demand between foreign and domestic imports are also governed by CES functions. Household incomes are derived through a two-stage process. Households are endowed with labor and capital. These factors are exchanged in factor markets, and through production generate value added. Value added expenditures flow first to the factor "institutions", and are then redistributed to households. Total factor payments to households from value added are net of factor taxes, depreciation allowances, rents attributable to the factor (which are distributed to households from corporations through enterprise income), and labor payments out-of-region.

Government behavior is admitted to the model in two layers: a Federal level and an aggregated State and Local government level. Government entities operate according to a balanced budget, produce and consume goods and activities related to tax and trade. Government revenues are from taxes (indirect business taxes, primary factor taxes, and income taxes all taken fixed as proportions of output), sales of governmentally produced commodities, and government borrowing and transfers. These revenues are then redistributed in lump sum to both consumers and producers.

Equilibrium conditions follow Ballard et al. (1985) and De Melo and Tarr (1992). Model closure is based on net financial inflows (from foreign and domestic sources) adjusting to balance the regional investment savings balance.

Welfare measures follow Ballard et al. (1985). Annual equivalent variations measure welfare changes for any single period across policy scenarios. Cumulative aggregate welfare measures are found using discounted summations of annual equivalent variations, which provide a comparative measure as they based upon a common baseline price vector.

Model Details

Behavioral foundations The CGE model incorporates actions and behaviors of firms, consumers, the government, and the ecosystem. Interconnecting the economy and using where possible constant elasticity of substitution (CES) functional forms consumers and firms substitute between goods and inputs, respectively, when incomes and prices are changing in the economy. For consumers, their consumption patterns are expected to be impacted by the invasion of the AIS, as they derive utility from production of fishing experiences that require biomass of fish species. At present, firms are not expected to be directly impacted by the AIS in their production though they may be indirectly affected through changes in consumption patterns. Only a general overview of the firm and government treatments is provided here, as they follow the standard CGE approach. Instead, the focus is on the model features that are novel to CGE analysis.

Firms within industries use capital and labor (primary factors), and intermediate inputs from other industries to produce their final product for sale. The production process is characterized by the two-level nest (De Melo and Tarr, 1992) shown in Figure (15).

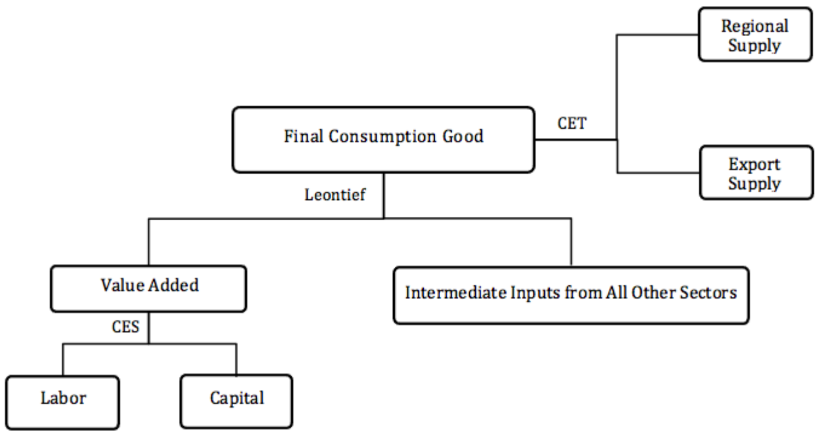

Figure 15: Firm Nest.

At the lowest level of the nest, firms substitute between the primary factor inputs to produce value-added, VA, using a CES function. The VA and intermediate inputs are then combined in fixed proportions following a Leontief production function to produce final output.

The firm's optimization is solved in two steps. First, the firm minimizes the costs associated with production of VA by choosing the amount capital and labor to employ based on the wage and rental rate of capital. And second, the firm minimizes the total cost of production using intermediates and value added. Final output is either exported or domestically consumed and is characterized by a constant elasticity of transformation (CET) function, following De Melo and Tarr (1992). The last optimization problem for the firm is the maximization of their revenue by choosing how much to export and sell domestically given regional and export prices.

As for the treatment of governing bodies and trade, the model includes both state and federal entities and domestic (out of the Lake Michigan region) and international (rest of the world) trade. Brevity is again favored in the description of trade and government as they follow the standard CGE approach. Each branch of government demands and supplies industry goods; demand is a constant proportion of government revenue and supply is a constant proportion of total industry output. For model closure, governments maintain a balanced budget and the current accounts for trade, domestic and international, are balanced.

Integrating Space and Species in the CGE Space- and species-specific impacts are introduced to the CGE through household recreational demand. Using the nine household divisions, it is assumed that a representative consumer from each division derives utility, U, from consumption of fishing, F, and a composite good, X. There are five different zones, as shown in Figure (7), in the Lake Michigan region where the fisherman may choose to fish.

The division of Lake Michigan into spatial zones was determined by ecological classifications of Lake Michigan habitats (Riseng et al., 2017) and the Level III Omernick classification of adjacency (EPA and NHEERL, 2003). The specific characteristics and amenities in each zone - fish biomass, boat docks, shoreline types - can influence the fisherman's demand for fishing in that zone. For this analysis, however, the focus is solely on the differences between fish biomass with and without the impacts from a bigheaded carp invasion.

Utility is nested following the structure in Figure (16).

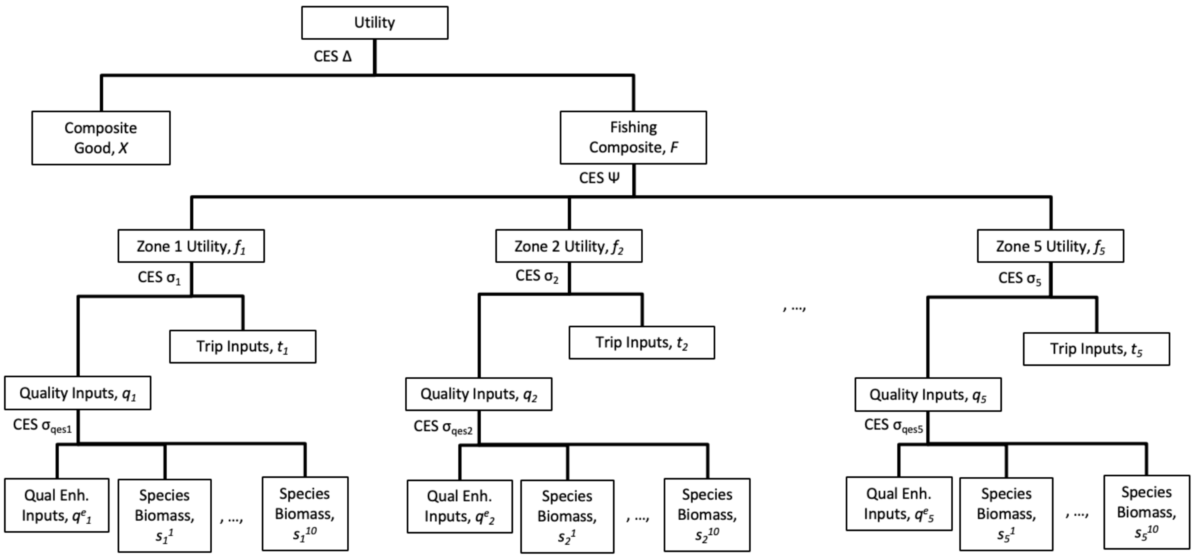

Figure 16: Household nesting.

The representative household from division, h, has a "top" tradeoff between normal consumption goods and recreational demand of fishing. Overall utility

$$U_h = U_h(F_h, X_h), \tag{1}$$

is a CES function of composite fishing consumption, F_h, and composite good consumption, X_h. The household chooses levels of fishing and composite good consumption to maximize utility subject to the budget constraint,

$$Y_h = p_{X_h} X_h + p_{F_h} F_h. \tag{2}$$

in which, Y_h represents household income, p_{X_h}, the composite price of the composite good, and p_{F_h}, the composite price of fishing, by household. Because treatment of each household division is the same, the household subscripts are omitted going forward for clarity. The composite good, X, is itself a CES composite of the nine other (non-recreation) goods; standard treatment of this composite, is to give the consumer options to substitute between domestic and non-comparable imported commodities.

