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Examining Movement Dynamics of the Gulf Menhaden Fishery Using an Individual-based Model

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EXAMINING MOVEMENT DYNAMICS OF THE GULF MENHADEN FISHERY

USING AN INDIVIDUAL-BASED MODEL

by

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ABSTRACT

EXAMINING MOVEMENT DYNAMICS OF THE GULF MENHADEN FISHERY USING AN INDIVIDUAL-BASED MODEL

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This study investigates the movement and harvest dynamics of the Gulf Menhaden *Brevoortia patronus* fishery. The fishery-dependent data collected by NOAA (years 2006-2009 and 2011) describe vessel-specific information on catch locations (latitude and longitude) and magnitude of harvest in metric tons (mt). A series of probability distribution functions (PDFs) were fit to the frequency distributions of number of harvests per day (Poisson), between-harvest distances (gamma), and harvest magnitude (log-normal). These analyses were used to inform an individual-based model (IBM). The IBM was run under several different spatial restriction regimes, including (1) current regulations in Texas, Louisiana, Mississippi, and Alabama; (2) additional restrictions off the coast of Jackson County, MS; (3) an extension of current regulations to 2.6 km (two miles) from shore; and (4) closures of all Mississippi waters. This study describes fleet dynamics of one of the more important commercial fisheries in the region and illustrates how they can be simulated using a spatially-explicit IBM.

ACKNOWLEDGMENTS

Partial funding for this work was provided by the University of Southern Mississippi. Fisheries-dependent data was provided by Joseph Smith at NOAA. I want to thank my advisor Dr. Robert Leaf for his guidance and encouragement. I would also like to thank Dr. Wei Wu for her courses in programming and geographic information science. Dr. Mark Peterson provided several thorough reviews of early drafts and excellent advice on the formatting, organization, and content of my work. Employees and students at the Gulf Coast Research Laboratory and the Leaf Fishery lab provided advice and encouragement. I would also like to thank the library staff at GCRL, specifically Joyce Shaw and Maryanne Anthony, for their help in finding articles and research materials. Finally, I would like to thank my family and friends for their inspiration and support.

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LIST OF ABBREVIATIONS

CDFRs	Captain's Daily Fishing Reports
GOM	Gulf of Mexico
IBM	Individual-Based Model
NOAA	National Oceanic and Atmospheric Administration
OFAT	One Factor At a Time
PDF	Probability Distribution Function
PMF	Probability Mass Function
SEDAR	SouthEast Data, Assessment, and Review

CHAPTER I – INTRODUCTION

The stock of Gulf Menhaden *Brevoortia patronus* in the northern Gulf of Mexico (GOM) supports a major commercial fishery, but also provides a variety of ecosystem services including transporting nutrients within marine food webs, regulating water quality, and supporting higher tropic level species (Deegan, 1993; Rabalais et al., 2002; Vaughan et al., 2007). Gulf Menhaden are a member of the family Clupeidae, which includes sardines, shads, and herrings, and are a schooling stock that are characterized as "forage fish" (Alder et al., 2008; Lassuy, 1983; Pikitch et al., 2012) to denote their trophic role. Gulf Menhaden spawn offshore in the winter (Stoecker and Govoni, 1984), and from November through June the filter-feeding post-larvae recruit to the nearshore coastal zone (Lassuy, 1983), and in late summer migrate offshore. This ontogenetic movement results in the transport of an estimated 5% to 10% of the total primary production of coastal waters to offshore waters (Deegan, 1993). In contrast, isotopic analyses of adult Gulf Menhaden dorsal muscle tissue indicate consumption of roughly equal amounts of zooplankton and phytoplankton (Olsen et al., 2014). The efficient conversion of both primary and secondary production by Gulf Menhaden at all life stages makes them an important part of both marine and estuarine food webs. The nutrient transport of Gulf Menhaden has implications for its ecological role as a prey fish because they are a food source for a variety of fishes, including Spotted Seatrout *Cynoscion nebulosus*, White Trout *Cynoscion arenarius*, Red Drum *Sciaenops ocellatus*, Bluefish *Pomatomus saltatrix*, Longnose Gar *Lepisosteus osseus*, Bull Shark *Carcharhinus leucas*, and others (Etzold and Christmas, 1979; Lassuy, 1983; Scharf and Schlicht, 2000; Simmons and Breuer, 1964).

The Gulf Menhaden fishery is one of the larger and longer-operating fisheries in the United States, producing raw materials for products ranging from animal feeds to margarine (Smith, 1991). Before the 20th century, menhaden stocks were primarily used as fertilizer; indeed, the term *menhaden* originates from the Algonquin *munnawhateaug*, meaning "they fertilize" (Harper, 2017). During the early 20th century, processed meal from Atlantic Menhaden *B. tyrannus* began to be used as poultry feed. By the end of World War II, the modernization of purse-seine menhaden fisheries and related industries which started on the Atlantic coast spread to the GOM (Smith, 1991). Menhaden oil is used in formulations of margarine in Europe, and medicines, fish oil supplements, and processed food in the United States (SEDAR, 2013). The oil is also used in lubricants, greases, inks, and plasticizers (Christmas et al., 1983; Hale et al., 1991). The Gulf Menhaden fishery constitutes a substantial part of the total annual commercial landings (9.44% to 14.1%) in the United States, and the estimated annual value of landings during the study period ranged from $44.9 million in 2006 to $92.8 million in 2011 (NOAA, 2014). Landings peaked in the mid-1980s with 1982 to 1987 exhibiting the greatest landings from 1950 to 2016.

Although Gulf Menhaden range from Veracruz, Mexico to Cape Sable, Florida, they are most abundant in the waters of Louisiana and Mississippi (Lassuy, 1983). Currently, the Gulf Menhaden purse-seine fishing season starts on the third Monday of April, and ends on 1 November annually (SEDAR, 2013). Gulf Menhaden fishing vessels generally leave port and travel to known or reported fishing grounds, often directed by spotter planes. Once vessels find a school of fish, two purse-seine boats leave the main vessel and surround the fish with a net. The fish are pumped on board after the net is tightened, then the purse-seine boats return to the main vessel which then continues to harvest from the remaining school or moves to the next school (Smith, 1991). When vessels are nearly full they return to the reduction plant to offload catch, and then return to the fishing grounds, sometimes staying overnight (Sharon Turner, Omega Protein, personal communication, 6 February 2014), though fishing occurs only during daylight hours (Smith, 1991).

All federally-managed fish stocks are subject to quantitative assessments that estimate historical and present status of fish stocks using historical catch, biological parameters, and estimated abundance (NOAA, 2017). The Beaufort Assessment Model (BAM) is used in the stock assessment of Gulf Menhaden. The BAM uses multiple data and parameter inputs to calculate catch-at-age and provides managers estimates of the status of the Gulf Menhaden fishery and stock (Williams and Shertzer, 2015). The data input for the BAM includes commercial landings, age and length data, and indices of recruitment and abundance. The BAM assumptions are that (1) Gulf Menhaden are a single population, (2) age-specific natural mortality is constant, (3) cohort sizes decay exponentially, (4) growth follows the von Bertalanffy growth function, (5) a sex ratio of 1:1, and (6) a “knife-edge” maturity where all fish of both sexes reach maturity upon reaching age 2. Based on the results of the model, the stock is currently not overfished and no overfishing is occurring, though the stock has experienced overfishing in the past (SEDAR, 2013). The stock assessment of Gulf Menhaden informs managers of the status of the stock, and this information is then used to determine if restrictions are warranted.

Although few regulations are in place for the Gulf Menhaden fishery, state and local governments have implemented spatial restrictions. Alabama law states that Gulf

Menhaden fishing by purse seine can occur only south of a line stretching from South Rigolets to Bayou LaBatre Channel marker “19” and west of a line from this channel marker south to Dauphin Island. In addition, no fishing may occur in any waters within 1.6 km (one mile) of land in Alabama (SEDAR, 2013). In Mississippi, fishing is not allowed within 1.6 km (one mile) of the Mississippi barrier islands or the shores of Harrison and Hancock counties (SEDAR, 2013). A similar restriction was proposed by Jackson County’s Board of Supervisors, though it was not approved by Mississippi Commission on Marine Resources (CMR; Nelson, 2016a, 2016b). In Louisiana, areas landward of the Inside/Outside Shrimp Line, defined in Louisiana Revised Statutes 56:495 (2016), are closed to commercial Gulf Menhaden fishing. Exceptions to this restriction are Breton and Chandeleur Sounds, defined in Louisiana Title 76 §307 (2014). An additional closed area at Grand Isle, LA, within 150 m (500 ft) from shore is in effect from 1 May to 15 September. Texas prohibits fishing within 800 m (one-half mile) of shore, though the Gulf Menhaden industry has an informal agreement with the Texas Parks and Wildlife Department to not fish within 1.6 km (one mile) of shore (SEDAR, 2013).

Individual Based Models (IBMs) are often used to model the behaviors of agents (Grimm and Railsback, 2005), here vessels, with each individual in the model following a set of simple rules, interacting with the landscape directly, and with each other indirectly (Grimm et al., 2005). For example, IBMs have been used in fields as diverse as epidemiology to model the transmission of disease (degli Atti et al., 2008; Milne et al., 2008; Ajelli and Merler, 2009), the social sciences to model the diffusion of innovation and novel behavior (Deffuant et al., 2005; Edwards et al., 2003), and in marketing to model the launch of new products (Delre et al., 2007). IBMs are widely used in the biological and ecological sciences (Grimm and Railsback, 2005), including understanding the behavior of fishing fleets (Bastardie et al., 2010; Helu et al., 1999; Little et al., 2004; Powell et al., 2016).

Little et al. (2004) created a spatially-structured IBM of the fishery of Coral Trout *Plectropomus leopardis* in the Great Barrier Reef. The authors hypothesized that information flow between vessels had implications in resource use and that the magnitude of information sharing had management implications. Their model tested two different fishing strategies, the cautious 'Cartesians' and the high-risk 'Stochasts' (Allen and McGlade, 1986). The model revealed that port-sharing vessels would have more similar fishing areas than vessels from different ports. When the model was executed without information flow, the Cartesians would over-fish the same areas. When information flow was included, Cartesians would fish in new areas, reducing the mean catch of the Stochasts. Their IBM demonstrated that the spatial distribution of catch and effort changed when information flow was added to the model because of its influence on the results of different fishing strategies (Little et al., 2004).

Helu et al. (1999) examined the stability of a simulated fishery under two alternatives, one with boats of equal ability and one with boats of unequal ability. One model output was an index of fishery stability, a function of the variability of the number of boats and fish. The alternative with unequally skilled boats had "ranked catch" that was dependent on the wealth of the boat owners, because Individual Transferable Quotas (ITQs) could be purchased from less successful fishers. The unranked-catch model with boats of equal ability resulted in an unstable fishery. In the ranked-catch model, competition and variation in profitability caused poor-performing vessels to sell their quotas to more successful vessels. In this model, a specific ITQ resulted in a fishery that was more stable in terms of fleet and stock size over time due to unsuccessful vessels gradually leaving the fishery (Helu et al., 1999).

