Consequences of Space and Species Aggregation in Welfare Estimates of Invasive Species

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Abstract

A computable general equilibrium (CGE) model is developed to assess the current threat in Lake Michigan of bighead carp, a 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 fisherman's decisions regarding when, where, and what species to fish. Their decisions are modeled using a spatially-explicit, zone-level application of the 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 focus being to uncover any biases that may exist in welfare estimates when space or species level information is ignored. Versions differ only in levels of aggregation over space and/or species. Preliminary results indicate that aggregating over one or both underestimates 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 species-specific preferences.

1 Introduction

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 welfare 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 welfare is key to making informed management decisions regarding prevention or control of the AIS. The model used to produce estimates of welfare for cost-benefit analysis of management options should not neglect any relationships between the natural and economic systems or biases may arise. Lost preferences or ecological processes can result in under or over-estimates of welfare, misleading policymakers' decisions. Building such a model, however, is 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 analysis is two-fold: (1) develop a model that disaggregates space and species preferences/tradeoffs to combine the systems and (2) show the biases that exist in welfare estimates when these disaggregations are ignored.

As a case study, 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 bighead 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 Atlantis ecosystem model of Lake Michigan, developed by Fulton et al. (2011), the impacts of invasion scenarios on biomass levels of fish species are produced. The forecasted biomass effects are then used to project changes in recreational fishing behavior. 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 at different times, the fisherman can substitute across zones in the Lake Michigan region. These choices are modeled as a spatially-explicit, zone-level application of the household production function approach discussed in Bockstael and McConnell (1981). All of these decisions are incorporated into a computable general equilibrium (CGE) model to produce welfare implications from the invasion. That welfare measure will then be compared to the welfare measures of three other versions of the model, which differ only in the levels of aggregation. One version aggregates over species, eliminating species-specific preferences, another over space, removing zone-level substitution possibilities, and the final version aggregates over both. When compared to the spatially-explicit and species-specific model, preliminary results indicate that aggregating over one or both may result in welfare biases because important preferences and tradeoffs are lost. The biases are most pronounced in models that neglect species-specific preferences; the models produce significantly lower, and in one case opposing, welfare outcomes.

Included in the sections that follow are the arguments for contributions, the current modeling framework for merging recreation demand with the CGE, the calibration approach, preliminary results of the comparative analysis, and closing remarks for moving forward.

2 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 both use and non-market 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, 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 include 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 on recreation demand outside of the system of equations in the CGE. They then treat those estimates as exogenous shocks to either the tourism, trade, or recreation sectors, limiting the ability for adjustment of prices to further influence the demand for recreation through tradeoffs in consumption of other goods. Zhang and Lee (2007) also constrain their results by modeling resident and non-resident demand for recreation as a constant proportion of their expenditure on wildlife.

To avoid the disconnect between the CGE and recreation demand, like those just discussed, the approach in this analysis combines techniques from Carbone and Smith (2013) and Bockstael and McConnell (1981). Carbone and Smith (2013) incorporate a non-separable utility function that includes consumer demand for both use and existence values of a natural resource, treating the natural resource as a choice variable in utility maximization. Their CGE model, though, only includes the demand for recreation at a single site. The approach here follows by allowing demand for environmental quality (or demand for species biomass) to be a choice variable, but across different zones in Lake Michigan. The individual fisherman chooses demands for species biomass as an input into the production of his own zone-level quality, a zone-level, spatially-explicit, application of the household production function (HPF) method described in Bockstael and McConnell (1981). By using a HPF (Bockstael and McConnell, 1981; Bockstael et al., 1987; Deyak and Smith, 1978; Becker, 1965) for recreation related trips/experiences, the analysis here is most similar to 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 model. Blandine et al. (2008) is one of the few to use a HPF in their CGE analysis. While uncommon, this approach is ideal for modeling recreation demand. Household recreation is a function of own time, energy, preferences, and money; it is natural and convenient to assume they produce their own experiences, which is why it is used here.

This analysis is also unique through its linkage with the spatially-explicit Atlantis ecosystem model of Lake Michigan. Atlantis has the capability to simulate dynamic (both space and time) changes in food webs and fisheries from AIS invasions, which translate directly into the HPF through demand for species biomass. As shown by Finnoff and Caplan (2004), Massey et al. (2006), Eichner and Tschirhart (2007), Finnoff and Tschirhart (2008, 2011), and Jin (2012), understanding this intricate role that natural resources and ecosystem services play in the broader economy is critical for effective implementation of policy. Equally important is knowing the full economy-wide impacts of invasive species on those ecosystems (Warziniack et al., 2011, 2013; McDermott et al., 2013). McDermott et al. (2013) also perform a comparative welfare analysis. Though, instead of comparing aggregation schemes of zones and species specifics, the authors assess welfare implications of prices being fixed or endogenous when an invasive species causes economic and environmental damages. Like McDermott et al. (2013), discrepancies in welfare estimates when certain relationships are ignored, are found in this analysis.

3 Model

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 are able to 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 the 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.

3.1 The Basic CGE Model

There are nine aggregated industries included in the analysis - agriculture, commercial fishing, power generation and supply, gasoline/fuel, air transportation, rail transportation, water transportation, truck transportation, and a miscellaneous sector. 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 1 in Appendix A. 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.

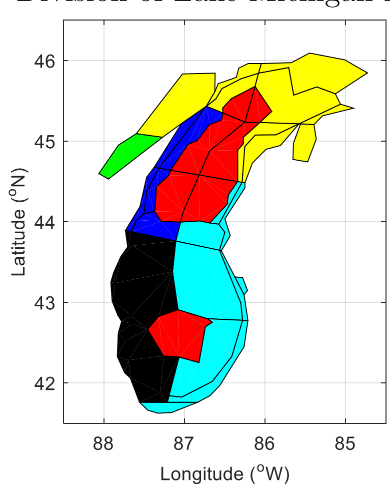
The firm's optimization is solved in two steps. First, the firm minimizes the costs associated with production of VA by choosing the amount capital and labor to employ based on the wage and rental rate of capital. And second, the firm minimizes the total cost of production using intermediates and value added. Final output (also shown in Figure 1 of Appendix A) 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. The complete mathematical depiction of the firms, governments, and trade, is in the Technical Appendix.