The recreational demand decisions of households that comprise the fishing experience F is given on the right hand side of Figure (16). With options to fish in different parts of Lake Michigan, F is given by a CES subutility function of fishing at each zone, z, such that

$$F = F(f_1, f_2, ..., f_z) \qquad z = 1, 2, ..., 5 \ . \tag{3}$$

Households choose zone-level fishing (or consumption), f_z, to maximize F subject to

$$Y - p_X X = p_F F = \sum_z p_{f_z} f_z. \tag{4}$$

The unit price of zone-level fishing subutility for each zone is p_{f_z}, a combination of the cost of traveling to the zone and the costs of activities to enhance zone-level quality.

Households choose the optimal amount to spend (in aggregate) on fishing, $p_F F$, which is whatever they have left over from choosing composite good consumption, $Y - p_X X$, and uses that amount to decide how much to spend on fishing in each of the zones to maximize utility from fishing. This nested (multi-step) budgeting process is used throughout the optimization problem to keep each nest consistently connected through the budget constraint. The solution from optimization of (3) subject to (4) produces the demand equations for zone-level fishing subutility in each zone f_z. Once the fisherman has decided on his desired level of fishing subutility in each zone, he combines travel/trip inputs t_z^1, and quality inputs, q_z, to produce that level of subutility through a modified household production function approach (Kolstad, 2011). Travel inputs collectively represent travel (i.e., time and distance) and all other inputs that can be purchased to increase the number of trips/travel to each zone, while quality is an input that can be thought of as the fisherman's perception of the overall fishing quality at that zone. The tradeoff in zone-level fishing production is between quantity of travel and quality of fishing similar to that of Bockstael and McConnell (1981). Optimization at the third level of the nest is the maximization of the fisherman's zone-level fishing utility of consumption,

$$f_z = f_z(t_z, q_z) \qquad \forall z, \tag{5}$$

which is characterized as a two-input CES subutility function. The fisherman maximizes (5) subject to the following budget constraint,

$$Y - p_X X - \sum_j p_{f_j} f_j = p_{f_z} f_z = p_{tz} t_z + p_{q_z} q_z, \quad j = 1, 2, ..., 5, \quad j \neq z, \quad \forall z \tag{6}$$

by purchasing trip/travel inputs at a unit cost of p_{tz} and quality inputs at a unit cost of p_{q_z}. For the fourth and final nest, quality itself is treated as endogenous to the consumer like in Bockstael and McConnell (1981); the fisherman can influence his perception of fishing quality at each zone by purchasing quality-enhancing (QE) inputs, q_z^e, (e.g. bait purchases, boat or equipment rentals, lures) at a per unit price of $p_{q_z^e}$ to offset any changes in demand for biomass values, s_z^b. Production of this zone-level quality is then characterized as,

$$q_z = q_z(q_z^e, s_z^b) \qquad \forall z, \quad b = 1, 2, ..., 10 \ , \tag{7}$$

a CES function of quality-enhancing inputs and species biomass levels for the ten sport fishing species in Lake Michigan. Even though species biomass levels are a non-market good and changes are out of the control of the fisherman, the fish still have value to him. This value can be assigned following the virtual price concept described in Carbone and Smith (2013). The fisherman assigns a value, or virtual price of p_{s_b} to each species based on preferences and the relative scarcity of biomass in each zone.

Without being able to influence biomass levels, the change in his willingness to pay (or virtual prices) for each species informs how the consumer purchases quality-enhancing inputs to produce overall zone-level quality. Like other prices, the fisherman's virtual prices adjust based on the equilibrium condition that requires the demand for biomass levels to meet the total supply; the total supply is given by the simulation data from the Atlantis model. Therefore, when maximizing utility of zone-level quality (equation 7) the fisherman chooses quality-enhancing inputs while simultaneously determining their valuation of the fish, or willingness to pay, subject to the following budget constraint:

$$Y - p_X X - \sum_j p_{f_j} f_j - p_{tz} t_z + \sum_b p_{s_z^b} s_z^b = p_q{}^z q_z = p_{q_z^e} q_z^e + \sum_b p_{s_z^b} s_z^b. \tag{8}$$

Note in (8) that the fisherman is endowed with a benchmark level of virtual income $\sum_b p_{s_z^b} s_z^b$ that can only be used for spending on species biomass, the specifics of which will be discussed in more detail in the calibration section. This virtual income allows the fisherman to account for levels and virtual prices of all other species and the costs of QE inputs when making his decisions.

What follows is a discussion of data sources and the calibration techniques used to find benchmark values of parameters and variables for the simulations.

Specification to Michigan

Building and using CGE modeling applied to a specific case or region using real world data is a four step process. First, we gather data that reflects the circular flow of goods, services and currency in an economy. Second, we assume the data is representative of a competitive equilibrium in the economy, which we call the "benchmark equilibrium". Third, we use the benchmark data (collected in a social accounting matrix, SAM) to parameterize our model of behavior, in a calibration process. Fourth, we run the model using the calibrated parameters to check it replicates the benchmark equilibrium.

The majority of the data for this analysis comes from IMPLAN. It covers industry inputs and outputs for the state of Michigan in 2014. The social accounting matrix (SAM) describes the relationship between inputs and outputs throughout the economy. These relationships in the data are required to be consistent with equilibrium in our model, which requires the data set be balanced:

- Zero Profits: value of input expenditures must equal value of output
- Market Clearance: demand must equal supply
- Income Balance: value of consumer expenditures must equal value of endowments

Given the complexities of units and prices, a normalization procedure is employed to convert all units to value or expenditure terms (dollars) such that in our benchmark data all prices are 1. As values of flows of goods and services in the economy are typically observed rather than independent prices and physical quantities. Our normalization technique chooses units of expenditures such that prices in the model are one, which allows us to treat the expenditures data as physical quantities.

SAMs are presented as square matrices in which row i and column i refer to a single institution. Institutions consist of industries, commodities, factors, households, government and trade. Industries are the production side of firms that produce/make goods. Commodities are the marketing side of firms that sell goods. Factors of production are owned by households and are used to make the goods. Households buy goods and earn income. Government levies taxes and redistributes tax revenue. Trade represents domestic and foreign trade into and out of the region. Rows correspond to receipts and columns to expenditures.

Incorporation of spatial recreational demand To link the spatial, species specific Atlantis model with an appropriately scaled recreational demand component in the CGE (details given below) requires a significant extension to the SAM. Following the theoretical development, recreational demand is modeled by households deciding to spend a portion of their income on recreational fishing. Households decide to take to trips to each zones, and make expenditures in each zone to influence the quality of their fishing experience.

Because IMPLAN does not have a sector specific to recreation or recreation inputs, the "2011 National Survey of Fishing, Hunting, and Wildlife - Associated Recreation (NSFHWA)" (DOI and DOC, 2011) and the American Sportfishing Association's "Sportfishing in America - An Economic Force for Conservation" (ASA, 2013) was used to build the recreational trip and quality-enhancing input sectors. The recreation input sectors were then broken into five zones, which are assumed equal in the benchmark. Both the "2011 National Survey of Fishing, Hunting, and

Wildlife - Associated Recreation" (NSFHWA) and the American Sportfishing Association's (ASA) "Sportfishing in America" (2013) were used to develop the trip and quality-enhancing (QE) input sectors.

The NSFHWA survey reported in Table 15 (page 61) that total expenditures in the Great Lakes were approximately $1.8 billion. Of those fishing in the Great Lakes (GL), 25% of the anglers fished Lake Michigan (page 14), making the estimate for overall Lake Michigan expenditures around $467 million or 25% of the $1.8 billion. Michigan anglers who fished in their home state account for about 86% of the GL anglers and the remaining 14% were non-Michigan residents. The expenditures of non-Michigan residents were treated as domestic trade receipts.