A bioeconomic IBM created by Bastardie et al. (2010) examined Danish fisheries in the context of catch per unit fuel (CPUF). The modelers had both economic and environmental concerns and were interested in reducing carbon emissions through reduced fuel use in fishing vessels. The model produced energy-efficiency measurements with regard to three different fishing strategies: (A) fishing nearshore with lower potential catch, (B) changing to a nearshore fishery to reduce fuel use, and (C) a per-trip optimization based on individual vessels' operating expenses and potential catch. Strategies A and B were potentially profitable if total catch was over a minimum amount. Strategy C resulted in increased catch and increased CPUF relative to actual CPUF data. Bastardie et al. (2010) recommended modeling fuel use and spatial distribution of effort and catch on a per-vessel basis to increase profits and CPUF and decrease carbon emissions.

The overall goal of this project is to explore how spatial closures impact the movement dynamics of the Gulf Menhaden fishery fleet. Specific goals are to (1) simulate vessel movements and spatial fishing dynamics from fishery-dependent data and (2) evaluate the impact of alternative spatial restriction scenarios on the fishery. I will create an IBM of the fishery, analyze the IBM's output to diagnose spatial patterns which exist in the fishery, and perform sensitivity analyses of model parameters. Model fit will be evaluated by its ability to reproduce the observed spatial pattern of effort, and patterns examined include (1) depth at harvest, (2) distance from shore, (3) total annual harvest, (4) proportion of harvest events in Mississippi waters, (5) longest distance from the reduction plant for each vessel day, (6) distance to the reduction plant of the last net set of the day, (7) longest between-harvest distance of each vessel day, and (8) total distance traveled per vessel day. Sensitivity analyses will be used to determine the effects of parameters, derived from the fishery-dependent data, on model output. To examine the possible effects of the gridded structure of the spatial network on model output, an alternative spatial network will be created whose grid structure will be rotated 45°. This project also examines how spatial patterns of harvest vary under different fishing restrictions and evaluates the cost to the industry of spatial restrictions, in terms of the extra distance that must be traveled when additional spatial restrictions are enacted.

CHAPTER II - METHODS

The primary source of data used in the construction of the IBM is fishery-dependent data supplied by NOAA Fisheries, called the Captain's Daily Fishing Reports (CDFRs). These data are voluntarily provided to NOAA by the Gulf Menhaden fishing industry, and compliance with the data collection program is at or near 100%. The CDFR data are collected from the vessels operating from reduction plants at Moss Point, Mississippi; Empire, Louisiana; Abbeville, Louisiana; and Cameron, Louisiana. The data consist of the spatial distribution of fishing effort for 2006 to 2009 and 2011 (the CDFR data for 2010 is not available to me due to legal complications associated with the Deepwater Horizon oil spill). The CDFRs are the daily set-specific information made by each fishing vessel and include a unique vessel identification code, associated reduction plant, the location (latitude and longitude), date, and estimated amount caught (in metric tons, mt). I performed quality control on the CDFR data: missing information or net set locations reported outside the latitude range of 28.0° to 31.0° N and the longitude range of 95.0° to 87.5° W were removed, and processing plant identification numbers that did not correspond to the four coastal reduction plants. As there is no way of knowing from the CDFR data if net sets with zero metric tons of harvest were mistakes in data records or possible instances of equipment malfunction, vessel days with any net sets of zero metric tons were removed. Vessel days with missing net sets were also removed. From the CDFR data, I calculated the distance between successive net sets (km), the length of the workday (hours), and the depth at the harvest location (m). All data was aggregated at a monthly basis for each plant over all years and over all vessels, with a focus on vessels whose home plant was Moss Point, Mississippi. Net set locations from each plant were binned into monthly gridded spatial bins of 0.05° longitude by 0.05° latitude. The spatial patterns of aggregated harvest were used to understand the general spatial distribution of fishing effort in the study area and the variation in the monthly spatial distribution of harvest over the course of an "average" fishing season.

The IBM I constructed has a spatial framework that serves to define the movement dynamics of the vessels. The spatial extent of this model is from 95.0° W to 87.5° W and from 28.0° N to the coastlines of Texas, Louisiana, Mississippi, and Alabama in the northern Gulf of Mexico. The model framework is constructed as a spatial network, composed of vertices linked by edges; this spatial network is a modified a graph created in R (Csardi and Nepusz, 2006) by adding additional vertex and edge attributes and by removing those vertices and edges which lay over land. Each vertex has spatial attributes: longitude and latitude, and a depth attribute derived from digital elevation models (DEMs). Vessels can move through, but do not fish in waters deeper than 10 m, nor do they harvest fish in closed areas. To initialize the spatial network, a set of vertices was created with a grid size of 0.01° longitude by 0.01° latitude. A uniform random deviation ranging from -0.001° to 0.001° was added to the latitude and longitude coordinate of each vertex. This random deviation was applied to the vertex's spatial attributes in order to prevent directional biases when selecting a random vertex within a 0.05° longitude by 0.05° latitude grid square; otherwise the vertexes whose coordinates were on the edge of a grid square always be considered within the southern grid square, or the eastern grid square, due to the nature of half-bounded intervals. The vertices were connected via edges to the closest vertices in eight cardinal and intercardinal directions [North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West

(W), and Northwest (NW)]. Each edge's distance was calculated on the WGS84 ellipsoid (Hijmans et al., 2016), and range from 0.77 to 1.76 km. There are 130,148 vertices and 512,192 edges in the spatial network. The vertices and edges of the network are in areas of navigable waters, and paths through the spatial network represent all the possible routes that modeled vessels may move. The spatial network approach in this work was inspired by the methods reported by Bastardie et al. (2010).

To parametrize the IBM, I fit probability distribution functions (PDFs) to the number of net sets per vessel day, the magnitude of harvest (mt), and the distances traveled by vessels between net sets (km). These data were aggregated by month over all years with a focus on the Moss Point, Mississippi, plant. The number of harvest events in each vessel-day was simulated using a Poisson distribution. The IBM uses a gamma distribution to determine the distance to the next harvest event, the between-harvest distance (km). Finally, the harvest amount for each net set was simulated using a log-normal distribution (mt). Each of the PDFs were fit to the observed data from the CDFR data set using the method of moments (Pearson, 1894), which enables the estimation of parameters using algebraic relationships of moments (mean and variance) and the parameters of PDFs.

The between-net-set distances, d_i, for each vessel day were described using gamma PDFs, whose parameters were derived from between-net-set distances for each month in the CDFR data, aggregated across all years and all vessels for each month This distribution has two parameters: alpha α, the shape parameter and beta β, the rate parameter, which here determine the probability of a given distance (km):

$$Pr(d_i|\alpha,\beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} d_i^{\alpha-1} e^{-\beta d}$$

where $\Gamma(x)$ is the gamma function, a generalization of the factorial ($n!$) to all real numbers. The moments of the gamma distribution are:

$$\mu = \frac{\alpha}{\beta}$$

and

$$\sigma^2 = \frac{\alpha}{\beta^2}$$

The mean and variance of the observed distance data (km) were set equal to the mean and variance of the gamma distribution to derive parameter values using the method of moments (Pearson, 1894).

The Poisson distribution was used to model the number of net sets in a "workday," which I define as any vessel-day greater than or equal to four hours from the start of the first net set to the end of the last net set. The Poisson distribution's has a rate parameter, λ, the mean number of net sets in a "workday." The Poisson probability mass function (PMF), a discrete version of a PDF, is defined as:

$$Pr(n|\lambda) = \frac{\lambda^n}{n!} e^{-\lambda}$$

where $n! = 1 * 2 * 3 * \ldots * n$ is the the factorial of n, the number of net sets in a "workday."

The harvest amounts (mt) for all net sets were described using a log-normal PDF, based on historical harvest data for each plant-month. The log-normal PDF is:

$$Pr(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(ln(x)-\mu)^2}{2\sigma^2}}$$

where σ is the shape parameter of the PDF and the standard deviation of the log-transformed data, and μ is the location parameter of the PDF and the mean of the log-transformed data. The log-transformed harvest amount data from the CDFRs provided mean and standard deviation parameters for the log-normal PDF.

The depth at each vertex was determined using nearest-neighbor interpolation from two DEMs. Initially the NOAA National Centers for Environmental Information (NCEI) U.S. Coastal Relief Model (CRM) was chosen as the data source for depths in the spatial network (NGDC, 2001). The CRM is a 3 arc-second bathymetric and topographic DEM with a spatial extent covering all U.S. waters. Additionally, the northern Gulf Coast 1 arc-second DEM (whose extent is a subset of the CRM) was used for interpolation in the region of its spatial extent, 28.5° to 31.25° N and 90.75° to 85° W (Love et al., 2012), because the CRM data set has interpolation problems in the regions of Breton and Chandeleur Sounds (Christopher Amante, NOAA, personal communication, 30 August 2016).

IBMs are composed of agents which act according to control rules. In this IBM, the agents are defined as fishing vessels deployed from the Moss Point, Mississippi reduction plant. Vessels in this model each have a certain number of net sets, or harvests, per day and move through the spatial network between each net set. The IBM simulates one vessel at a time, and after all vessels have completed their net sets for that day the model proceeds to the next day of fishing. Parameters vary each month of the simulated fishing season, April through October. Vessel attributes included a unique identification number, geographic location, movement parameters (α, β), harvest-frequency parameter (λ), and harvest-amount parameters (μ, σ). At each daily time step, a vessel's movement and fishing dynamics were determined by random draws from the associated PDFs. The monthly parameter values for fishing vessels determined the number of harvest events per vessel day by a random draw from the associated Poisson PDF. The harvest amount (mt) at each fishing location was determined by a random draw from the month- and plant-specific log-normal PDF. Similarly, distances that each vessel travels between harvest events were drawn from gamma PDFs, whose parameters change by plant and month to represent intra-seasonal variation.