3.2 Integrating Space and Species in the CGE

Space and species-specific impacts are introduced to the CGE through consumers. Using nine household divisions, which are differentiated by their level of income, 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 below, in the Lake Michigan region where the consumer may choose to fish:

Figure 1: Division of Lake Michigan into Zones



Colors represent different zones: Zone 1 - Green, Zone 2 -Yellow, Zone 3 - Blue, Zone 4 - Black, Zone 5 - Light Blue. Note that deep water areas (Red), are excluded from this analysis.

The division of Lake Michigan was determined by ecological classifications of Lake Michigan habitats (Riseng et al., In Review) 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 consumer'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 bighead carp invasion.

Utility is nested following the structure in Figure 2 in Appendix A. As shown, the representative consumer from household division, h, has an overall utility of

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

a CES function of composite good consumption and fishing. The consumer chooses his levels of F and X to maximize his utility in (1), subject to his budget constraint,

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

In which, Y_h represents household income, p_X, 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 composite goods, as shown by the nest in Figure 3 in Appendix A, is to give the consumer options to substitute between domestic and non-comparable imported commodities.

Parallel to the composite good nest, is the nest for F shown in Figure 2, Appendix A. With options to fish in different parts of Lake Michigan, F is assumed to be a CES function of the zone-level fishing consumption (or zone subutility) derived from fishing, f, at each zone, z, such that

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

The consumer chooses desired levels of zone-level fishing consumption, f_z, to maximize (3) subject to

$$Y - p_x X = \sum_z p_{f_z} f_z. \tag{4}$$

In which, the unit price of zone-level fishing consumption from fishing in each zone is p_{f_z}, a combination of the cost of traveling to the zone and the willingness to pay for zone-level quality. Budgeting for this level of the nest is a result of the optimization using (1) and (2); the consumer is able to spend a total of $p_F F$, or whatever he has left over from choosing composite good consumption, $Y - p_x X$. While computationally sound, choosing levels of subutilities seems a bit abstract in application. To avoid this, a household production function approach (Bockstael and McConnell, 1981) that allows consumers to produce their zone-level fishing consumption, by choosing travel/trip inputs, ${w_1}^z$, and quality inputs, q^z, is introduced. Stepping down now to the third level of the nest, the consumer's production of zone-level fishing consumption,

$$f_z = f_z({w_1}^z, q^z) \qquad \forall z, \tag{5}$$

is characterized as a two-input CES. The 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 consumer's perception of the overall fishing quality at that zone. The tradeoff in zone-level fishing consumption production is between quantity of travel and quality of fishing. The consumer will minimize the cost of producing zone fishing consumption,

$$C_{f_z} = {p_1}^z {w_1}^z + {p_q}^z q^z, \tag{6}$$

by purchasing trip/travel inputs at a unit cost of ${p_1}^z$ and quality inputs at a unit cost of ${p_q}^z$ to meet the production (zone fishing consumption) demand chosen from the optimization of (3) and (4). Treating quality itself as endogenous to the consumer, like Bockstael and McConnell (1981), he can influence his perception of fishing quality at each zone by purchasing quality enhancing (QE) inputs, ${w_2}^z$, (i.e. bait purchases, boat or equipment rentals) at a per unit price of ${p_2}^z$ or altering his demand for certain levels of species biomass, ${s_b}^z$. Shown in the fourth and final nest, is the last part of the consumer's problem. Here, he chooses QE inputs and desired levels of species biomass to minimize the cost of producing zone-level quality,

$$C_{q_z} = {p_2}^z {w_2}^z + \sum_b {p_{s_b}}^z {s_b}^z, \tag{7}$$

subject to his production constraint,

$$q^z = q^z({w_2}^z, {s_b}^z) \qquad \forall z, \quad b = 1, 2, ..., 10 \ , \tag{8}$$

which is a CES function of quality enhancing inputs and species biomass levels, ${s_b}^z$, for the ten sport fishing species in Lake Michigan. Note, that in (7) a unit of species biomass costs p_{s_b}. Even though species biomass levels are a non-market good, a value can be assigned to them following the virtual price concept described in Carbone and Smith (2013). The consumer assigns a value, or virtual price, to each species based on preferences and the levels of biomass in each zone. Thus, when choosing biomass input demands, the consumer accounts for levels and virtual prices of all other species and the costs of QE inputs. With this approach, the consumer is not only able to substitute between species if one becomes too expensive, but also between different combinations of biomass levels and QE inputs. Like other prices, virtual prices adjust based on an equilibrium condition requiring the demand for biomass levels to meet the total supply; the total supply coming from the Atlantis model simulations. All of the optimization steps and results, are shown in the complete Technical Appendix. What follows is a discussion of data sources and the calibration techniques used to find benchmark values of parameters and variables for the simulations.

4 Data and Calibration

4.1 Data

The majority of the data for this analysis comes from IMPLAN. It covers industry inputs and outputs for the state of Michigan in 2014 and was used to build a social accounting matrix (SAM) that includes the nine industries discussed above. 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 trip (${w_1}^z$) and quality enhancing input (${w_2}^z$) sectors. The recreation input sectors were then broken into five zones, which are assumed equal in the benchmark. Please see the Technical Appendix for more detail on the building of these sectors and snapshots of the SAM. As for biomass data, the Atlantis ecosystem model provides the estimates for each species, in each zone, over 100 years, if an invasion does or does not occur. Total biomass data is reported in g/m^2.

4.2 Calibration

While standard calibration techniques were followed for the firms, governments, and trade channels[1], the calibrated share form, described by Rutherford (2002), was used for CES utility and the household production functions. This 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,

[1]Calibration of the firm, government, and trade is shown in the Technical Appendix.

the only assumed parameter is the elasticity of substitution and the only calibrated parameter is the value share 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 to find the value share parameters for each species and the quality enhancing inputs are available.

Benchmark demands for species biomass, for each household division, are found using Atlantis output 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[2]. Then, the biomass levels from the Atlantis output are divided by the proportion of fishers to get a benchmark demand, $\overline{s_b}^z$, for each individual species and each HHD. To determine the benchmark value (or virtual price, $\overline{p_{s_b}}$) each HHD puts on individual species, willingness to pay (WTP) estimates from Melstrom and Lupi (2013) are used. The authors report WTPs for an increase in catch by one fish for six of the ten species included in the Atlantis output, as shown in Table 1 below. The remaining species not estimated in Melstrom and Lupi (2013) - burbot, bloater, lake whitefish, and rainbow smelt - were assigned the same WTP as the lowest valued species, to keep from over inflating estimates.