In their breakdown of household expenditures on recreational fishing (RF), the NSFHWA includes auxiliary equipment (e.g., binoculars and special clothes) and special equipment (e.g., purchases of ATVs, UTVs, campers, and boat trailers). These two categories were excluded, making total household expenditures closer to $323 million. This value was broken into expenditures by residents ($278 million) and non-residents ($45 million) using the percentages discussed above.

The NSFWHA did not report the percentage of anglers by income bracket for the GL because the sample size was too small. They did, however, provide the percentage of freshwater anglers by income bracket in table 9 (page 63). Therefore, the freshwater estimates were used as a proxy for these recreation sectors. The income bracket (IB) breakdowns were slightly different than the Household Divisions used by IMPLAN in the SAM. Six of the breakdowns matched one another, so they were not changed. Listed below are the steps for the other HHDs:

- IB5 and IB6 were combined to form HHD5

- IB3 and IB4 were combined to form HHD4

- IB2 and 2% of IB1 were combined to form HHD3

- The remainder of IB1 was split evenly into HHD1 and HHD2

Upon determining the percentage of anglers per household division, the $278 million was divided amongst households to get each HHD's expenditures on recreational fishing. Total recreational fishing spending was then broken down further to trip and QE related expenses. Trip expenditures (including transportation) accounted for 49% of recreational fishing spending while QE accounted for the remaining 51%. To add these in the SAM, all HHD expenditures on these activities were pulled from the respective HHD's miscellaneous (MISC) expenditures account.

The estimate for non-resident expenditures was broken into trip and QE accounts for Domestic Trade (DT). DT spending on trip was approximately $22 million and QE $23 million. The values of TRIP/DT and QUAL/DT were pulled from MISC/DT.

Additional details were gathered from the ASA publication. The ASA estimated expenditures for the Great Lakes, by state, and calculated the full economic value using a multiplier. To get only pure exchanges and not multiplier values, the estimated wages and government tax revenues for Michigan were reduced by the size of the multiplier. These estimates were broken into the trip and QE sectors using the 49 - 51% split discussed above.

Completing the specification of the sector follows from the IMPLAN specification of the commercial fishing sector, trip and QE are assumed to receive receipts from intra-industry exchanges (e.g. Trip/Trip) and from MISC. The MISC receipts received by trip and QE were calculated using the household demand and domestic trade receipts as a preliminary total for the industry and by using the % of MISC receipts received by MISC. The reason for choosing MISC as opposed to FISH, as the percentage, is because MISC receipts from the FISH sector represented more than half of the FISH sector's total receipts. Instead, MISC receipts from MISC accounted for about 34% of the total, which seemed more reasonable for the recreational fishing sector. The following formula shows how MISC receipts from RF were found: MISC/(RF Prelim Total + MISC) = 34%. This result is then broken down by TRIP and QUAL and subtracted from MISC/MISC cell to keep the SAM balanced.

To determine capital expenditures, the MISC sector's capital to labor ratio was found. Then, because the FISH sector shows that fishing is more capital intensive, the MISC ratio was flipped to get the capital expenditures for RF. Subtracting the values for wages, capital, and tax revenues (INDT) from the estimated total value of each sector's receipts left a remaining balance to be spread across all other industry exchanges. Using the FISH sector as a baseline for expenditures, a total for the FISH sector was found by excluding the accounts that already had values and foreign imports. Then to determine the values for the remaining accounts, each activities proportion of the FISH sector total was calculated. Using these same proportions, the remaining expenditures balance for RF was spilt across all other accounts.

Finally, the MISC sector was used to estimate the within industry exchanges for recreational fishing (WIE). The value of these exchanges for the MISC sector (MISC/MISC) as a % of the total expenditures/receipts is found by dividing the MISC/MISC cell value by the total expenditures. The result is that WIE in the MISC sector represent about 34% of the total expenditures/receipts. For the RF sectors to stay relatively small, this percentage was reduced. Household demand for RF is less than a percent (0.08%) of the demand that households have for MISC, so using that proportion, the new percent of the total was about 0.23%. The WIE for overall recreational fishing, was estimated using the following formula: WIE/(RF Expenditure Total + WIE) = .23%. The sum total of recreational fishing expenditures is then broken into each subcategory. The WIE are offset by subtracting the values from the MISC/MISC cell. The final estimates for trip and QE were then divided evenly amongst the five zone.

Given the recreation demand extensions, the SAM employed is shown in Figures (17) and (18).

Reading rows as receipts, from the LAB row of the SAM that $969.980 million is spent (paid) to labor inputs by agriculture production. Likewise, agriculture pays capital $4105.840 million. Reading across the household row we can see households receive payments from labor, capital, federal government transfer payments, state government transfer payments, and investment income (their aggregate income). Households spend their income (columns under each household group) on commodities, zone trips, zones quality enhancing inputs, and pay taxes to the federal and state government.

This format emphasizes how the model structure is connected to the benchmark

	AGR	FISH	POW	FUEL	MISC	AIRT	RAILT	WTRT	TRKT	Z1TRIP	Z2TRIP	Z3TRIP	Z4TRIP	Z5TRIP	Z1QUAL	Z2QUAL	Z3QUAL	Z4QUAL	Z5QUAL	LAB	CAP
AGR	625.076			0.787	5763.261																
FISH					235.192																
POW	29.179		6720.325	24.293	6704.667	5.685	0.302	5.313	14.669												
FUEL	0.353	0.002	1.677	0.491	558.509	0.009	0.066	0.702	8.261	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001		
MISC	3030.616	14.434	7708.433	689.247	441515.544	2889.321	595.678	437.201	5324.417	7.997	7.997	7.997	7.997	7.997	8.306	8.306	8.306	8.306	8.306		
AIRT	3.952	0.006	22.676	1.399	2041.558	0.214	0.406	1.185	62.164	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.004	0.004		
RAILT	22.305	0.017	129.843	0.183	1791.196	2.145	2.609	0.210	94.682	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010		
WTRT	14.548	0.015	4.371	0.048	358.470	1.580	0.333	0.160	2.773	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008		
TRKT	64.604	0.033	12.485	17.073	6443.092	13.152	6.213	2.973	144.738	0.018	0.018	0.018	0.018	0.018	0.019	0.019	0.019	0.019	0.019		
Z1TRIP					16.640					0.169											
Z2TRIP					16.640						0.169										
Z3TRIP					16.640							0.169									
Z4TRIP					16.640								0.169								
Z5TRIP					16.640									0.169							
Z1QUAL					17.284										0.176						
Z2QUAL					17.284											0.176					
Z3QUAL					17.284												0.176				
Z4QUAL					17.284													0.176			
Z5QUAL					17.284														0.176		
LAB	969.980	4.627	2742.449	607.760	247863.258	1368.357	360.050	63.243	2772.712	10.837	10.837	10.837	10.837	10.837	11.256	11.256	11.256	11.256	11.256		
CAP	4105.840	23.225	3556.615	213.761	154191.693	698.614	152.377	55.961	1385.161	17.407	17.407	17.407	17.407	17.407	18.081	18.081	18.081	18.081	18.081		
INDT	-93.655	11.554	1869.163	336.688	30497.709	383.410	-1.991	12.760	82.876	4.421	4.421	4.421	4.421	4.421	4.592	4.592	4.592	4.592	4.592		
HHD1																				796.440	236.319
HHD2																				856.857	173.813
HHD3																				5001.821	1022.862
HHD4																				8694.814	1621.636
HHD5																				18521.416	3300.508
HHD6																				39541.132	6572.286
HHD7																				37219.299	6631.997
HHD8																				51761.324	10588.901
HHD9																				62289.371	25129.764
FGOV	87.941				3.712															31399.523	2233.572
SGOV	6.016	9.651			14257.639					5.347	5.347	5.347	5.347	5.347	5.554	5.554	5.554	5.554	5.554	553.210	391.848
INV	119.934	0.093			3315.463					0.052	0.052	0.052	0.052	0.052	0.054	0.054	0.054	0.054	0.054		106035.873
FT	1062.486	368.230	169.048		92864.999	1146.020	15.567		144.851												-232.370
DT	2876.996	4.122	1804.312	286.756	275569.172	899.123	1422.062	557.575	843.175	2.284	2.284	2.284	2.284	2.284	2.372	2.372	2.372	2.372	2.372	227.690	853.678

Figure 17: SAM Part I.

data. In the SAM, the commodity rows and columns represent every market (traded commodity). The industry row is the supply side of the market (from production) and the commodity row the demand side of the market. When demand equals supply the SAM is balanced and each row and column total must be equal (i.e., the value of what is supplied in equilibrium is equal to the value demanded).