This IBM progresses using the following structure and schedule that simulates the movement and harvest dynamics of vessels. The mean number of vessels per plant-month were used to determine the number of vessels as the model executed. The number, n, of harvests each day ("net sets") were randomly sampled from a Poisson distribution derived from historical fishing days greater than or equal to four hours (Figure 1). The general fishing area for each vessel-day was determined by a random weighted sample of the gridded spatial bins, e.g., a grid square with 100 net sets from the CDFR data set would be selected on average twice as many times than a grid square with 50 recorded net sets. The location of the first harvest of each vessel day was chosen at random from all vertices within the sampled grid square; vertices with depth greater than 10 m or those in areas of spatial restrictions were excluded from this random selection. The location of the next net set of the vessel-day was randomly selected from all vertices which are about distance d (Figure 2) from the previous net set and are not in areas of spatial restrictions. The shortest path between net set i and net set $i + 1$ was calculated using Dijkstra's algorithm as implemented in the igraph package (Csardi and Nepusz, 2006; Dijkstra, 1959). Dijkstra's algorithm serves to explore all neighboring vertices of the starting

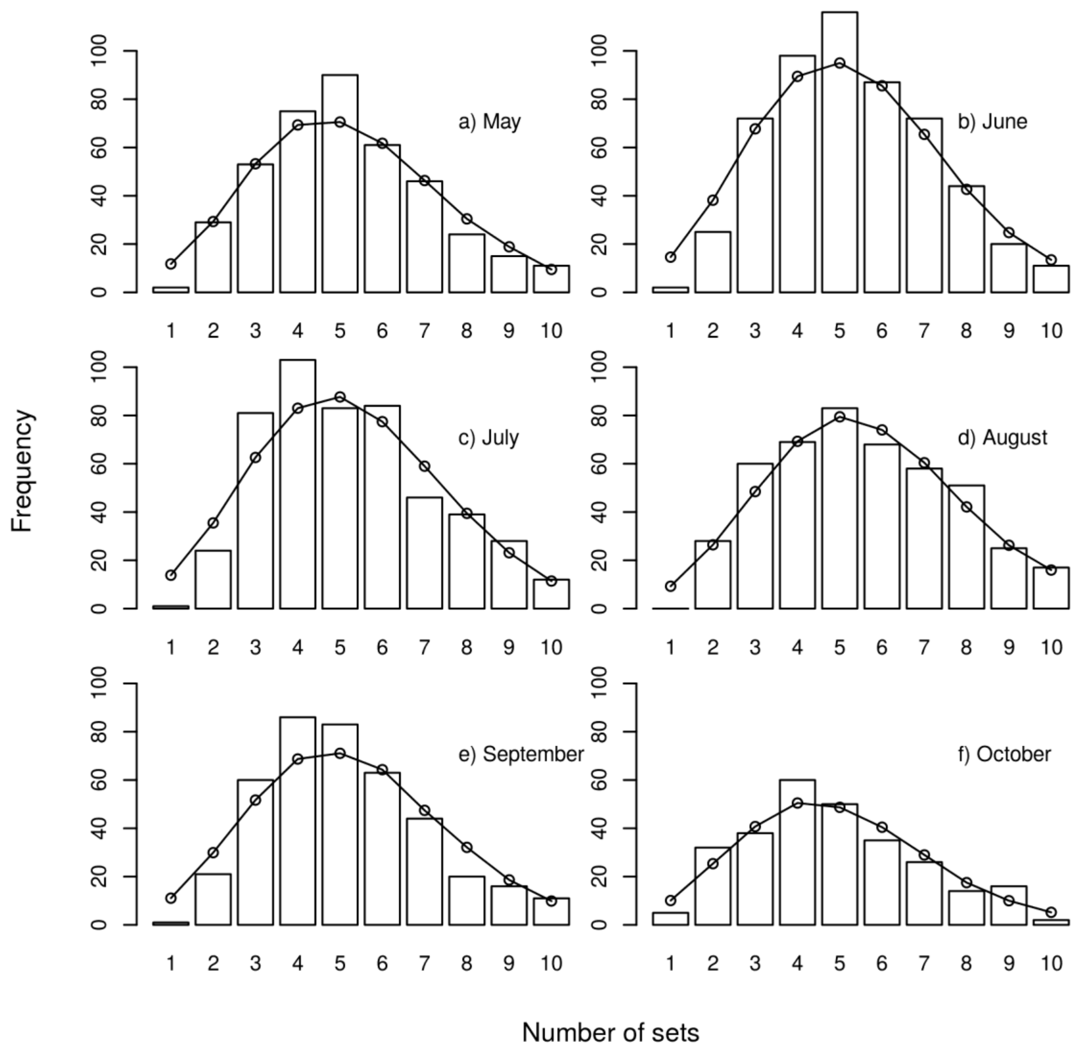

Figure 1. Observed net sets.

Observed frequency of net sets per vessel day for days of greater than or equal to four hours of fishing for vessels from Moss Point, Mississippi, grouped by month. Monthly data for May through October was aggregated for years 2006-2009 and 2011. The open circles are predicted data from the Poisson distribution and the lines serve as a guide for the eye.

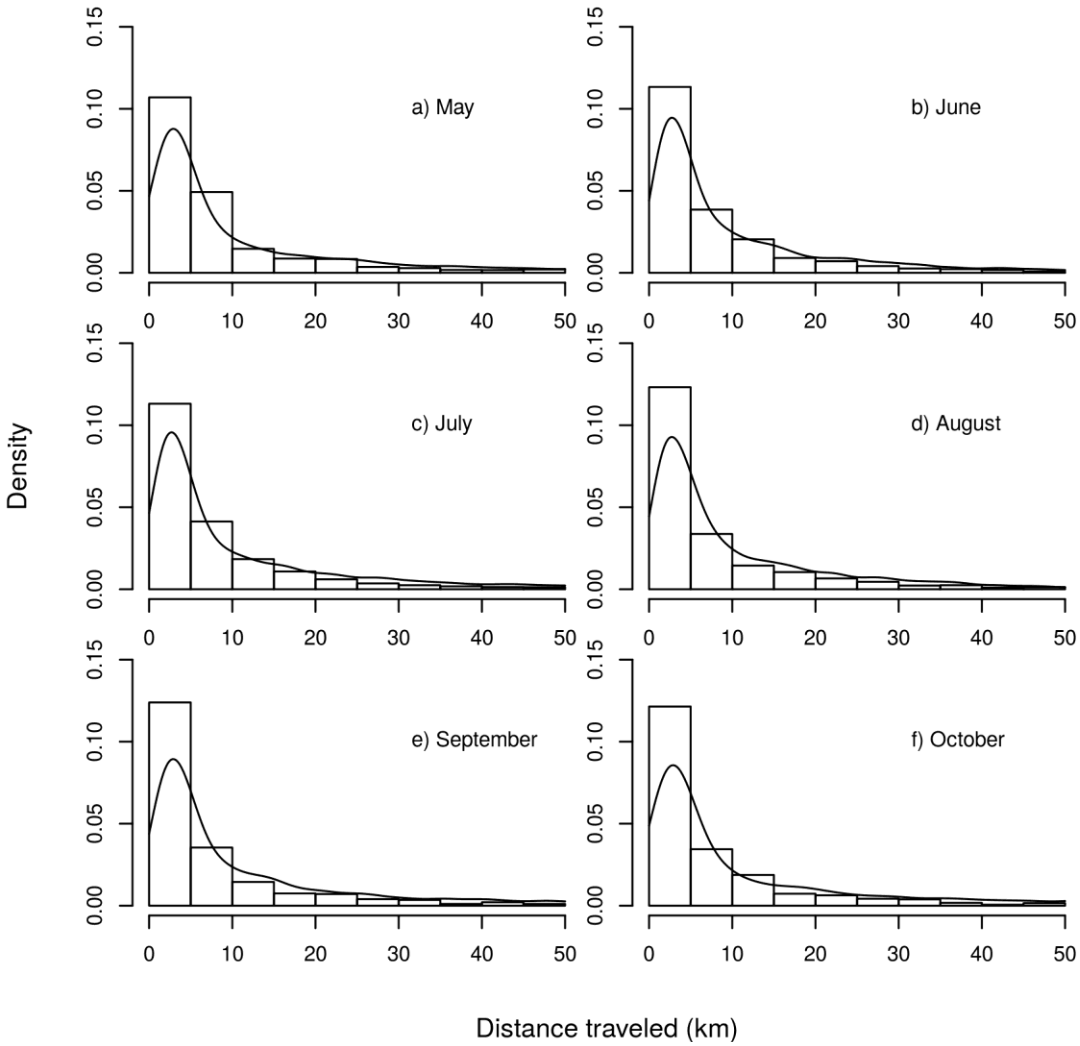

Figure 2. Distances traveled.

The observed distances vessels fishing from the Moss Point, Mississippi, plant travel between net sets for each month. Distances above 50 km are not depicted. Predicted distances (black lines) are overlaid, representing the gamma probability distribution functions (PDFs) used in the model. The histogram of the observed distances traveled was scaled to the range, i.e. the codomain, of the gamma PDF.

location and expands outward until the destination vertex is found, while keeping track of the shortest path to each vertex of the expanding ring. A number of state variables were tracked for each vessel in the simulation, including harvest locations and harvest amounts (Figure 3) recorded for each net set for all simulated vessels. Each day in the model was completed by repeating the process of randomly selecting distances, locations, and harvest amounts (mt) for each net set for all agents (Figure 4). Model simulations were performed 100 times.

I integrated the state statutes, local ordinances, and areas of depth greater than 10 m to determine the set of vertices where fishing does not occur in the model. Spatial restriction polygons representing current regulations in Texas, Louisiana, Mississippi, and Alabama were created and used to determine vertices where modeled vessels could not fish in the spatial network. Restrictions were imposed by masking the vertices in the base model, making travel to locations included in the restricted areas unfishable but navigable.

Model output was qualitatively and quantitatively evaluated to determine the effects of alternative spatial restriction regimes on the movement dynamics of Gulf Menhaden fishing vessels fishing from the Moss Point, Mississippi plant. Four different model scenarios were executed: a “base” model and three scenarios that included additional spatial restrictions. Simulated restrictions included (1) current regulations, (2) a 1.6 km (one mile) zone of fishing restrictions added to the Jackson County mainland, (3) an extension of Mississippi restrictions to 3.2 km (two miles) from all shores, and (4) a complete closure of Mississippi waters to Gulf Menhaden harvest. Alternative spatial restriction scenarios were evaluated for vessels with Moss Point as their home plant. I

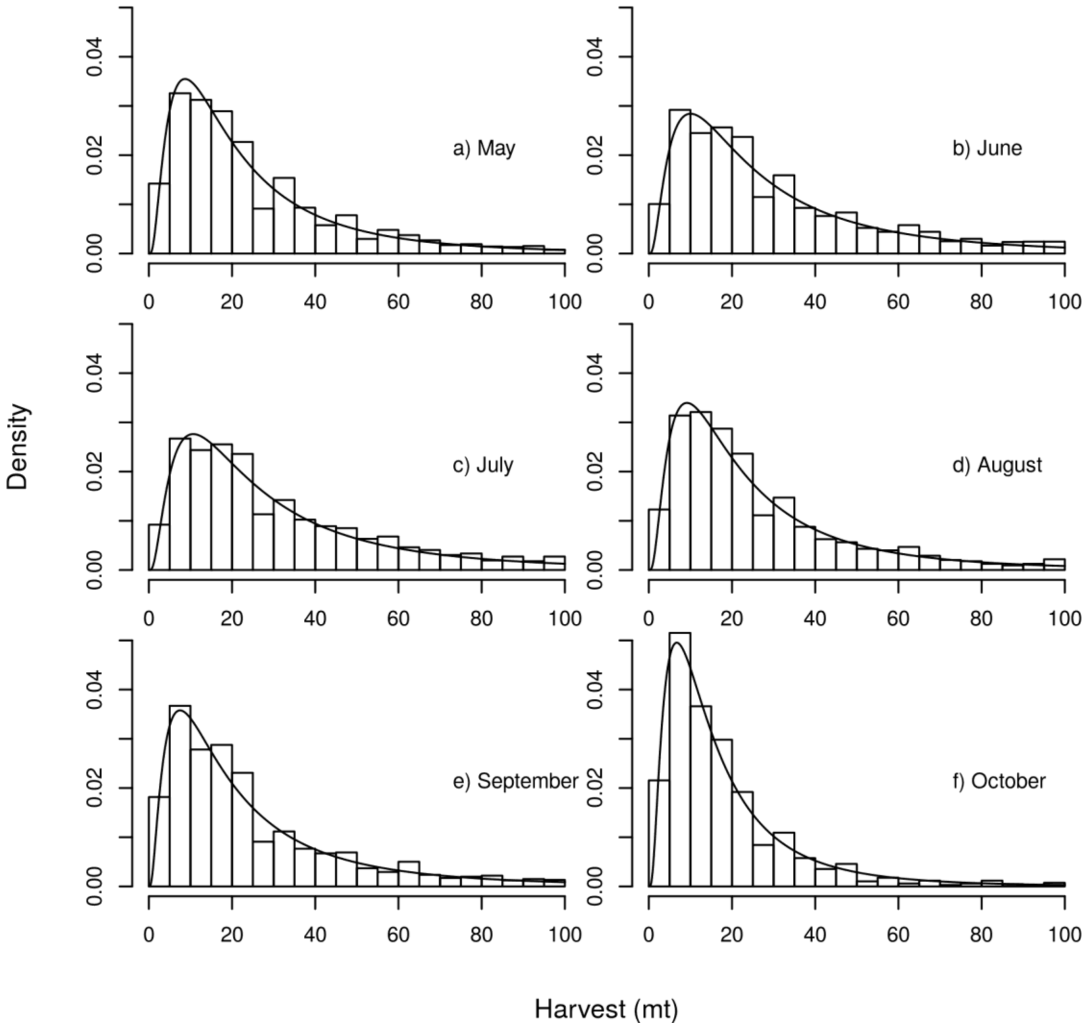

Figure 3. Harvest amounts.