[2]Specific details on this can be found in Technical Appendix.

Table 1: 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 estimates needed to complete the calibration of value shares are the benchmark expenditures on quality enhancing inputs, $\overline{w_2{}^z}$, and the price, $\overline{p_2{}^z}$. The benchmark QE expenditures come from the SAM and as with most other prices, $\overline{p_2{}^z}$ is normalized and set equal to one. With that, the value shares are

$$\alpha_b = \frac{\overline{p^z_{s_b}}\ \overline{s_b{}^z}}{\sum_b \overline{p^z_{s_b}}\ \overline{s_b{}^z} + \overline{p_2{}^z}\ \overline{w_2{}^z}} \qquad \forall b, z \tag{9}$$

$$\alpha_{qz} = \frac{\overline{p_2{}^z}\ \overline{w_2{}^z}}{\sum_b \overline{p^z_{s_b}}\ \overline{s_b{}^z} + \overline{p_2{}^z}\ \overline{w_2{}^z}} \qquad \forall b, z \tag{10}$$

for species biomass and QE inputs, respectively.

There is one final parameter, unique to this level of the nest, that needs to be calibrated for households. With representative consumers virtually pricing their demand for species biomass, this price gets 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 (virtual) costs. Therefore, it is assumed that the household is endowed with a value share (virtual income) of the natural resource - species biomass. This virtual income is

$$HHStkShare_{z,b,h} = \frac{\overline{p^{z}_{s_b h}}\ \overline{s_b{}^{z}_{h}}}{\sum_h \overline{p^{z}_{s_b h}}\ \overline{s_b{}^{z}_{h}}} \qquad \forall b, z, h, \tag{11}$$

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

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 total costs can be assumed equal to benchmark output values. Thus, the benchmark value of self-produced quality is assumed equal to the total benchmark costs of producing that quality. 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):

$$\overline{Q_z} = \overline{p_2{}^z}\ \overline{w_2{}^z} \quad \forall z. \tag{12}$$

In the benchmark, the 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, $\overline{w_1{}^z}$, from the SAM and a benchmark price of 1 for $\overline{p_1{}^z}$, the value share for trips is

$$\alpha_z = \frac{\overline{p_1{}^z}\ \overline{w_1{}^z}}{\overline{p_{q_z}}\ \overline{Q_z} + \overline{p_1{}^z}\ \overline{w_1{}^z}} \quad \forall z \tag{13}$$

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

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

$$\overline{f_z} = \overline{p_{q_z}}\ \overline{Q_z} + \overline{p_1{}^z}\ \overline{w_1{}^z} \quad \forall z. \tag{14}$$

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:

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

Calibration for the nest parallel to the subutilities, all other non-fishing goods, 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

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

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, let the benchmark value of fishing, $\overline{F}$, be 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

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

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

This completes the calibration necessary for the utility nest. Note that calibration of the three comparative models, uses the same techniques as above just with aggregated values for space and species biomass. To aggregate, zones are added together to get a single space estimate and/or all species summed to get a non species-specific total biomass value.

5 Results

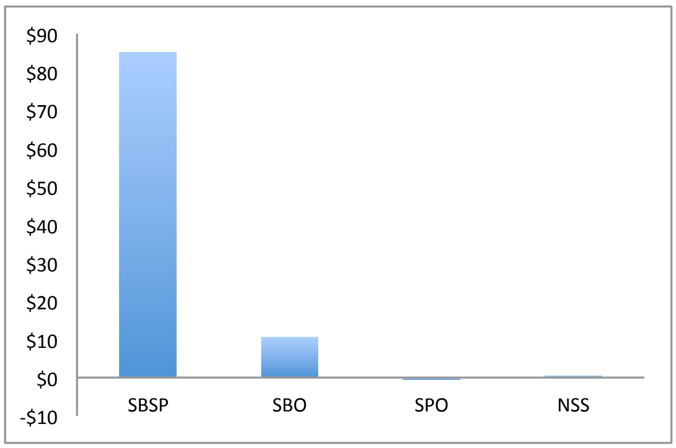
The results are presented as a comparative analysis between the space and species-specific model (SBSP) and three other versions: species-specifics only (SBO), space only (SPO), and no space, nor species-specifics (NSS). Using the SBSP as the baseline framework, the three other versions were developed using different aggregation schemes. The aggregation for the SBO model was over space, treating the entire Lake Michigan as the only "zone", yet maintaining species-specific details. Conversely, the spatial structure of five zones was maintained for the SPO model, while species specifics were 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 were aggregated to get a total biomass for the entire Lake Michigan that is not species, 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, the first year following the year of calibration. 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[3] (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 the aggregation scheme, the welfare estimates across the four models can be directly compared.

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

Figure 2 is a graphical representation of how the welfare impacts from a bighead carp invasion, over the course of 25 years, differ depending on the aggregation approach.

Figure 2: Measure of Discounted CV for All Models



*Welfare estimates are multiplied by one million for easier readability

Though the overall effects from the invasion are somewhat small[4], the most important result is how the models diverge from one another. As shown, the SBSP model generates greater cumulative welfare loss from the invasion than that of the SBO, SPO, and NSS models. The impact drops off for the SBO and NSS models and changes sign for the SPO model. The biases result as a direct consequence of the aggregation scheme.

When using the SBSP approach, the required compensation needed for consumers to be equally well off is going to be highest, because the model includes both space and species substitution possibilities, along with economic and ecological

[4]This is mainly due to the biomass impacts being small.

tradeoffs. First, notice in Figures 3 and 4 the SBSP zone-level impacts of the invasion on chinook, coho, steelhead, and walleye, the four highest valued species[5].