As for biomass data, the Atlantis ecosystem model provides the estimates for each species, in each zone, over 25 years, if an invasion does or does not occur. Taking

	HHD1	HHD2	HHD3	HHD4	HHD5	HHD6	HHD7	HHD8	HHD9	FGOV	SGOV	INV	FT	DT
AGR	77.760	52.629	141.774	152.527	229.175	363.108	287.147	338.647	269.050	0.032	70.283	273.566	1058.681	3222.666
FISH	5.871	4.025	10.330	10.753	16.249	25.104	19.536	22.093	15.994		10.252		60.034	0.576
POW	273.507	212.481	523.661	543.605	768.111	1046.365	733.535	780.195	547.422	14.719	262.556		58.727	5472.081
FUEL	59.566	31.769	124.085	136.413	168.131	252.583	199.912	282.560	258.129	0.036	0.904	77.558		16.763
MISC	12889.329	8431.928	25488.591	28387.800	40672.167	64598.680	51352.045	64203.305	56161.559	15873.119	62796.792	73635.366	70199.763	247167.900
AIRT	104.207	47.986	162.262	185.762	266.498	468.906	389.837	582.352	683.021	122.976	96.232	56.927	1191.229	915.842
RAILT	6.814	2.887	8.767	10.369	16.557	31.694	26.978	41.121	52.318	11.756	84.537	46.473	151.951	18.162
WTRT	15.700	7.050	23.327	26.889	39.519	71.043	59.428	89.411	107.533	5.665	29.566	4.764	255.477	19.530
TRKT	69.747	34.222	158.096	185.662	263.143	444.511	374.800	493.280	474.652	55.108	143.270	498.265	977.997	3.177
Z1TRIP	1.425	1.425	2.245	2.518	4.156	5.248	4.429	3.610	2.245					4.445
Z2TRIP	1.425	1.425	2.245	2.518	4.156	5.248	4.429	3.610	2.245					4.445
Z3TRIP	1.425	1.425	2.245	2.518	4.156	5.248	4.429	3.610	2.245					4.445
Z4TRIP	1.425	1.425	2.245	2.518	4.156	5.248	4.429	3.610	2.245					4.445
Z5TRIP	1.425	1.425	2.245	2.518	4.156	5.248	4.429	3.610	2.245					4.445
Z1QUAL	1.480	1.480	2.331	2.615	4.317	5.451	4.600	3.749	2.331					4.617
Z2QUAL	1.480	1.480	2.331	2.615	4.317	5.451	4.600	3.749	2.331					4.617
Z3QUAL	1.480	1.480	2.331	2.615	4.317	5.451	4.600	3.749	2.331					4.617
Z4QUAL	1.480	1.480	2.331	2.615	4.317	5.451	4.600	3.749	2.331					4.617
Z5QUAL	1.480	1.480	2.331	2.615	4.317	5.451	4.600	3.749	2.331					4.617
LAB														
CAP														
INDT														
HHD1										1983.467	460.946	9777.812		
HHD2										3486.511	786.640	3359.516		
HHD3										8964.193	2040.603	8897.077		
HHD4										8518.062	1946.768	8508.436		
HHD5										10668.412	2437.109	8441.793		
HHD6										13137.242	2990.325	10070.801		
HHD7										8811.628	2018.103	5392.863		
HHD8										8857.370	2080.696	3967.199		
HHD9										8575.224	2257.382	8245.741		
FGOV	-380.486	-215.961	-966.624	-705.658	111.002	3272.277	4795.064	7745.262	22688.125	8406.306		31586.803		
SGOV	118.442	39.792	229.408	329.931	776.324	1684.020	1790.463	2585.543	4309.143	16788.020	28996.966	7664.413		
INV								54.926	20907.657	0.000		13038.919	51553.283	
FT	568.202	429.486	1325.671	1508.172	2275.737	3863.804	3124.202	3802.502	3282.845	1452.000	1447.388	6888.303		
DT	-568.202	-429.486	-1325.671	-1508.172	-2275.737	-3863.804	-3124.202	-3802.502	-3282.845	-1452.000	-1447.388	-5405.921		

Figure 18: SAM Part II.

the mean value of each of the spatially explicit, species-specific Atlantis results and using those means as the starting point, biomass changes for each species over the 25 years were simulated following the process described above.

Calibration

While standard calibration techniques were followed for the firms, governments, and trade channels[2], the calibrated share form described by Rutherford (2002) was used for the representative fisherman's utility. Rutherford's technique is convenient because it requires calibration of fewer parameters and reduces the chances of coding errors. Using benchmark demands and prices, costs of production, and output, the only assumed parameter is the elasticity of substitution and the only calibrated parameters are the value shares of each input or good. Even still, calibrating the parameters within the nested utility for consumers is a bit more complex, due to the non-market nature of the problem. Calibration starts at the bottom nest of the utility function where all of the necessary estimates are available for finding the value share parameters for each species and quality-enhancing inputs.

Benchmark demands for species biomass for each household division are found using the simulated biomass data in conjunction with results from the NSFHWA survey. The NSFHWA reports both the number of fishers by income level and the total fishers in the Great Lakes. These values are used to find an estimate of the proportion of fishers by HHD (to match the SAM) in Lake Michigan. Then, the simulated biomass levels are divided by the proportion of fishers to get a benchmark demand, $\overline{s_z^b}$, for each individual species and each HHD. Benchmark expenditures on quality-enhancing (QE) inputs, $\overline{q_z^e}$ derive directly from the SAM. As with all other prices, the benchmark value (or virtual price, $\overline{p_{s_z^b}}$) for each species and benchmark price of QE inputs are normalized and set equal to one. The final calculation needed

[2]Calibration of the firm, government, and trade parameters follow standard practices.

for the share parameters at this level of the nest is the combined total expenditures on species biomass and QE inputs. Because there is not a monetary value associated with total biomass levels, the calculation of total benchmark expenditures on biomass is unique; some assessment of value is needed. The chosen assessment is willingness to pay (WTP) estimates from Melstrom and Lupi (2013). The authors report WTPs for six of the ten species included in the Atlantis output, as shown in Table 9 below.

Table 9: Willingness to Pay Estimates

Chinook:	$80.17	Lake Trout	$2.11
Coho:	$52.08	Burbot*	$2.11
Steelhead:	$49.42	Bloater*	$2.11
Walleye:	$22.95	Lake Whitefish*	$2.11
Yellow Perch:	$2.29	Rainbow Smelt*	$2.11

*Species not estimated by Melstrom and Lupi, (2013).

The remaining species not estimated - burbot, bloater, lake whitefish, and rainbow smelt - are assigned the same WTP as the lowest valued species, to keep from over-inflating estimates. Total benchmark expenditures or value placed on each species, in each zone, for all households (household subscripts are omitted for clarity) are then calculated as $\left(WTP_z^b * \ \overline{s_z^b}\right)$. With that, the value shares are

$$\alpha_b = \frac{WTP_z^b * \ \overline{s_z^b}}{\left(\sum_{b,z} WTP_z^b * \ \overline{s_z^b}\right) + \overline{p_{q_z^e}} \ \overline{q_z^e}} \qquad \forall b, z \tag{9}$$

$$\alpha_{qe} = \frac{\overline{p_z^2} \ \overline{w_z^2}}{\left(\sum_{b,z} WTP_z^b * \ \overline{s_z^b}\right) + \overline{p_{q_z^e}} \ \overline{q_z^e}} \qquad \forall b, z \tag{10}$$

for each species and QE inputs, respectively. There is one final parameter special to this level of the nest that needs to be calibrated for households. Given that the representative fisherman puts a virtual value on species biomass, these values (or virtual prices) get factored into production and consumption decisions at this lowest level. The full model will not converge unless the budget for this level is adjusted to account for the extra costs. Therefore, it is assumed that each household is endowed with virtual income from their value share of the natural resource - species biomass. This virtual income is

$$HHVI = \sum_{b,z} (WTP_z^b * \ \overline{s_z^b}) \qquad \forall b, z, \tag{11}$$

and can only be used for spending on species biomass demands.