Observed harvest (mt) per net set of the Moss Point, Mississippi, Gulf Menhaden fishery. Overlaid are the predicted probability distribution functions of log-normal distributions (black lines), which the individual-based model uses to simulate harvest amounts. The histogram of observed harvest was scaled to the range, i.e. the codomain, of the log-normal PDF.

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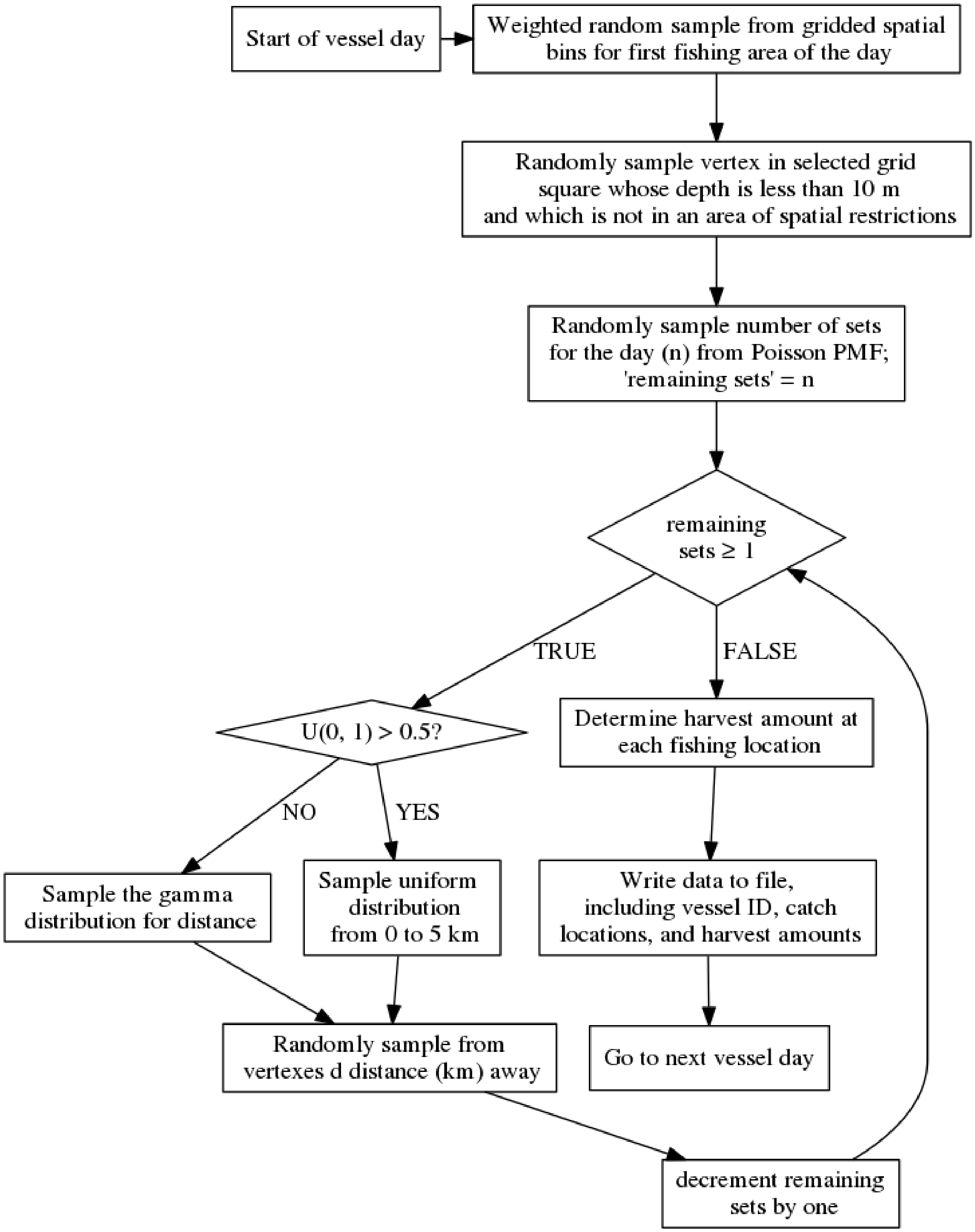

Figure 4. Model flowchart.

Flowchart of processes to generate simulated data for one vessel day.

used a pattern-oriented approach (Grimm et al., 2005) to examine the spatial distribution of harvest and the distances from the reduction plant of the last net set of each vessel day. To qualitatively compare the spatial distributions of effort for the three alternative spatial restriction scenarios, I plotted the differences between the base model and the alternative scenarios using a method analogous to examining to the residuals of a linear regression, aggregating data over the 100 simulations for each scenario. Additionally, I compared the results of running the model with current regulations in the base spatial network to the results of running that model using an alternative spatial network with a 45° rotation of its gridded structure. To make these comparisons, the number of net sets in each grid square for the two associated data sets were rescaled from zero to one, with one representing the value in the grid square with the maximum number of net sets; these values were stored in matrices with each element of a matrix representing a 0.05° x 0.05° longitude and latitude grid square. The values of one matrix were subtracted from the other. For example, to compare the base model to the scenario with 3.2 km of restrictions, the matrix associated with the 3.2 km scenario was subtracted from the matrix associated with the base model; in this way I created "spatially-specific deviations." Negative deviations represented areas of more fishing in comparison to the base model, whereas positive deviations represented areas of less fishing in comparison to the base model. Deviations of greater than or equal to 0.10 were considered areas of "much less fishing," deviations greater than or equal to 0.05 and less than 0.10 were considered areas of "less fishing," and deviations greater than or equal to -0.05 and less than 0.05 were considered areas of "near-equal fishing." Similarly, deviations greater than or equal to -0.10 and less than -0.05 were considered areas of "more fishing" and deviations less than -0.10 were considered areas of “much more fishing.” The interpretation of the spatially-specific deviations provided a qualitative assessment of the change in spatial distribution of harvest under the different scenarios. Emergent patterns, those not explicitly programmed into the model, were also compared between the base model and the observed data, and between the base model and the three alternative scenarios. To quantitatively evaluate the differences between models, the means and 95% confidence intervals were examined for (1) depth at harvest, (2) distance from shore, (3) total annual harvest, (4) proportion of harvest events in Mississippi waters, (5) longest distance from the reduction plant for each vessel day, (6) distance to the reduction plant of the last net set of the day, (7) longest between-harvest distance of each vessel day, and (8) total distance traveled per vessel day.

Sensitivity analyses were used to examine the relationship between input parameters and model output for modeled vessels whose home port was Moss Point, Mississippi. An alternative graph structure, rotated 45° in comparison to the base spatial network, was also examined for effects on model output by the structure of the spatial network. The IBM had five parameter inputs ($\alpha, \beta, \lambda, \mu, \sigma$) that varied each month. The relationship between the modeled vessels’ parameter attributes and model output, e.g. the mean distance from the reduction plant of the last net set of the vessel day, was examined by holding parameters at certain values for the entirety of the model’s execution. This one-factor-at-a-time (OFAT) method was used to examine the effects of changing individual parameter values on model output (ten Broeke, 2016). A range of values for each parameter were analyzed: the value of the parameter derived from all years of the CDFRs data set for vessels fishing from Moss Point, Mississippi, and 10% and 20%

increases and decreases of this parameter value. I determined the effect of model parameters on the patterns in model output by executing the model while holding one parameter value constant and letting the others parameters vary for 100 replicated fishing seasons. I also determined the effects of the structure of the spatial network by running the model in an alternative, rotated, graph for 100 replicated fishing seasons using the current regulations on spatial restrictions.

CHAPTER III - RESULTS

The fishery-dependent CDFR data were examined for quality control purposes, and vessel-days with any questionable data were removed. Less than 0.01%, ($n = 148$) of data had coordinates outside the spatial extent of the study area, representing 0.11% ($n = 19$) of all vessel-days. Missing harvest amount records, or those recorded as zero, composed 1.5% of the CDFRs ($n = 125$) vessel-days. Only one record had an identification number which did not correspond to one of the four coastal reduction plants. A total of 81 vessel-days had missing net sets, i.e., the total number of net sets for a vessel-day did not match the net set number for the last net set of that vessel-day. Non-sequential net set numbers comprised 0.24% of the CDFRs ($n = 227$), while unnumbered net sets were rarer, at 0.026% of the CDFRs ($n = 25$). Invalid times and dates made up 0.57% of the CDFRs ($n = 540$). Only "complete cases" (Schafer and Graham, 2002), 86.7% of the original CDFRs data (82,276 records total and 14,352 records from fishing out of Moss Point, Mississippi), were used to determine model parameters.