Figure 3

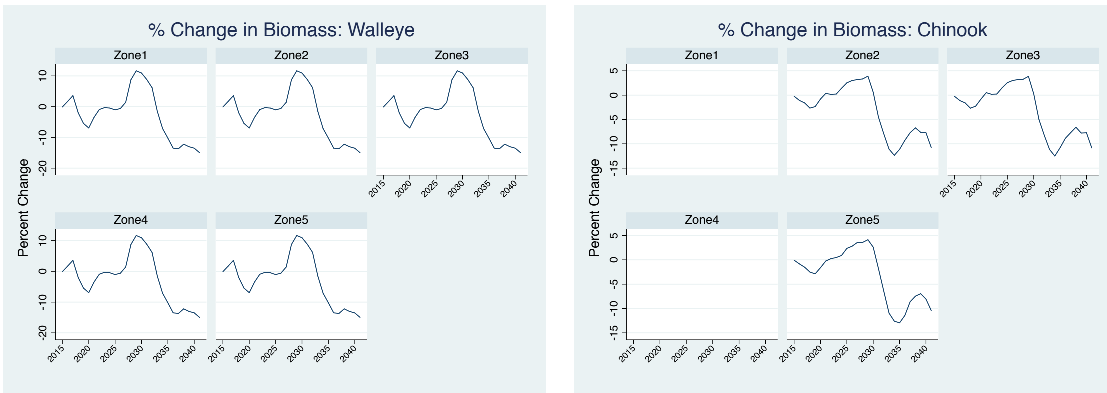
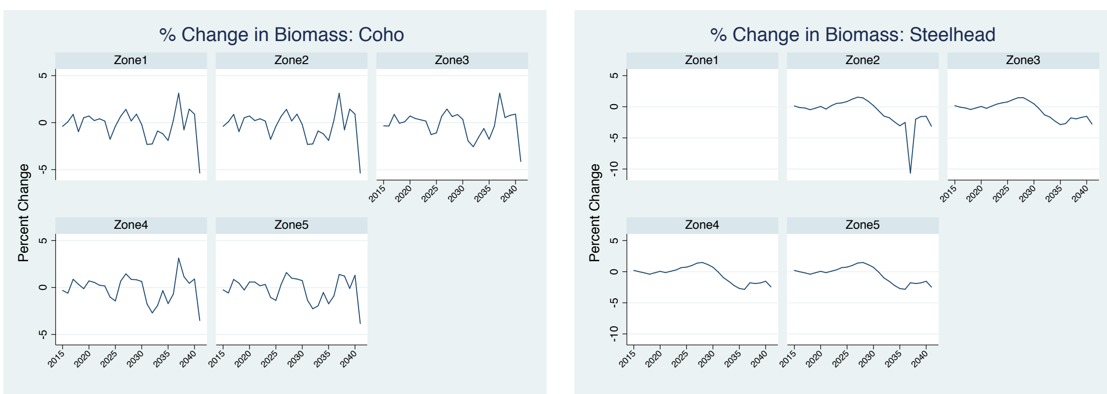


Figure 4



[5] All biomass charts can be found in Appendix B.

Following a brief period where biomass levels are increasing, chinook levels begin to decrease over time, as do walleye and steelhead, while coho levels are a little less defined. Recognizing the impacts that bighead carp have on these specific species, the representative consumers from each household division are faced with a tradeoff at the lowest level of the utility nest: the tradeoff between species biomass demand and quality-enhancing inputs in the production of their overall zone-level quality. To best describe the decisions and model responses, a snapshot of results for two households and two zones will be discussed, since the large dimensions of the model present challenges for displaying and reporting much more detail. The chosen household divisions and zones capture the general stories of consumer decisions and how their actions impact the greater economy.

Table 2: SBSP Average Direction of Change During Invasion: Zone-Level

Zone-Level Changes for Household Division 2

		Zone 3	Zone 4
SBSP	Demand Quality Enhancing Inputs	-	+
	Price of Quality Enhancing Inputs	-	-
	Demand Quality Inputs	-	+
	Price of Quality	+	-
	Demand for Trip Inputs	-	-
	Price of Trip Inputs	-	-
	Value of Zone Subutility	-	+
	Unit Price of Subutility	+	-

Zone-Level Changes for Household Division 6

		Zone 3	Zone 4
SBSP	Demand Quality Enhancing Inputs	+	+
	Price of Quality Enhancing Inputs	-	-
	Demand Quality Inputs	+	+
	Price of Quality	-	-
	Demand for Trip Inputs	+	+
	Price of Trip Inputs	-	-
	Value of Zone Subutility	+	+
	Unit Price of Subutility	-	-

As shown in Table 2, the selected HHDs are those with low (HHD2) and high (HHD6) baseline recreational fishing demand, and selected zones represent the typical case, where all species are present (Zone 3), and the unique, where chinook, the highest valued species is absent (Zone 4).

The SBSP results from the table above suggest that the reductions in biomass of the most desired species, across zones, generally increases consumer demand for quality enhancing (QE) inputs. Households want to offset the biomass losses by purchasing more QE inputs to meet their zone-level quality production. As the demand for QE inputs rises, suppliers respond by increasing output causing the price to fall. The price drop, however, does not cause HHD2 to increase demand in Zone 3, mainly due to the ecology and portfolio of species. Zone 3 is one of the most affected zones, because the highly desired species are all present and significantly impacted by the invasion. This impact makes quality production, even with the fall in prices, relatively more expensive. With HHD2 having low demand for fishing and more income constraints than HHD6, they respond by decreasing zone-level quality production in 3. For all other cases self-produced quality increases.

A similar story results at the next level of the nest. Along with the increase in demand for quality, HHD6 increases their demand for trip related inputs. This increase, from a high fishing demand HHD, results in firms increasing output and reducing prices. Despite the fall in trip price, HHD2 decreases trip demand to both zones. This happens for one of two reasons (1) the price of quality dropped more than the price of trips (HHD2: Zone 4 case) or (2) the price of quality increased more than the price of trips decreased (HHD2: Zone 3 case). For HHD2, they are able to meet subutility demands in Zone 4, due to falling input prices, however, in Zone 3 the losses in biomass are too high and too expensive to cover, given the HHD's income constraints. As shown in Table 3 below, HHD2's overall fishing consumption drops and their price rises, suggesting that Zone 3 represents a greater portion of the HHD's fishing composite. While Zone 3 might also represent a greater proportion for HHD6, this division is less constrained. HHD6 has devoted a larger share of income toward fishing in general and can take advantage of the reductions in input prices across all zones. Though HHD6 seems better off from a fishing perspective, both it and HHD2 must reduce consumption of all other goods due to decreased household income. Falling household income is the result of redistributions of labor and capital from non-recreational fishing industries to recreational fishing (RF) industries. In order for the economy to meet increased demand for QE and Trip inputs, it must redistribute resources to increase supply in these industries. The RF industries are more capital intensive, which means that when pulling capital from other industries there is extra labor that must be absorbed. Wages fall to employ all workers; less income and higher prices, results in welfare loss.