Stepping up to the next level in the nest, the required components for calibration are benchmark values and prices of self-produced quality and purchased trip inputs. Self-produced quality is a non-market good; there is no technical market price or benchmark expenditure level reported in the SAM. But, because everything in the CGE model is in value terms, benchmark expenditures (costs) can be assumed equal to benchmark demands (output) values. Thus, the benchmark value of self-produced quality is assumed equal to the total benchmark expenditures on producing or meeting that benchmark level of quality $\overline{q_z}$. To keep the consumer from being able to spend virtual dollars from (11) on anything other than species biomass, the real costs of self-produced quality are assumed to be equal to the total expenditures on quality-enhancing inputs only (from the SAM):

$$\overline{q_z} = \overline{p_{q_z^e}}\ \overline{q_z^e} \quad \forall z. \tag{12}$$

Like all other prices, the benchmark unit price of produced quality, $\overline{p_{q_z}}$, is normalized to 1. The final step in calibration for this level of the nest is to find the value shares of self-produced quality and trip inputs in production of zone-level fishing consumption. Using benchmark expenditures on trip/travel inputs, $\overline{t_z}$, from the SAM and a benchmark price of 1 for $\overline{p_{tz}}$, the value share for travel is

$$\alpha_z = \frac{\overline{p_{tz}}\ \overline{t_z}}{\overline{p_{q_z}}\ \overline{q_z} + \overline{p_{tz}}\ \overline{t_z}} \quad \forall z \tag{13}$$

and the quality value share is $(1 - \alpha_z)$.

Taking another step up in the nest, to the zone-level fishing consumption (zone subutility) nest, parameters are calibrated like before. Since subutility is also a non-market variable, the benchmark expenditure on consumption is assumed equal to the total benchmark costs of producing it:

$$\overline{f_z} = \overline{p_{q_z}}\ \overline{q_z} + \overline{p_{tz}}\ \overline{t_z} \quad \forall z. \tag{14}$$

And again, the benchmark price, $\overline{p_{f_z}}$, for all zones equals 1. Using the estimates from (14), the value share of each zone's fishing consumption in the overall fishing composite is:

$$\beta_z = \frac{\overline{p_{f_z}}\ \overline{f_z}}{\sum_z \overline{p_{f_z}}\ \overline{f_z}} \qquad \forall z. \tag{15}$$

Calibration for all other non-fishing goods - the nest parallel to the subutilities - is done using the benchmark expenditures from the SAM. Labeling these goods as AOG (i.e., all other goods), the value shares of each in the overall composite good is

$$\beta_{aog} = \frac{\overline{Demand_{aog}}}{\sum_{aog} \overline{Demand_{aog}}} \qquad \forall aog \in 1...9, \tag{16}$$

because prices for each good, $\overline{P_{aog}}$, in the benchmark are normalized to 1.

The last step in the calibration of the utility nest is determining the value shares of the overall composite good, X, and the fishing composite. To ensure that the benchmark calculations of the non-market variables do not exceed the values reported in the SAM, the benchmark value of fishing, $\overline{F}$, is whatever benchmark income, $\overline{Y}$, the consumer has not spent on consumption of all other goods:

$$\overline{F} = \overline{Y} - \sum_{aog} \overline{Demand_{aog}}. \tag{17}$$

Benchmark value shares are then

$$\beta_u = \frac{\sum_{aog} \overline{Demand_{aog}}}{\overline{Y}} \qquad \forall aog, \tag{18}$$

$$(1-\beta_u) = \frac{\overline{F}}{\overline{\overline{Y}}}. \tag{19}$$

This completes the calibration for the utility nest. Note that calibration of the three comparative models (introduced and discussed below) uses the same techniques as above just with aggregated values for space and species biomass.

Objective 3

Coupling the Atlantis model with the CGE through the recreational demand of households follows a growing line of literature. Recognizing the role that natural resources and ecosystem services play in feedbacks between the entire economy and the ecosystem has inspired a number of CGE models that explicitly incorporate the environment. Some applications focus on public goods and policy measures, given their non-market values (Sieg et al., 2004; Berrittella et al., 2007; Carbone and Smith, 2008). Others account for use or non-use values in models of deforestation (Persson and Munasinghe, 1995), climate change (Berrittella et al., 2006), pollution (Bovenberg et al., 2008), and environmental quality (Smajgl, 2006; Carbone and Smith, 2013; Sakamoto and Nakajima, 2014). When considering use values in these models, the environment often comes in through recreation demand, tourism, or as an intermediate input in the production of another good.

Of particular relevance to this analysis are CGE models that value the environment through recreation demand. Seung et al. (1999, 2000), Watts et al. (2001), Lew and Seung (2010), and Hussain et al. (2012) each include demand for recreational activities in their analysis, but do so in a way that is not fully integrated with the

CGE model. The authors of these studies estimate impacts of the environment on recreation demand outside of the system of CGE equations. They then treat those estimates as exogenous shocks to either the tourism, trade, or recreation sectors, limiting the ability for adjustment of all other prices in the economy to further influence the demand for recreation through tradeoffs in consumption of other goods. In a similar manner, Zhang and Lee (2007) constrain their results by modeling resident and non-resident demand for recreation as a constant proportion of their expenditure on wildlife.

To avoid welfare biases that might result from disconnecting the CGE and recreation demand, the approach in this analysis combines techniques. Figure (19) illustrates our coupling strategy as documented in preceding sections.

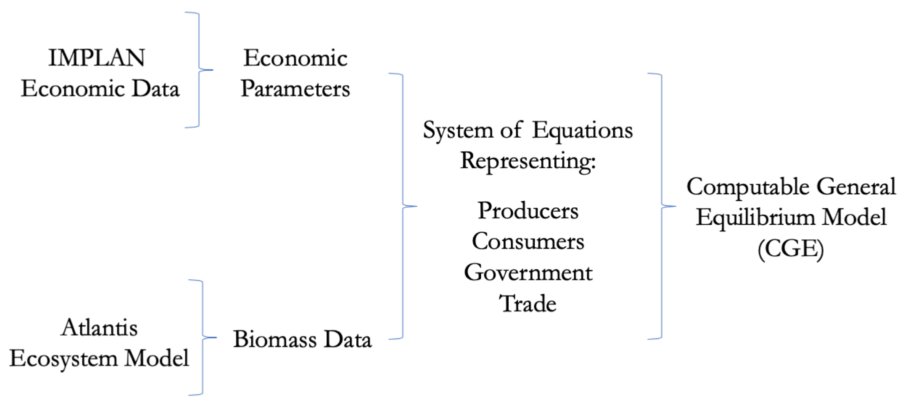

Figure 19: Model coupling.

Using nested utility and modified household production functions, the model is consistent with Carbone and Smith (2013), Varian (1992), Ballard et al. (1985), and Kolstad (2011). Carbone and Smith (2013) incorporate a non-separable nested utility function that includes consumer demand for both use and existence values of an ecosystem, letting consumption of the resource be a choice variable in one nest of the utility optimization. Their CGE model though only includes the demand for a single area. The analysis here extends Carbone and Smith (2013) by allowing demand for environmental quality (or demand for species biomass) to enter into the nested utility function across multiple zones in Lake Michigan. This demand for species biomass acts as an input into the production of the fisherman's own zone-level quality in a modified application of the household production function (HPF) method. Use of production functions is a relatively common revealed preferences valuation technique in partial equilibrium settings[3], because it allows for goods such as recreation to be a function of the agent's own time, energy, preferences, and money. While it is natural and convenient to assume the fisherman produces his own fishing experiences, one of the few to directly extend use of a HPF to CGE analysis is Blandine et al. (2008). These authors employ the HPF to evaluate the recreational services of land use and natural forest areas in the presence of biofuel regulations. Their analysis, however, is performed at a global scale, an aggregation scheme that is much too large to capture the important components of this particular case study.