For all years combined, fishing from the Moss Point, Mississippi plant during the start of the fishing season, in April, was mainly focused between Breton and Chandeleur Sounds, near the mouth of the Mississippi River Gulf Outlet (MRGO, Figure 5). In May, fishing continued near the MRGO, but also was concentrated in Chandeleur Sound near Drum Bay, Louisiana (Figure 6a). June and July months exhibited a shift of effort to Mississippi waters, though much fishing still occurred near the MRGO Figures 6b and 6c). A high concentration of fishing near the mouth of the MRGO and also south of

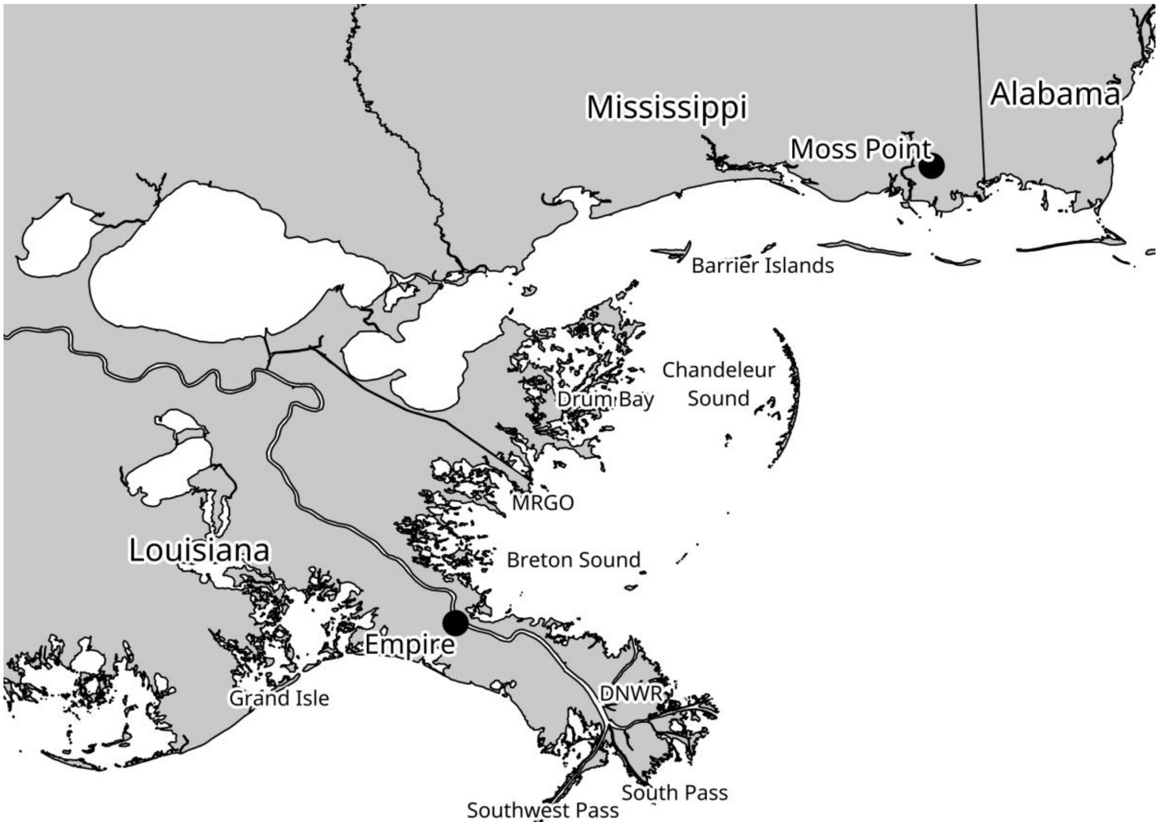

Figure 5. Places of interest.

Biloxi Bay, Mississippi, was observed in August months (Figure 6d). On average, September and October months exhibited a general shift away from the waters near the mouth of the MRGO to 1) Mississippi waters, 2) waters near the Delta National Wildlife Refuge (DNWR), Louisiana, and 3) the waters northeast of the Southwest Pass of the Mississippi River (Figures 6e and 6f). The base model, with spatial fishing restrictions equivalent to current regulations, showed a similar distribution of catch compared to the observed data (Figure 6) though the predicted catch was more dispersed (Figure 7).

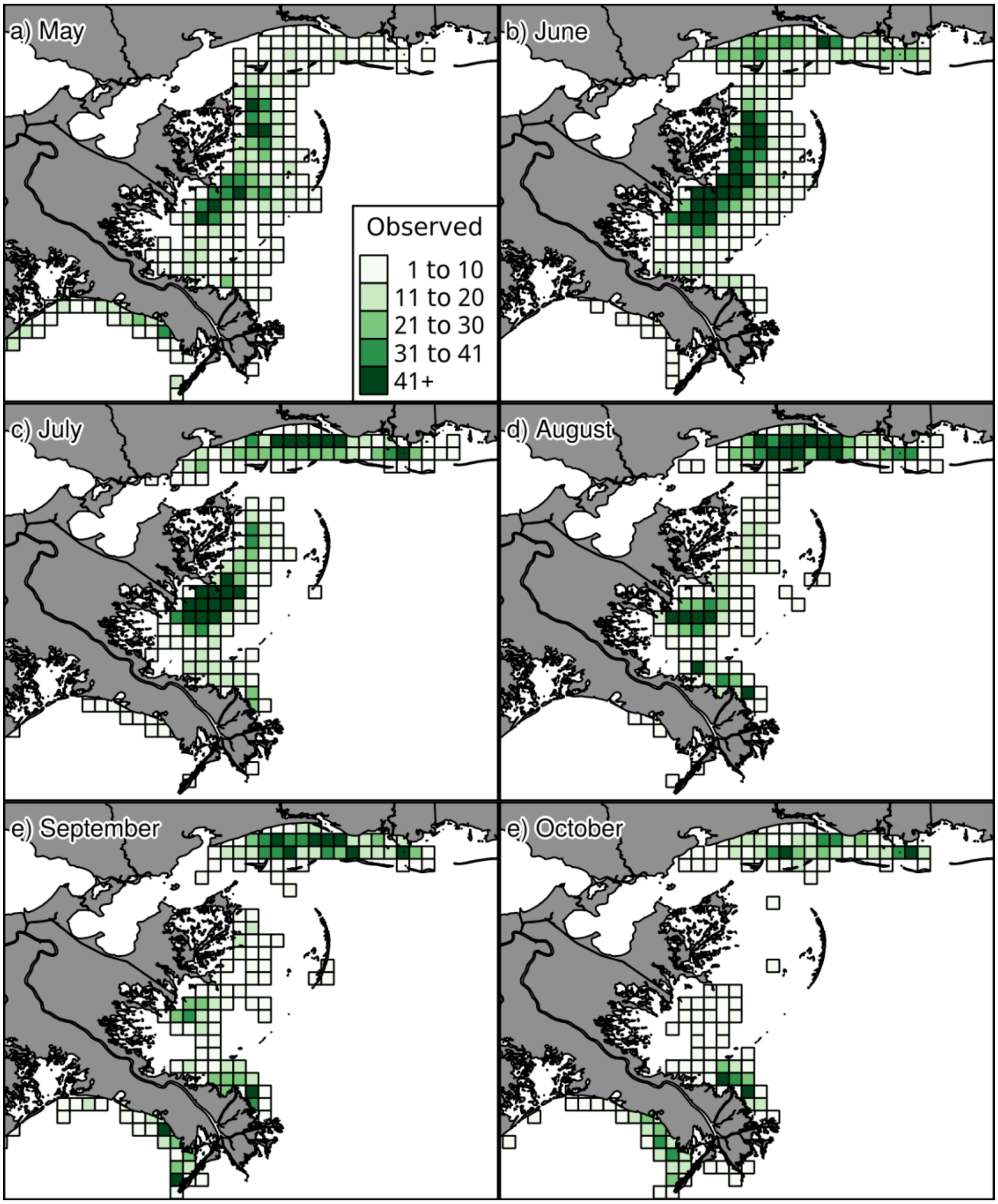

Figure 6. Monthly observed harvest

Spatial distribution of the observed number of net sets (n = 14,352) for May through October aggregated for all years for vessels with Moss Point, Mississippi as a home port.

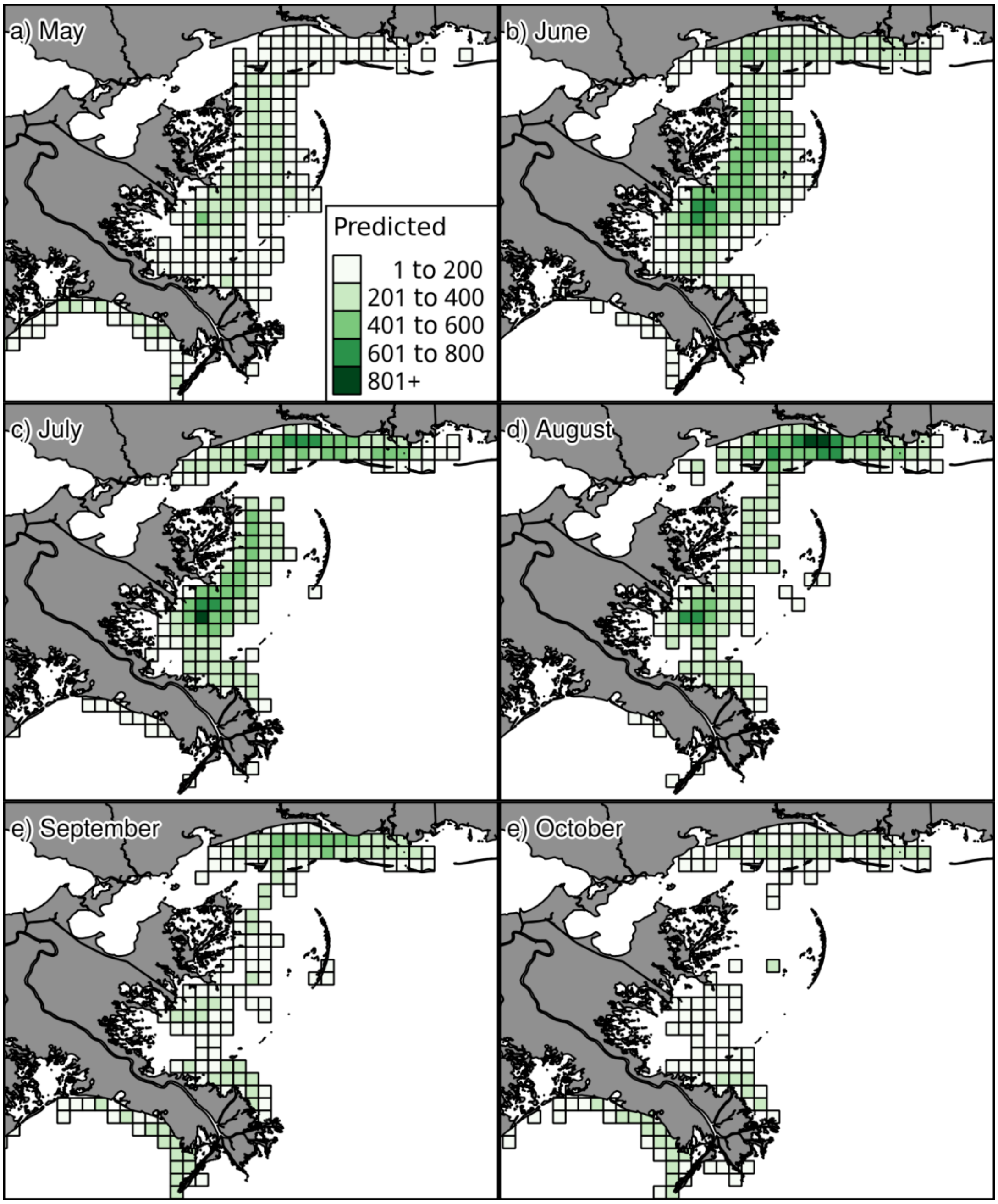

Figure 7. Monthly predicted harvest.

Spatial distribution of the predicted number of net sets for May through October, aggregated over all years for simulated vessels with Moss Point, Mississippi as a home plant. Bins were scaled by a factor of 20 (100 simulated seasons versus 5 years of observed data) for comparison to observed data.