Table 3: SBSP Average Direction of Change During Invasion: HH Level

Household Level Changes for Household Division 2

SBSP	Fishing Composite Consumption	-
	Price of the Fishing Composite	+
	AOG Composite Consumption	-
	Price of the AOG Composite	+
	Household Income After Taxes and Savings	-

Household Level Changes for Household Division 6

SBSP	Fishing Composite Consumption	+
	Price of the Fishing Composite	-
	AOG Composite Consumption	-
	Price of the AOG Composite	+
	Household Income After Taxes and Savings	-

Welfare loss also occurs when considering only species-specific preferences. Table 4 below shows the results snapshot for the SBO model. In comparison to the full space and species model, many of the responses to the invasion stay the same. HHD6 continues to offset reductions in biomass of the most desired species by increasing QE inputs, quality production, and trip related inputs. And, the increased demand and consequently increased supply, results in industry price drops for QE and Trip inputs. HHD2 follows its pattern for Zone 3 in the SBSP model, by reducing all inputs, regardless of the fall in most prices. For this HHD it is too costly to make up for what is lost in species biomass, so it decreases overall demand for fishing.

Table 4: SBO Average Direction of Change During Invasion

Changes for Household Division 2

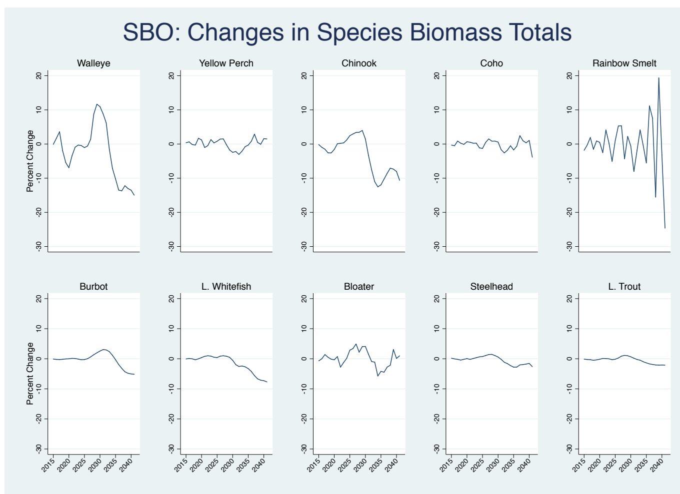
SBO	Demand Quality Enhancing Inputs	-
	Price of Quality Enhancing Inputs	-
	Demand Quality Inputs	-
	Price of Quality	+
	Demand for Trip Inputs	-
	Price of Trip Inputs	-
	Fishing Composite Consumption	-
	Price of the Fishing Composite	+
	AOG Composite Consumption	-
	Price of the AOG Composite	-
	Household Income After Taxes and Savings	-

Changes for Household Division 6

SBO	Demand Quality Enhancing Inputs	+
	Price of Quality Enhancing Inputs	-
	Demand Quality Inputs	+
	Price of Quality	-
	Demand for Trip Inputs	+
	Price of Trip Inputs	-
	Fishing Composite Consumption	+
	Price of the Fishing Composite	-
	AOG Composite Consumption	+
	Price of the AOG Composite	-
	Household Income After Taxes and Savings	-

The main differences between the SBO and the SBSP is the ecology and the broader economy outcomes. Note that although the composite price of all other goods in the economy decreased, incomes also decreased. Incomes will have dropped for the same reason as before: capital and labor shifts into RF industries, labor is freed up because RF is capital intensive, and wages fall. The impact, or magnitude, of this effect is what has changed between the two models. By summing over the zones and leaving species-specifics only, there are no more instances of species being absent from a zone (See Figure 5).

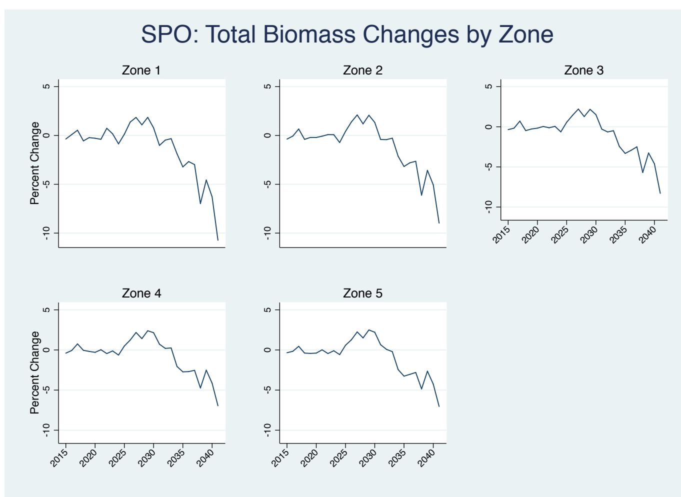
Figure 5



Altogether the effects of the invasion appear to be less severe. Having the ability to fish every species and a seemingly larger amount of each, artificially reduces the need for QE inputs to offset losses. This is relayed through the utility nest: demands for QE, quality, and trip inputs still increase, but less than in the SBSP model. That is, welfare losses still occur, but at a much lower magnitude.

As for the SPO model welfare estimates shift direction, but it is worth noting that it hovers just below zero. The sign of the result implies that consumers would be willing to let the invasion happen, because they end up slightly better off. Part of this can be explained by the change in the composition of the ecological data. Referring to Figure 6, by removing species-specific preferences, total biomass in each zone, on net, is less affected by the invasion; a one unit drop in the biomass of any one species is balanced out by a one unit increase in any other species. In all zones, it takes about 18 years before total biomass levels start to decrease. With the fisherman having no preferences for individual species but rather a sum total, in zones where biomass levels improve he does not have to increase QE inputs.

Figure 6



As shown in Table 5, each HHD only increases QE inputs in one of the zones, choosing to substitute to the zones where fishing is relatively less expensive for the respective household. Even though prices rise, each HHD increases subutility in the zone where fishing is cheaper; they are able to take more trips to those zones and boost quality production in a more cost-effective way. And, because each zone has become more similar in its portfolio of species biomass levels, each zone carries close to equal weight in the composition of the fishing composite.