Using the results from Atlantis, the effects of the invasion on species biomass levels are simulated for each zone over the course of 25 years, to reflect the interval of time from 2015 to 2040. Biomass levels enter the CGE directly through the representative fisherman's demand for zone-level quality. Making this connection and understanding the intricate role that natural resources and ecosystem services

[3]See de Groot et al. (2012) for a discussion and meta-analysis of valuation approaches.

play in the broader economy is critical for effective implementation of policy, as shown by Finnoff and Caplan (2004), Massey et al. (2006), Eichner and Tschirhart (2007), Finnoff and Tschirhart (2008, 2011), and Jin (2012). Equally important is knowing the full economy-wide impacts of invasive species on those ecosystems (Warziniack et al., 2011, 2013; McDermott et al., 2013). Following McDermott et al. (2013)'s comparative welfare analysis of prices being fixed or endogenous when an invasive species causes economic and environmental damages, the analysis here compares welfare outcomes from different aggregation schemes across space and by species. Like McDermott et al. (2013), discrepancies in welfare estimates are found when certain relationships are ignored.

Objective 4

Our first use of the coupled model is an assessment of the consequences of a potential invasion of Lake Michigan by bigheaded carp (as outlined above). Two comparisons are considered:

Comparison 1: No invasion to Invasion

(a) Run model forward 25 years in both scenarios

(b) Calculate compensating variation in each year

(c) Estimate the Net Present Value of the invasion

Comparison 2: Space and Species-Specifics Outcomes to Aggregates

- Space and Species-Specifics (SBSP)
- Species-Specifics Only (SBO)
- Space Only (SPO)
- No Space, Nor Species (NSS)

Using the SBSP as the baseline framework, the three other versions were developed using different aggregation schemes. The aggregation for the SBO model is over space, treating the entire Lake Michigan as the only "zone", yet maintaining species-specific details. Conversely, the spatial structure of five zones is maintained for the SPO model, while species specifics are removed by summing over the 10 species in each zone to yield a total biomass per zone. For the NSS model, all zones and species biomass values are aggregated to get a total biomass for the entire Lake Michigan that is not species-specific, nor spatially explicit.

Aggregations are performed for both the invasion and non-invasion scenarios, forming the basis for the welfare calculations. Each model is run once with invasion data and once with non-invasion data for 25 years starting in 2015. At every time step, the indirect utility is calculated for use in estimating welfare. The specific measure of welfare in this analysis is compensating variation[4] (CV), or how much income each representative consumer would need to be compensated in order to stay at their original level of utility prior to (or without) the invasion. By changing only

[4]Equivalent variation measures are also calculated, but are not reported here as the EV results end up being the reciprocal of the CV results.

the aggregation scheme, the welfare estimates across the four models can be directly compared.

Graphical representations of the welfare impacts from a bigheaded carp invasion over intervals of time up to 25 years are provided in Figure (20).

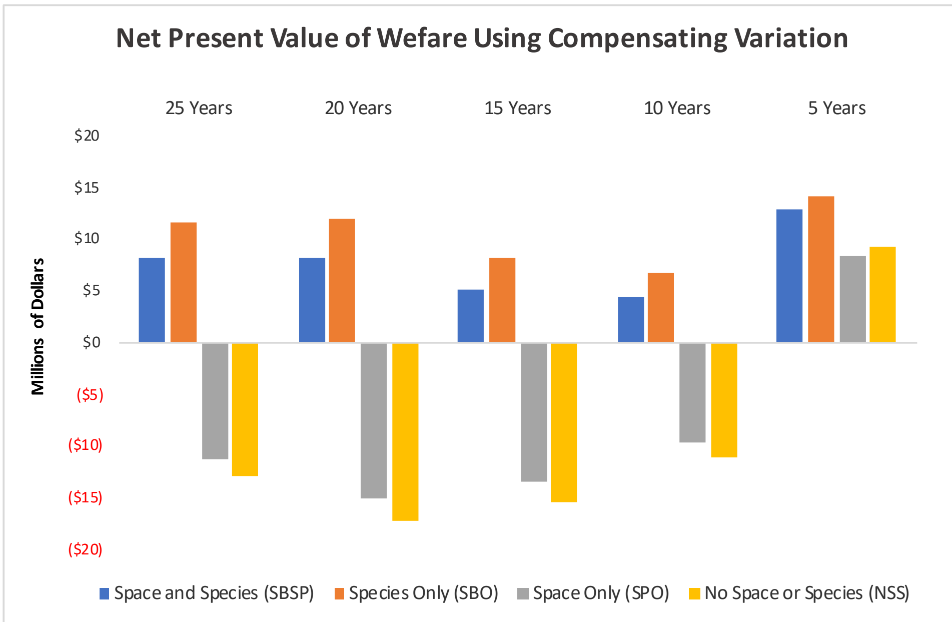

Figure 20: Welfare analysis. Positive values indicate welfare losses.

Given the ecosystem effects that vary over space, species and time, the economic consequences depend on the economic specification of the model and the interval of time employed to conduct the welfare calculation.

Comparison 1 For our baseline model, SBSP, under all time intervals we find a decline in economic welfare decline from the invasion, which ranges from under \$5 million to over \$10 million. The economic consequences follow from the ecological changes in zones and across species. In brief, the invasion impacts the species households desire the most, Figures (11),(12), (13), and Table (6). Figure (21) summarizes the aggregate SBSP results.

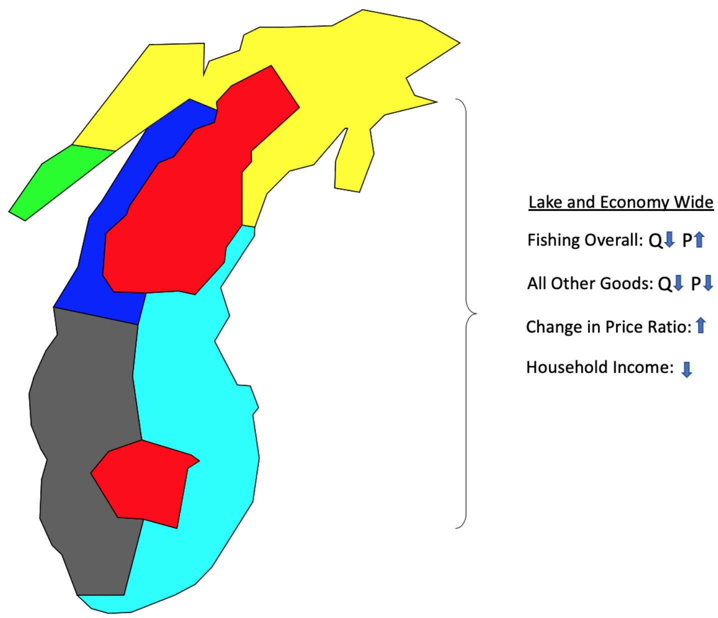

Figure 21: SBSP overall implications.

The declines in key species leads to fishing being costlier, p_F increasing, and consumption goods becoming relatively cheaper, p_X falling, the ratio of the two prices rising. The increased price of fishing rises to such an extent that households fish less and have less income to spend on consumption goods. Because consumers demand less of all products, supply/output of those products contracts, incomes fall, and the economy is worse off than it was before the invasion.

Within the aggregate consequences, there are spatial implications. The invasion is more severe in zones 3, 4, and 5. This leads to households switching to less impacted zones (1 and 2) that are relatively cheaper to fish in, although they are populated with increased biomass of species households desire less. To illustrate, consider a comparison of a heavily impacted zone 5, and a less impacted zone 2. Figure (22) illustrates the implications on spatial recreational demand decisions of households.