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Parameter values for the model were derived from the CDFR data (Table 1). The mean number of net sets per vessel day varies over the course of the fishing season, reaching its maximum of 5.6 net sets in August (Table 1). The mean number of vessel days per month reaches its maximum earlier in the season in June (Table 2). The mean number of net sets per vessel day is used directly in the model (λ in the Poisson PDF). The number of vessel days per month in the model is a multiplicative result of the mean number of vessels per month and the mean number of days those vessels fish per month (Table 2). The mean distance between harvest events reaches its minimum of 8.3 km in the month of August (Table 3). The variance of the distances between successive harvest events also reaches its minimum in August at 199 km^2. The associated monthly α and β parameters of the gamma PDF reach their maximums in June and August, respectively (Table 3). The mean harvest amount reaches its maximum during July with 35 mt, while the standard deviation reaches its maximum in June and July at 32 mt^2 (Table 4). Parameters μ and σ of the log-normal PDF, used to determine harvest amounts in the model, reach their maximums in July and June, respectively (Table 4).

In addition to the qualitative comparison of the distribution of fishing effort (Figures 6 and 7), the base model was compared to the observed CDFR data using several metrics, including measures of distance and depth for vessel with Moss Point, Mississippi as a home plant. The mean total annual harvest was greater in the IBM in comparison to the observed data, with a mean of 88,400 mt in the model compared to 84,200 in the fishery-dependent CDFR data (Table 5), an increase of almost 5%. The mean depth in the base model was slightly higher at 4.39 m as opposed to 4.31 m in the observed data.

Table 1 *Monthly parameter values.*

Month	λ	α	β	μ	σ
4	4.5	0.22	0.022	2.7	0.90
5	5.2	0.23	0.023	2.9	0.87
6	5.4	0.37	0.039	3.1	0.92
7	5.3	0.34	0.038	3.2	0.91
8	5.6	0.35	0.042	3.0	0.88
9	5.3	0.27	0.029	2.9	0.95
10	4.9`	0.25	0.023	2.6	0.85

Monthly parameter values for vessels with Moss Point as a home port, aggregated for all years. The λ parameter of the Poisson distribution represents the mean number of net-sets per vessel-day. The gamma distribution has two parameters, α, the shape parameter and β, the rate parameter; both determine the probability of a given distance (km) being traveled between harvests by modeled vessels. The parameters of the log-normal distribution, μ and σ, are the mean and standard deviation of the logarithm of harvest amounts (mt) per net-set

Table 2 *Vessel Days.*

Month	Observed	Predicted
4	31	30
5	82	77
6	110	110
7	100	100
8	93	96
9	83	80
10	57	56

The observed and predicted mean number of vessel days per month for fishing out of Moss Point, Mississippi.

Table 3 *Distances Traveled.*

Month	Mean (km)	Variance	α	β
4	10.0	447	0.22	0.022
5	10.1	445	0.23	0.023
6	9.5	240	0.37	0.039
7	8.9	231	0.34	0.038
8	8.3	199	0.35	0.042
9	9.5	333	0.27	0.029
10	10.7	454	0.25	0.023

Monthly means and variances of observed distances traveled (km) between net sets and parameters for the associated gamma probability distribution functions for vessels fishing by vessels from Moss Point, MS. The gamma distribution has two parameters, α, the shape parameter and β, the rate parameter; both determine the probability of a given distance (km) being traveled between harvests by modeled vessels.

Table 4 *Harvest amounts.*

Month	Mean harvest (mt)	Standard deviation	μ	σ
4	23	23	2.7	0.90
5	26	24	2.9	0.87
6	34	32	3.1	0.92
7	35	32	3.2	0.91
8	28	27	3.0	0.88
9	28	28	2.9	0.95
10	19	19	2.6	0.85

Monthly means and variances of observed harvest amount (mt) of individual net sets and the parameters for the associated log-normal probability distribution functions for vessels from Moss Point, Mississippi. The parameters of the log-normal distribution, μ and σ, are the mean and standard deviation of the logarithm of harvest amounts (mt) per net-set.

Additionally, the mean distance from shore in the base model, 5.72 km, was also greater than in the observed data, 5.52 km. The proportion of harvest in Mississippi waters was lower in the IBM than in the observed data with 0.299 versus 0.316 (Table 6). The distance of the last net set of the vessel day to the reduction plant was much higher in the model at 123.3 km compared to 113.6 km in the observed data. The mean maximum distance to the reduction plant for each vessel day was also greater in the base model at 137.6 km versus 126.3 km in the observed data (Table 7). The mean furthest between-harvest distance per vessel day was shorter in the observed data, with 25.1 km compared to 31.8 in the model with current spatial restrictions. The mean total between-harvest distance traveled per vessel day was also shorter in the observed data, 40.1 km versus 55.5 km in the base IBM. (Table 8).

The output of the three proposed spatial restriction scenarios for vessels fishing from the plant at Moss Point, Mississippi, were compared to the output of the base model. The addition of 1.6 km (one mile) resulted in a decrease in the number of net sets off the coast of the Jackson County mainland and an increase in the number of net sets in the area of the Mississippi Sound between the Mississippi mainland and the Jackson County barrier islands (Figure 8). These changes in spatial distribution of effort resulted in an increased mean distance from shore, with 5.79 km in the Jackson County scenario compared to 5.72 km in the base model (Table 6), and an increase of 1.4 km for the mean distance of the last net set of the day to the reduction plant and 1.0 km for the mean maximum distance from reduction plant for each vessel day (Table 7). The Jackson

County scenario also had a reduction in the proportion of harvest in Mississippi waters with 0.293 compared to 0.299 in the base scenario (Table 6).

Table 5 *Total annual harvest.*

Scenario	Total annual harvest (mt)	95% LCL	95% UCL
Observed, CDFR data	84,200	81,200	87,100
Current	88,400	87,500	89,400
Alternative graph structure	89,500	89,000	90,000
1.6 km in Jackson Co.	88,400	87,100	89,600
3.2 km on MS Gulf Coast	87,300	85,900	88,600
No fishing in MS waters	87,100	85,800	88,400
$\mu = 2.5$	54,100	53,500	54,700
$\mu = 2.85$	76,700	75,800	77,600
$\mu = 3.2$	109,000	108,000	110,000
$\sigma = 0.75$	78,100	77,300	78,900
$\sigma = 1.00$	97,000	96,000	98,100
$\sigma = 1.25$	128,000	126,000	130,000
$\lambda = 4.22$	71,900	71,400	72,300
$\lambda = 4.75$	80,300	79,800	80,800
$\lambda = 5.28$	88,800	88,300	89,300
$\lambda = 5.81$	97,600	97,100	98,100
$\lambda = 6.33$	106,000	105,000	106,000

Mean and 95% lower (LCL) and upper (UCL) confidence levels for total annual harvest for 10 model runs of sensitivity analyses. Parameters defined in Table 1. The sensitivity analyses of the gamma parameters (α and β) are not included as those analyses result in similar mean total annual harvests (mt) as the base model.

Table 6 *Depth, distance from shore, and MS proportion.*

Scenario	Depth (m)	95% LCL	95% UCL	Distance from shore (km)	95% LCL	95% UCL	Proportion in MS	95% LCL	95% UCL
Observed, CDFR data	4.31	4.28	4.34	5.52	5.46	5.57	0.316	0.290	0.341
Current	4.39	4.38	4.40	5.72	5.70	5.74	0.299	0.296	0.302
Alternative graph structure	4.40	4.39	4.41	5.73	5.71	5.75	0.298	0.295	0.300
1.6 km in Jackson Co.	4.43	4.42	4.44	5.79	5.77	5.81	0.293	0.290	0.296
3.2 km on MS Gulf Coast	4.44	4.43	4.45	6.08	6.05	6.10	0.269	0.267	0.272
No fishing in MS waters	4.32	4.31	4.33	6.37	6.34	6.39	0.000	0.000	0.000
$\alpha = 0.234$	4.39	4.38	4.40	5.70	5.68	5.73	0.298	0.295	0.301
$\alpha = 0.263$	4.40	4.39	4.40	5.73	5.71	5.75	0.298	0.295	0.301
$\alpha = 0.292$	4.39	4.38	4.39	5.71	5.69	5.73	0.298	0.295	0.301
$\alpha = 0.321$	4.39	4.38	4.40	5.73	5.70	5.75	0.301	0.297	0.304
$\alpha = 0.351$	4.40	4.39	4.41	5.71	5.69	5.73	0.302	0.300	0.305
$\beta = 0.0244$	4.40	4.39	4.40	5.67	5.65	5.69	0.296	0.293	0.298
$\beta = 0.0274$	4.39	4.38	4.40	5.69	5.66	5.71	0.297	0.295	0.300
$\beta = 0.0305$	4.40	4.39	4.41	5.72	5.69	5.74	0.298	0.295	0.301
$\beta = 0.0335$	4.39	4.38	4.40	5.72	5.70	5.75	0.298	0.296	0.301
$\beta = 0.0366$	4.39	4.38	4.40	5.74	5.72	5.77	0.299	0.296	0.302
$\lambda = 4.22$	4.39	4.38	4.40	5.66	5.64	5.69	0.298	0.295	0.301
$\lambda = 4.75$	4.39	4.38	4.40	5.69	5.67	5.71	0.297	0.294	0.301
$\lambda = 5.28$	4.41	4.40	4.42	5.71	5.68	5.73	0.300	0.297	0.303
$\lambda = 5.81$	4.40	4.39	4.41	5.72	5.70	5.74	0.297	0.295	0.300
$\lambda = 6.33$	4.41	4.40	4.42	5.71	5.69	5.73	0.294	0.291	0.297

Examination of patterns in observed and predicted data, including model output for each of the model scenarios and the sensitivity analyses of model parameters. Means and 95% lower (LCL) and upper (UCL) confidence levels for the means of each scenario of 10 model runs are given for each scenario. Model scenarios where the parameters of the log-normal probability distribution function were altered are not included, as they have identical results to the “current regulations” scenario. Parameters defined in Table 1.

Table 7 *Mean distances.*

Scenario	Distance of last net set to plant (km)	95% LCL	95% UCL	Maximum distance from plant (km)	95% LCL	95% UCL
Observed, CDFR data	113.6	107.2	120.0	126.3	119.8	132.9
Current	123.3	122.5	124.1	137.6	136.8	138.3
Alternative graph structure	122.6	121.9	123.2	137.0	136.4	137.6
1.6 km in Jackson Co.	124.7	124.0	125.5	138.6	137.9	139.4
3.2 km on MS Gulf Coast	127.5	126.8	128.1	141.0	140.4	141.6
No fishing in MS waters	171.7	171.1	172.3	185.6	185.0	186.2
$\alpha = 0.234$	123.1	122.5	123.8	137.0	136.3	137.7
$\alpha = 0.263$	123.5	122.9	124.1	137.7	137.1	138.3
$\alpha = 0.292$	123.7	123.0	124.5	138.0	137.3	138.8
$\alpha = 0.321$	123.4	122.7	124.1	137.9	137.2	138.6
$\alpha = 0.351$	123.0	122.4	123.6	137.8	137.3	138.4
$\beta = 0.0244$	124.6	123.9	125.3	141.4	140.7	142.0
$\beta = 0.0274$	123.3	122.5	124.0	138.9	138.1	139.6
$\beta = 0.0305$	123.7	123.1	124.4	138.4	137.8	139.1
$\beta = 0.0335$	122.7	122.0	123.3	136.5	135.8	137.1
$\beta = 0.0366$	122.0	121.4	122.6	135.3	134.7	135.8
$\lambda = 4.22$	122.9	122.1	123.6	134.7	134.0	135.3
$\lambda = 4.75$	123.4	122.7	124.2	136.5	135.8	137.2
$\lambda = 5.28$	123.5	122.8	124.2	137.8	137.1	138.4
$\lambda = 5.81$	123.5	122.8	124.2	139.1	138.5	139.8
$\lambda = 6.33$	124.0	123.4	124.7	141.0	140.3	141.7

Mean distances between (1) reduction plant to and the furthest net set from plant, (2) reduction plant and the last net set of each vessel day, and (3) the mean distance between all net sets and the reduction plant.