Table 5: SPO Average Direction of Change During Invasion: Zone-Level

Zone Level Changes for Household Division 2

		Zone 3	Zone 4
SPO	Demand Quality Enhancing Inputs	+	-
	Price of Quality Enhancing Inputs	+	+
	Demand Quality Inputs	+	-
	Price of Quality	-	+
	Demand for Trip Inputs	+	+
	Price of Trip Inputs	+	+
	Value of Zone Subutility	+	-
	Unit Price of Subutility	-	+

Zone Level Changes for Household Division 6

		Zone 3	Zone 4
SPO	Demand Quality Enhancing Inputs	-	+
	Price of Quality Enhancing Inputs	+	+
	Demand Quality Inputs	-	+
	Price of Quality	+	-
	Demand for Trip Inputs	+	+
	Price of Trip Inputs	+	+
	Value of Zone Subutility	-	+
	Unit Price of Subutility	+	-

Table 6: SPO Average Direction of Change During Invasion: HH Level

Household Level Changes for Household Division 2

SPO	Fishing Composite Consumption	+
	Price of the Fishing Composite	-
	AOG Composite Consumption	+
	Price of the AOG Composite	-
	Household Income After Taxes and Savings	+

Household Level Changes for Household Division 6

SPO	Fishing Composite Consumption	+
	Price of the Fishing Composite	-
	AOG Composite Consumption	-
	Price of the AOG Composite	+
	Household Income After Taxes and Savings	+

With the fisherman having more flexibility to substitute to cheaper zones, he is able meet his overall demand for fishing at a reduced cost, see Table 6. This result holds for both HHDs. Incomes improve as demands for most goods (both RF and Non-RF) increase, and welfare increases, albeit slightly. If the invasion continues and overall biomass levels continue to drop, this model may produce welfare losses.

The final model, the NSS approach, produces welfare estimates that are much smaller on magnitude than that of the SBSP. Welfare impacts from the NSS are almost zero, because the species-specific preferences and spatial relationships have been removed. There is no ability to substitute to other zones, where fishing might be more cost effective. And, once biomass is summed over all zones and species (see Figure 7), it doesn't change much from year to year.

Figure 7

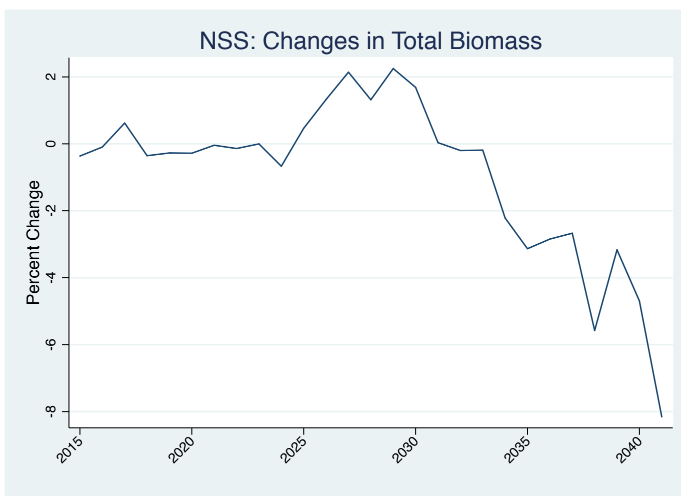


Table 7: NSS Average Direction of Change During Invasion

Changes for Household Division 2

NSS	Demand Quality Enhancing Inputs	-
	Price of Quality Enhancing Inputs	-
	Demand Quality Inputs	-
	Price of Quality	+
	Demand for Trip Inputs	+
	Price of Trip Inputs	-
	Fishing Composite Consumption	-
	Price of the Fishing Composite	+
	AOG Composite Consumption	-
	Price of the AOG Composite	-
	Household Income After Taxes and Savings	-

Changes for Household Division 6

NSS	Demand Quality Enhancing Inputs	+
	Price of Quality Enhancing Inputs	-
	Demand Quality Inputs	+
	Price of Quality	-
	Demand for Trip Inputs	+
	Price of Trip Inputs	-
	Fishing Composite Consumption	+
	Price of the Fishing Composite	-
	AOG Composite Consumption	-
	Price of the AOG Composite	+
	Household Income After Taxes and Savings	-

Therefore, removing flexibility of substitutions from the model, seems to be the contributing factor to the small positive welfare assessment rather than the negative in the SPO case. As shown in Table 7, HHD2 (low demand household) reduces overall fishing consumption and HHD6 (high demand) chooses to meet demands by increasing all factor of production. In comparison to the SBO and SBSP models, changes in demand for inputs, prices, and incomes from labor and capital redistributions are quite small.

6 Discussion and Conclusion

The SBSP model results provide support for modeling economic and ecological relationships that reflect preferences and tradeoffs. It suggests that portfolio of species in each zone, fisherman preferences, and the biological impacts on certain species matter for estimating welfare. When zones contain highly desirable species and these species are significantly impacted by an invasion, the cost of sustaining desired quality levels is expensive. Households with lower demands and greater constraints, reduce quality, trips, zone-level fishing consumption, and the overall fishing composite, while households with high demand increase these inputs where possible to meet desired demand. Economy-wide redistributions of labor/capital and reduced demand for all other non-recreational fishing goods contracts the economy; households earn less income and welfare falls.

A similar story exists when only species-specifics are included. Without zones, the species impacts from the invasion seem less severe. The implication is the model's underestimate of the welfare impacts. Alternatively, when the portfolio of is species condensed to one, non species-specific value, 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 both 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 much smaller than the species-specific and spatially-explicit model.

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 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.