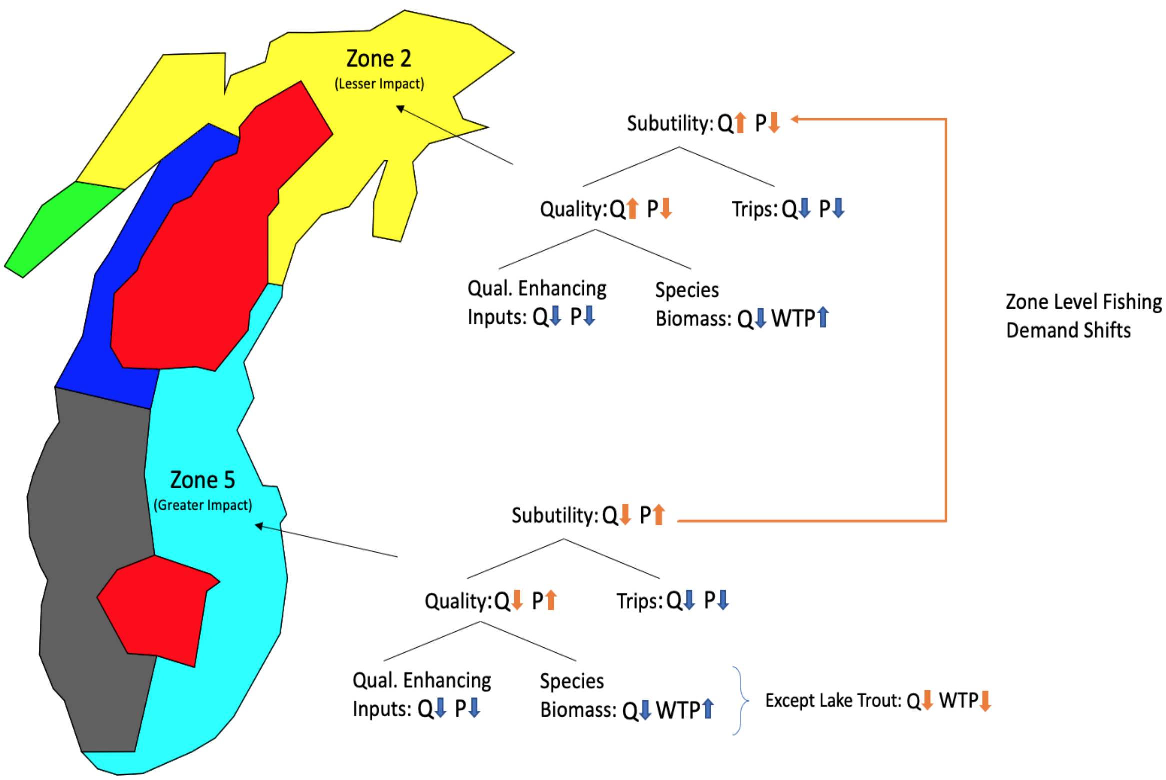

Figure 22: Spatial consequences on households.

The ecological differences in zones are reflected by biomass of species decreasing more in zone 5 than zone 2, leading to a greater increase in households WTP for species in zone 5. The price of q_z^e inputs falls. This is because that price is set in the market. Production in this sector falls as does demand and the price drops. This is in relation to zone 2, which has an increase in biomass of less desired species. As zone 2 is relatively cheaper, households switch to this zone.

Comparison 2 The results are clear: aggregation causes welfare estimates to diverge. In all years the SBSP and SBO models generate greater cumulative welfare loss than that of the SPO and NSS models. More notable is that with the SPO and NSS models, after the first five years[5], suggest that there are welfare gains from the invasion —a surprising result from the perspective of ecologists, economists, and recreational fishermen. These differences and biases are a direct consequence of the aggregation scheme.

As discussed previously, when using the SBSP model the ecological differences in zones causes households to substitute between zones and species. Households prefer to fish in zones where it is relatively cheaper to fish, in terms of the portfolio of species. Very little about this story changes when considering the species-specific preferences (SBO) only model. Households still fish less and demand less of all other goods. The low demand leads to contractions in the economy, incomes fall, and the economy is worse off than before. However, now that the spatial components have been aggregated out of the model the households are unable to substitute across zones to fish in relatively cheaper zones; there is no cost smoothing across zones. By being constrained to one area, the welfare losses appear to be of greater magnitude than those from the SBSP model.

When comparing the SBSP model to the space only (SPO) model, the SPO

[5]In the first five years the ecological data shows a significant negative shock, but it levels out in later years.

model underestimates welfare impacts considerably. Most of this result can be explained by the change in the composition of the ecological data. Removing species-specific preferences results in total biomass values (excluding bigheaded carp) in each zone that on net, are less affected by the invasion, Figure (23); a one unit drop in the biomass of any one species is balanced out by a one unit increase in any other species.

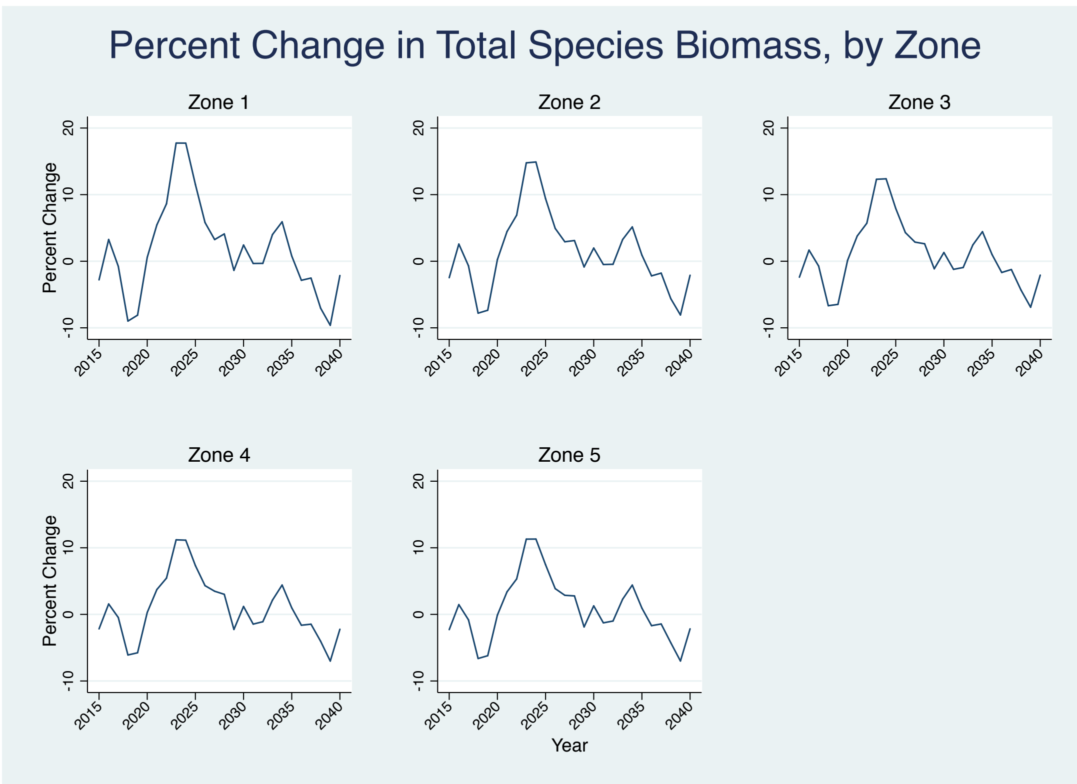

Figure 23: Changes in total biomass.

As a result, the invasion appears to have a net positive effect on the total biomass in the lake. There are more fish in the lake after the invasion then before. With households having no preferences for individual species but rather a sum total, the invasion generates greater welfare. Households increase fishing consumption and consumption of all other goods, incomes rise, and welfare increases.