Included are 95% lower confidence limits (LCL) and upper confidence limits (UCL). Parameters defined in Table 1

Table 8 *Distances travelled.*

Scenario	Furthest distance (km)	95% LCL	95% UCL	Total distance (km)	95% LCL	95% UCL
Observed, CDFR data	25.1	19.3	31.0	40.1	33.2	47.0
Current	31.8	26.1	37.5	55.5	45.9	65.2
Alternative graph structure	31.6	26.0	37.3	55.3	45.7	65.0
1.6 km in Jackson Co.	31.7	26.0	37.4	55.4	45.8	65.0
3.2 km on MS Gulf Coast	31.7	26.0	37.4	55.4	45.7	65.0
No fishing in MS waters	31.3	25.6	36.9	54.8	45.2	64.4
$\alpha = 0.234$	30.5	24.9	36.1	53.4	44.0	62.9
$\alpha = 0.263$	31.2	25.5	36.9	54.8	45.2	64.4
$\alpha = 0.292$	31.6	25.8	37.3	55.2	45.5	64.9
$\alpha = 0.321$	32.2	26.4	38.0	56.4	46.4	66.3
$\alpha = 0.351$	32.8	26.9	38.8	57.1	47.0	67.2
$\beta = 0.0244$	38.4	31.4	45.5	64.9	53.1	76.7
$\beta = 0.0274$	35.3	29.1	41.6	60.7	50.0	71.4
$\beta = 0.0305$	32.5	26.9	38.1	56.7	46.9	66.5
$\beta = 0.0335$	30.3	25.2	35.5	53.6	44.5	62.8
$\beta = 0.0366$	28.7	24.0	33.5	51.5	43.0	60.0
$\lambda = 4.22$	27.8	22.3	33.2	42.4	33.8	50.9
$\lambda = 4.75$	29.9	24.3	35.5	49.1	39.9	58.3
$\lambda = 5.28$	32.0	26.2	37.7	55.8	46.0	65.6
$\lambda = 5.81$	33.9	28.0	39.8	62.5	52.0	72.9
$\lambda = 6.33$	35.9	29.9	41.9	69.3	58.4	80.2

. Mean furthest between-harvest distance per vessel day and mean total between-harvest distances traveled per vessel-day. Parameters defined in Table 1

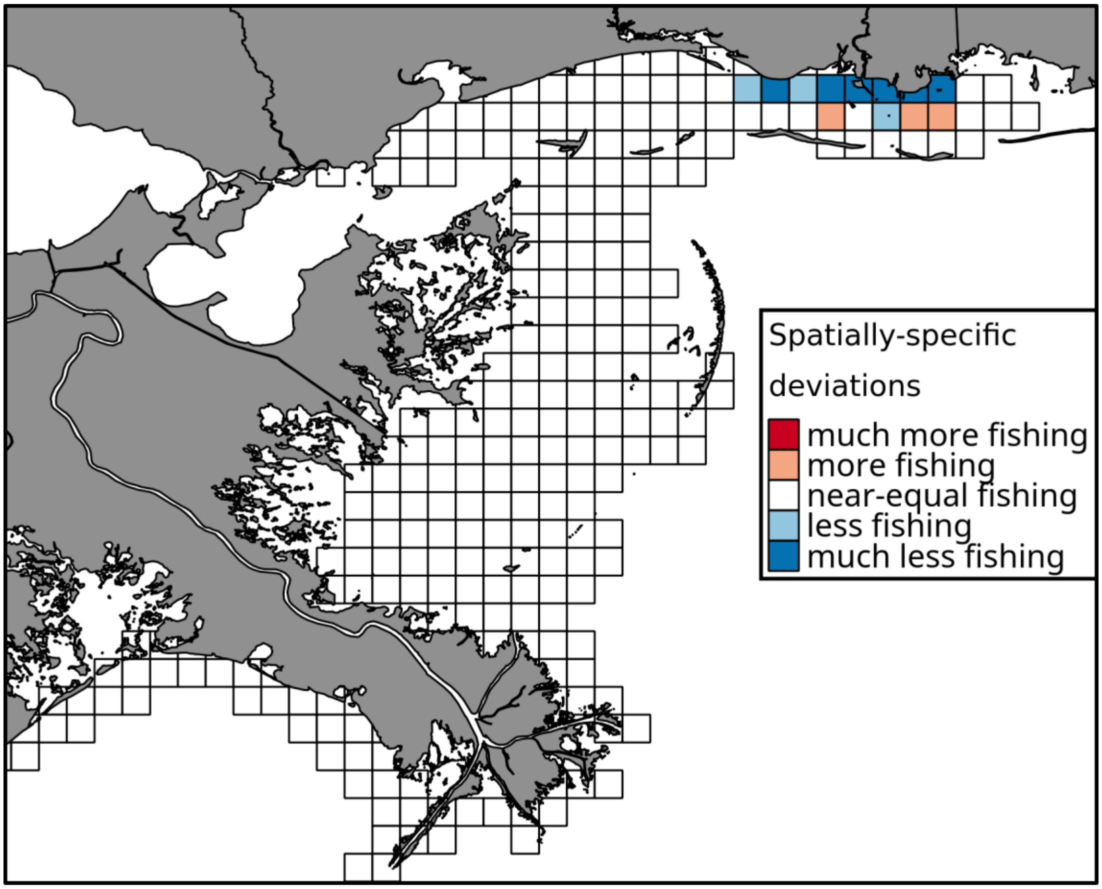

Figure 8. Jackson County restrictions.

Spatially-specific deviations of alternative spatial restriction scenarios in comparison to the base model. Addition of 1.6 km restrictions to Jackson county mainland.

The model output from the scenario with an additional 3.2 km (two miles) of spatial restrictions was compared to the base model with current regulations; the additional restrictions caused a decrease in fishing near the Mississippi mainland and island coastlines, and an increase in fishing in the areas between the barrier Islands and the mainland of Mississippi (Figure 9). These additional restrictions resulted in a reduced proportion of harvest in Mississippi waters, with 0.269 in the 3.2 km scenario versus 0.299 in the base scenario (Table 6). These restrictions also resulted in an increase in the distance from shore of 0.36 km to a mean of 6.08 km, an increase in the distance of the last net set of the day to the reduction plant of 4.2 km to a mean of 127.5 km, and an increase in the maximum distance from plant per vessel day of 3.4 km to a mean of 141.0 km (Tables 6 and 7).

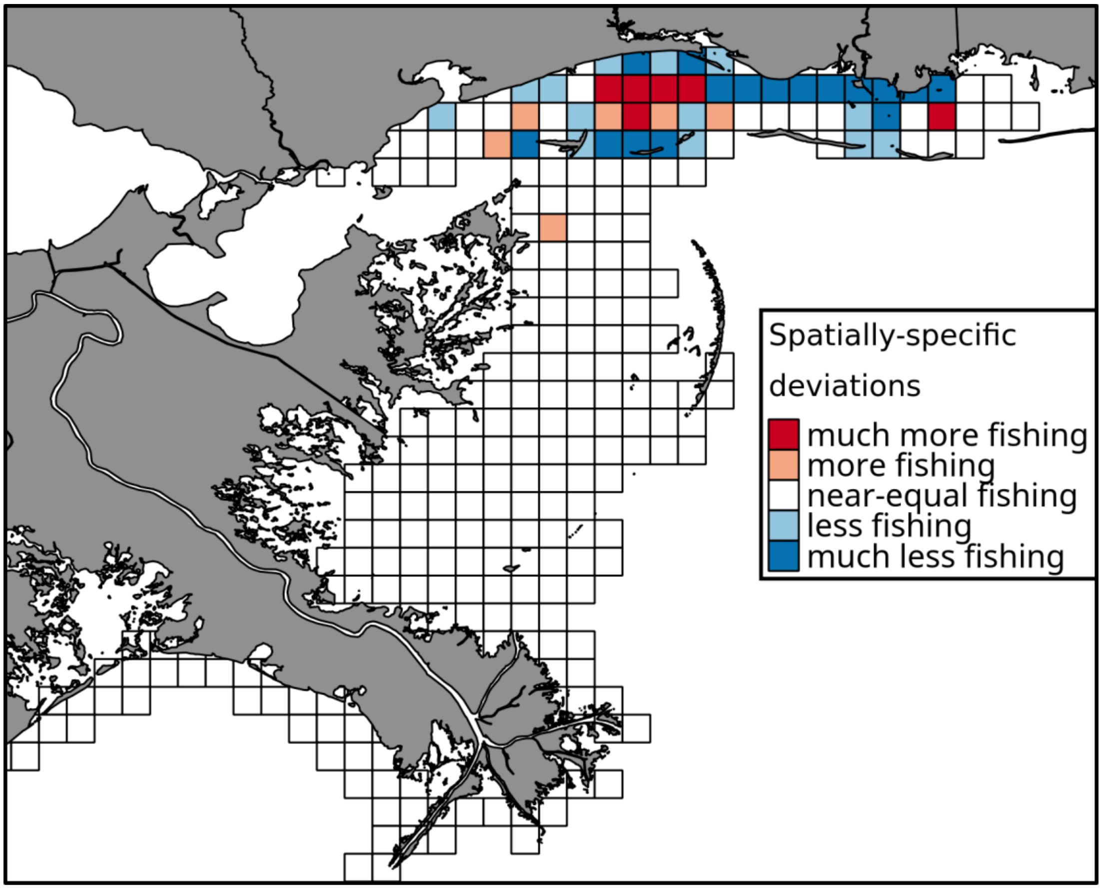

Figure 9. 3.2 km (two miles) of restrictions.

Spatially-specific deviations of alternative spatial restriction scenarios in comparison to the base model. Extension of restrictions to 3.2 km from Mississippi coasts.

The complete closure of Mississippi waters to Gulf Menhaden fishing caused an increase in fishing off the coast of the Delta National Wildlife Refuge and the Southwest and South Passes of the Mississippi River (Figure 10). The mean distance from shore, in comparison to the base model, increased by 0.65 km to a mean of 6.37 km when all Mississippi waters were closed to fishing (Table 6).