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Appendix A

Figure 1: Firm Production and Supply Nest

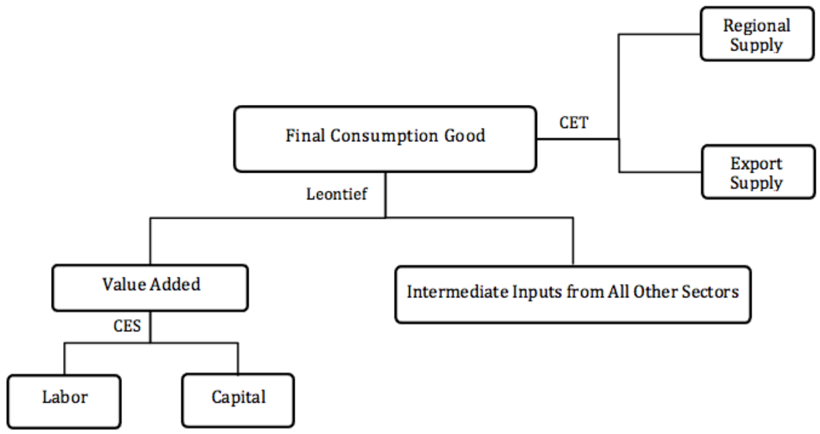


Figure 2: Utility Nest

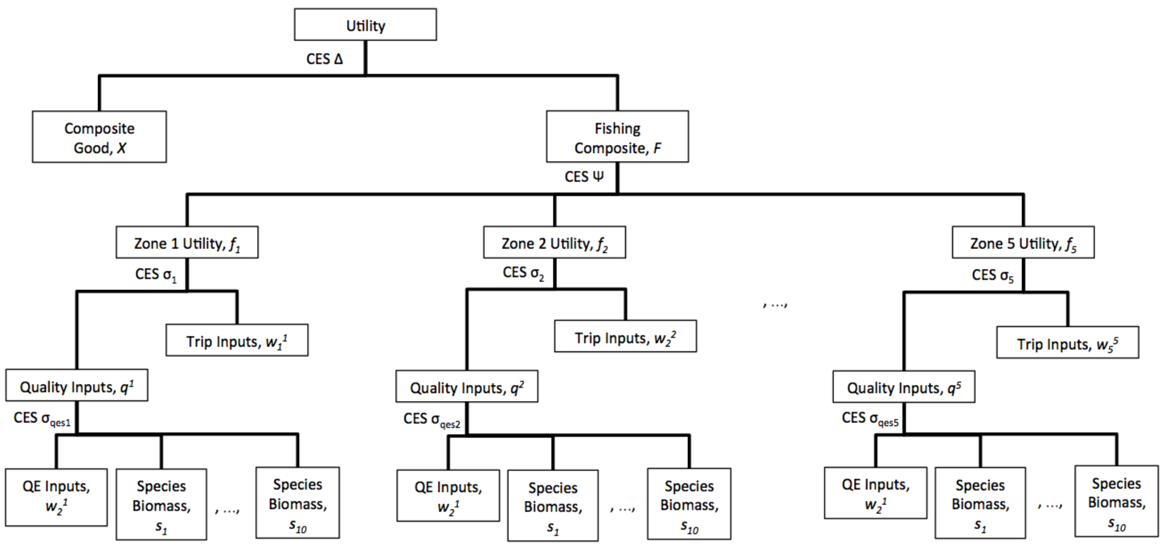
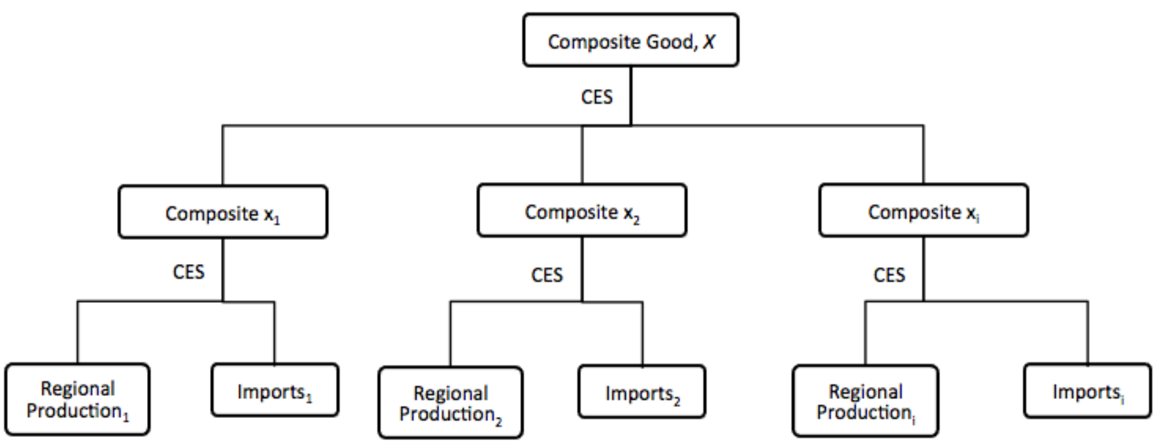
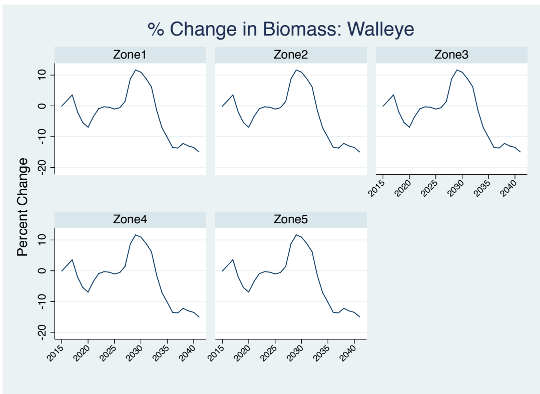
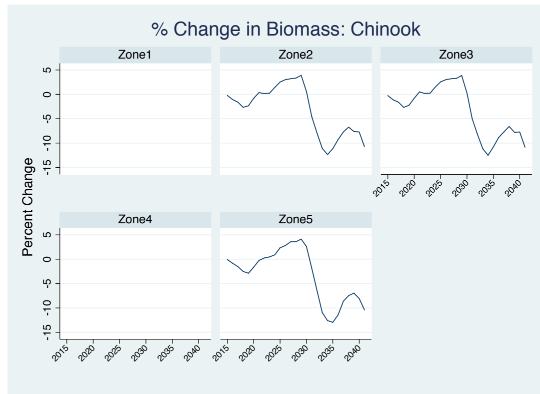