Similar to the space only model, the no space, nor species (NSS) model produces welfare estimates that are significantly lower than the models that include species specifics. The total effects of removing space and species are the combined effects from the SBO and SPO models. Aggregating out spatial relationships leaves no ability to substitute to other zones where fishing might be less costly and aggregating out species details results in increased total biomass values. The take-home message is clear: both space and species-specifics matter; aggregating out one or both may bias welfare estimates.

Objective 5

We consider a limited policy analysis of alternative management scenarios, and use it to illustrate the implications of ignoring the importance of space and species composition. Ten hypothetical policy applications were run for the space and species-specific model (SBSP) to assess the effectiveness of possible policies. The policies included Lake-wide reductions in the invasion by 5%, 15%, 25%, and 50% and results are shown in Figure (24) (for example, the effects of the invasion were reduced by 5% in all zones and in all years).

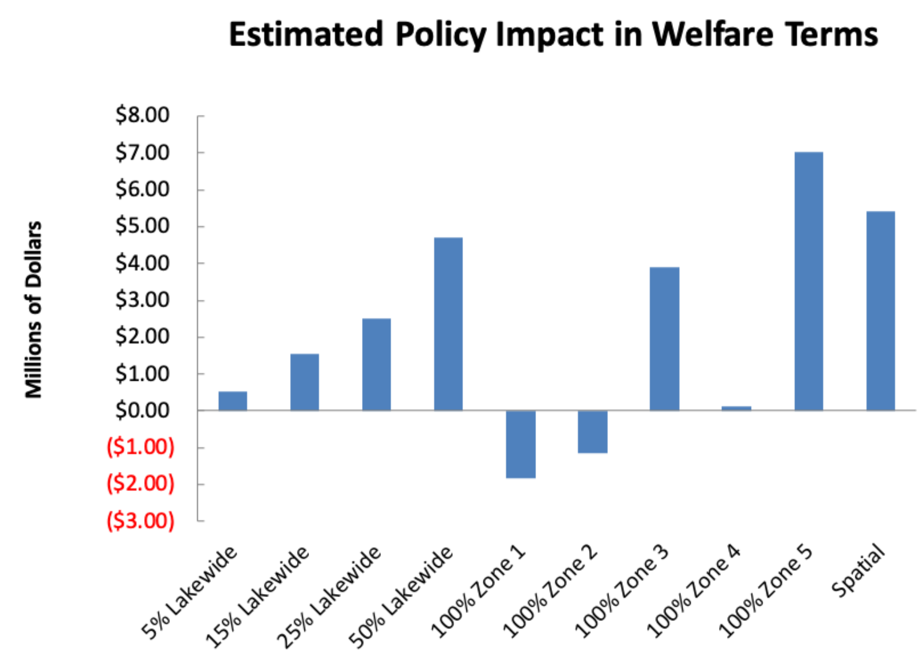

Figure 24: SBSP welfare differences of policies.

Other policies considered the welfare impacts associated with complete control (or complete protection from the invasion) by zone. That is, if the invasion is 100% controlled in Zone 1, the biomass levels and population dynamics match those in the no-invasion scenario. The final policy run was a spatial policy —control heavily in the zones where the invasion is likely to start, slowing down the invasion throughout the lake. The hypothetical spatial policy applies a 50% control in Zones 4 and 5 in all years of the invasion. In the first five years of the invasion, it is assumed that this level of control keeps bigheaded carp from invading the other parts of the lake (Zones 1, 2, and 3). After five years, the invasion spreads to the neighboring zones (Zones 2 and 3), but the impact is only a quarter of what was observed in the no policy scenario. The invasion reaches the final zone (Zone 1) after 15 years. However, with the control efforts being applied to Zones 4 and 5 throughout the duration of the time frame, the invasion progressed less rapidly and has less impact. The results shown in Figure (24) are presented as the difference in welfare outcomes between the policy and no policy runs. Implementing a 5% Lake-wide reduction in the invasion improves the welfare outcome of the model by approximately half a million dollars. Notice that all policies improve the welfare outcomes of the invasion, except for 100% control in Zones 1 and 2.

Complete control in zones 1 and 2 lead to worse welfare outcomes because these zones are those that households switch to in the no policy-invasion scenario. In the no policy-invasion run, zone 2 has the most species that increase in biomass as a result of the invasion. By controlling 100% in this zone those biomass increases are lost and the substitution effect (households cost-smoothing by fishing in relatively cheaper zones) is no longer present. The zone 1 implications are similar, except that this zone is unique in that it does not have the full portfolio of species; there are only 7 species in this zone. The biomass increases then of Lake whitefish and Rainbow smelt in the no policy-invasion run, offsets the losses of comparatively fewer species. As a result, Zone 1 in the no policy-invasion scenario is more appealing and relatively cheaper to fish in. Just as with zone 2, when 100% control is applied to zone 1, biomass increases are lost, the substitution effect is no longer present, and households are made worse off.

Results

Main Results From Each Model

- SBSP: Show contractions in economy, resource redistributions
- SBO: Constrains consumers, reduces smoothing
- SPO: Attenuates invasion impacts
- NSS: Counterbalances attenuated invasion impacts and smoothing

The spatially explicit and species-specific model results provide support for modeling economic and ecological relationships that reflect preferences and tradeoffs. The model suggests that the portfolio of species in each zone, fisherman preferences, and the biological impacts on certain species matter for estimating welfare. When zones contain desirable species and these species are significantly impacted by an invasion, the cost of sustaining preferred quality levels is expensive. Households reduce quality-enhancing inputs and overall quality demand, trips, and zone-level fishing consumption in the zones were fishing is more expensive because of the impacts on biomass of the most desired species. In zones where the biomass impacts are less severe shift to fishing in these zones, though the households still decrease quality-enhancing input and trip input demand. Fishing, however, becomes more expensive overall. Economy-wide redistributions of labor/capital and reduced demand for both recreational and non-recreational fishing goods contracts the economy. Households earn less income and welfare falls.

A similar story exists when only species specifics are included, yet without space the impacts from the invasion are overestimated due to inefficient constraints on cost minimization. When the portfolio of species is condensed to one, non species-specific value but space remains, the model only captures a small part of the story: the ability to substitute across fishing locations. Consistent with Besedin et al. (2004), Johnston et al. (2006), and Melstrom and Lupi (2013), it is an oversimplification to assume that fisherman value each species the same. Doing so in this analysis produced the greatest discrepancy in welfare estimates. The final comparative model neglected space and species specifics. Leaving out both created a net effect on welfare that fell between the species-only and space-only models. Regardless, each of the three alternative aggregations produced welfare estimates that were different from one another.

To conclude, when choosing which version to use for welfare estimates in cost-benefit analysis of prevention or control strategies, it is important that the researcher identify and understand the economic and ecological tradeoffs and preferences in space and amongst affected species when there is an invasive species threat. The added complexity of modeling space and species in a CGE may not be necessary or needed if it can be determined that the impacts are homogenous (portfolios are the same) across space and species. However, if it is suspected that the invasion has heterogenous effects, it is in the best interest of the researcher to disaggregate. Disaggregation maintains relationships that influence the welfare estimates; neglecting them may bias results. It is worth noting that the scale at which this analysis was performed may be too aggregated, implying results should be seen as a guide for bounds of welfare predictions rather than a systematic approach. Aggregation or further disaggregation over household divisions can be considered, along with approaches other than summation, as steps moving forward. Also, though not the case for this particular invasion, firms are often affected by AIS (e.g., zebra mussels) indicating that direct firm implications should be modeled. Finally, to further assess bounds, it would be beneficial to use this approach under a different AIS scenario. Discussion of additional aggregation approaches and estimation of welfare bounds is the direction this research is headed.

Future work

We plan to continue the research by taking the following four steps.

- Perform comprehensive policy analysis
- Include location-based decisions for households
- Integrate Random Utility Model estimates of demand
- Add additional feedback loops between the CGE and Atlantis models

Lessons learned

The expansion of ecological modeling to including spatial and species specific ecological implications was non-trivial and remains a work in progress. Calibration of the Atlantis model and the specification of migratory processes was challenging. In a similar fashion, on top of developing a model of human behavior over space and by species, gathering data to parameterize the model proved more challenging than anticipated.

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