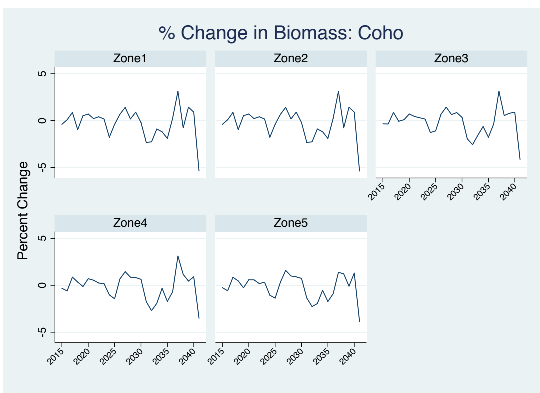
Figure 3: Composite Good Nest

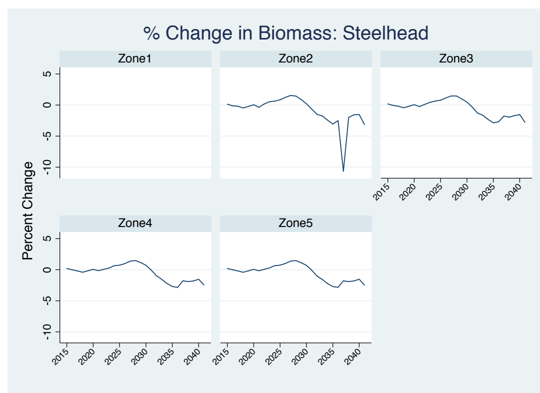


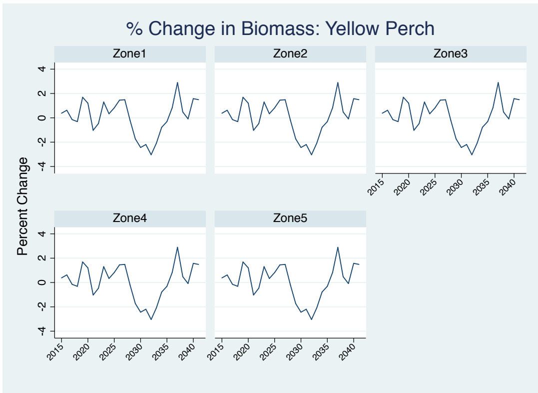
Appendix B: All Biomass Charts

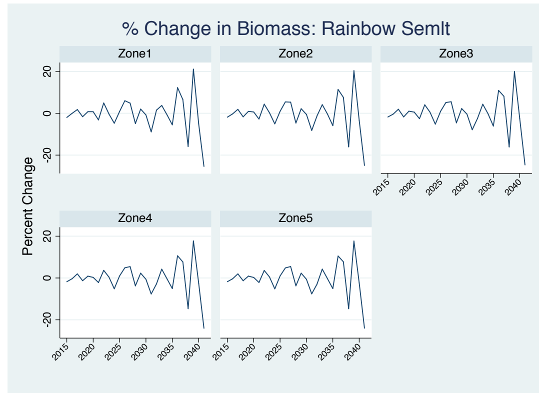


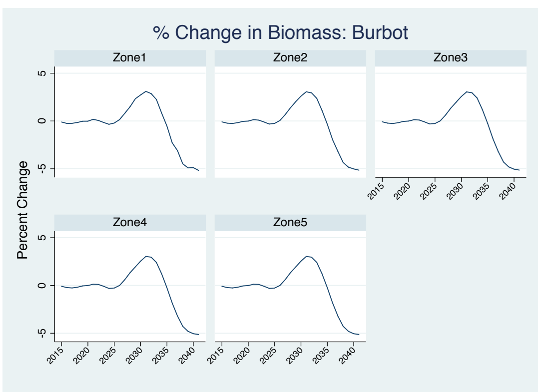


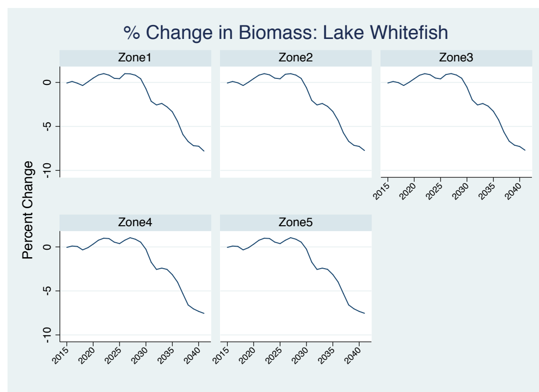


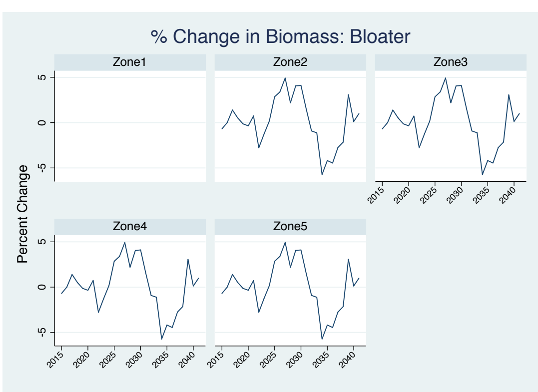


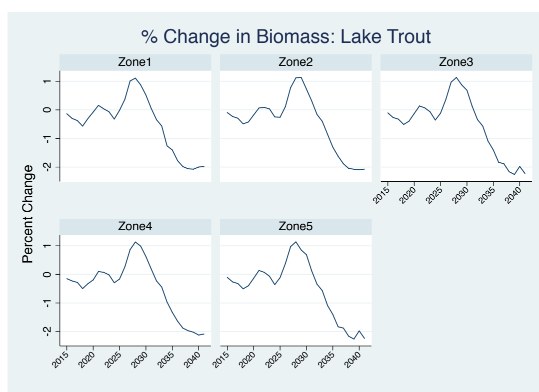

% Change in Biomass: Yellow Perch
Zone1
Zone2
Zone3
Zone4
Zone5
Percent Change


% Change in Biomass: Rainbow Semlt
Zone1
Zone2
Zone3
Zone4
Zone5
Percent Change


% Change in Biomass: Burbot
Zone1
Zone2
Zone3
Zone4
Zone5
Percent Change


% Change in Biomass: Lake Whitefish
Zone1
Zone2
Zone3
Zone4
Zone5
Percent Change


% Change in Biomass: Bloater
Zone1
Zone2
Zone3
Zone4
Zone5
Percent Change


% Change in Biomass: Lake Trout
Zone1
Zone2
Zone3
Zone4
Zone5
Percent Change