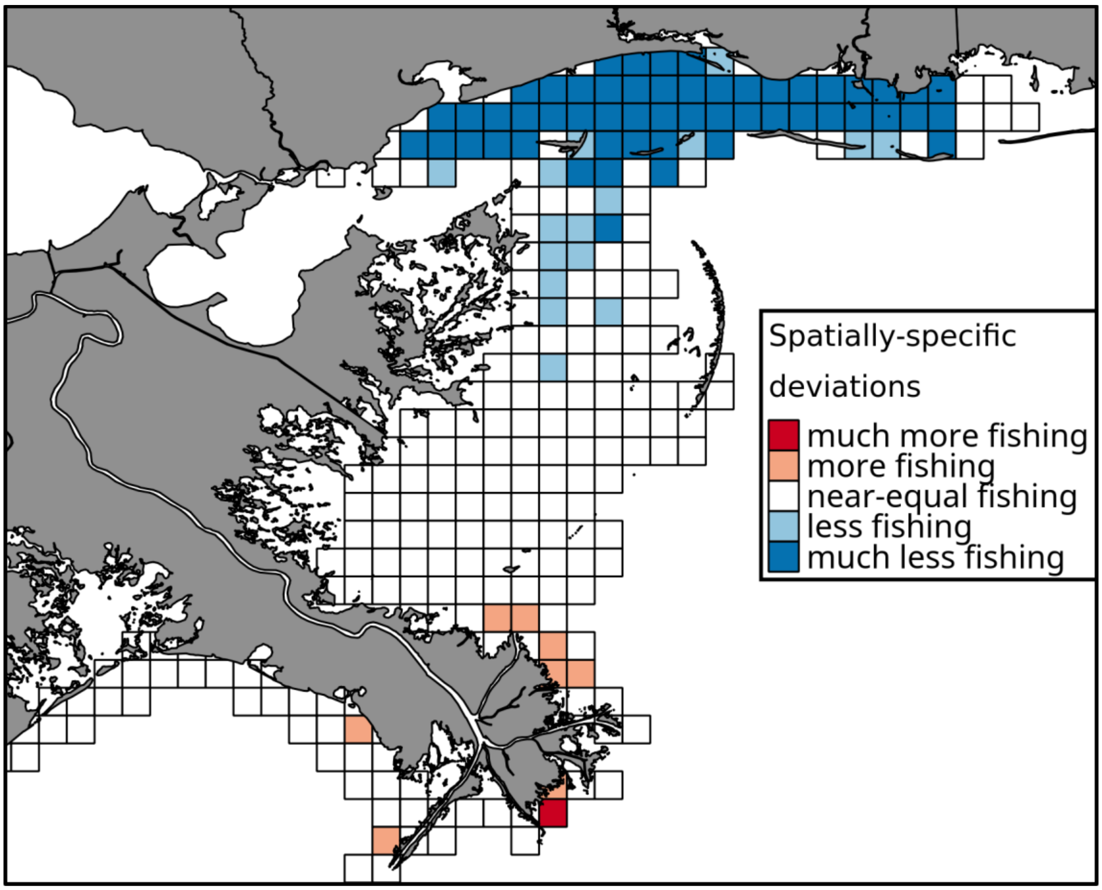

Figure 10. Closure of Mississippi waters.

Spatially-specific deviations of alternative spatial restriction scenarios in comparison to the base model. Complete closure of Mississippi Sound.

This drastic scenario resulted in much larger differences than the previous two scenarios in comparison to the base model, with a mean distance to the reduction plant of the last net set of the day of 171.7 km, an increase of 48.4 km. The mean maximum distance from the reduction plant was 185.6 km, an increase of 48.0 km (Table 7).

The mean and 95% CI of total annual harvest (mt) were calculated for the 100 simulations of each sensitivity analysis (Table 5). The mean number of net sets per vessel day for the entire five years of observed data was $\lambda = 5.28$ for vessels with Moss Point as their home plant. This value of λ, and four other values representing increases and decreases of 10% and 20%, formed the parameter space for the sensitivity analysis of the mean number of net sets per vessel day. The λ parameter directly effects the number of net sets per vessel day, but changes in its value do not change the spatial distribution of effort. Instead, λ influences the number of net sets in each grid square. There were significant differences in the mean total annual harvest as the mean number of net sets per vessel day, as λ, increased from 4.22 to 6.33 sets per vessel day with total annual harvest increasing from 71,900 mt to 106,000 mt as the λ increased, representing an approximately double percentage change in harvest from changes in the parameter. (Tables 5 and 10). The five sensitivity analyses of λ showed a general, but not significant, trend of increased depth as λ increased. A trend of increased mean distance from shore (km) of harvests also existed in the sensitivity analyses as λ was increased (Table 6). No apparent pattern existed in the proportion of catch in Mississippi waters during the sensitivity analysis of λ (Table 6).

In the scenarios to evaluate the impact of the gamma parameters, α and β, which determine the distances traveled by vessels in the model, I also used the OFAT approach. There was no discernible changes in mean depth at harvest (m), mean distance from shore (km), or mean distance to reduction plant for the last net set of the day (km) during the sensitivity analysis of α for any of the five values tested (Tables 6, 7, and 10). There were slight increases in the proportion of harvest in Mississippi waters (Tables 6 and 10) and the mean maximum distance from plant for each vessel day (Tables 7 and 10) as α increased in the sensitivity analyses, but these increases were not significant. The β parameter of the gamma distribution was also analyzed for its effect on model output. A general trend of increased mean distance from shore (km) was observed as β increased from 0.0244 to 0.0366, along with a non-significant increase of proportion of harvests in Mississippi waters (Tables 6 and 12) As beta increased, the distance of the last net set to the reduction plant and the maximum distance from the reduction plant per vessel day (km) decreased (Tables 7 and 12). There were no significant differences or trends in the mean depth at harvest (m) for the sensitivity analysis of β (Tables 6 and 12). Overall, model output was more sensitive to changes in the β parameter as compared to proportional changes in the α parameter of the gamma PDF.

The IBM was also run in an alternative spatial network, which had a graph structure whose gridded structure was rotated 45° in comparison to the base spatial network, to determine the effects of the spatial network's structure on model output. The spatial distribution of harvests was not greatly changed with the alternative graph structure in comparison to the base model (Figure 11). When the IBM was run embedded in this alternative spatial network, the model had a larger, but not significant, mean annual harvest compared to the base spatial network; 89,500 mt with 95% CI [89,000 mt, 90,000 mt] compared to the base spatial network model mean of 88,400 mt with a 95%

CI of [87,500 mt, 89,400 mt] (Table 5). The mean depth at harvest, distance from shore, and proportion of harvests in Mississippi waters did not significantly vary between the model results for the base model and those of the alternative graph structure (Table 6).

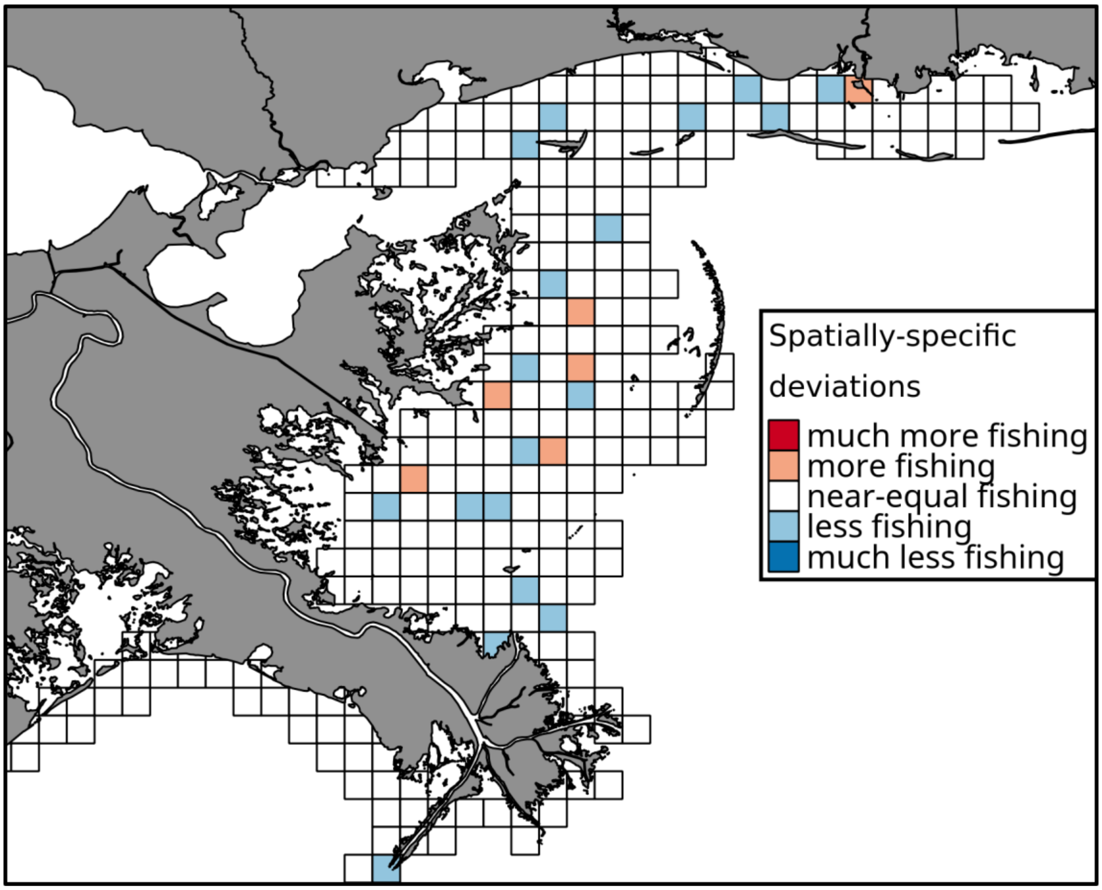

Figure 11. Alternative graph structure.

. Spatially-specific deviations of alternative graph structure in comparison to the base spatial network. The underlying gridded structure of the alternative graph was rotated 45° in comparison to the base spatial network.

The mean distance to the last net set of the vessel day to the reduction plant was also very similar for the two structures with the alternative spatial network at 122.6 km and the base spatial network at 123.3 km for the 100 replicated seasons. The mean maximum distance from the reduction plant per vessel day for the alternative spatial network showed no significant difference with a mean of 137.0 km versus 137.6 km for the base network (Table 7). The mean furthest between-harvest distance per vessel day (km) and total distance traveled per vessel day (km) also showed no significant differences between the base spatial network and the alternative spatial network (Table 8).

CHAPTER IV DISCUSSION AND CONCLUDING REMARKS

This is the first known spatially-explicit IBM of Gulf Menhaden vessels which examines the effects of spatial closures on their movement dynamics and spatial distribution of effort. The examination of patterns in the fishery, inspired by Smith et al. (1991), extends the understanding of basic physical and economic aspects of the operations of the fishery. Understanding the impacts of spatial closures on a major commercial fishery, their effect on the distribution of effort, and their economic costs are all significant for future assessments of the fishery and potential changes in state and local spatial-restriction regulations.

The approach for studying the effects of spatial restrictions on the Gulf Menhaden fishery, specifically the vessels with Moss Point, Mississippi as a home port, was to create a IBM with a spatial network as its underlying structure (see Bastardie et al., 2010). Vessels in this IBM move and fish based on random draws from PDFs, whose parameters were derived using the method of moments (Pearson, 1894) using data derived from the fishery-dependent CDFRs. I also adopted the construct of fishing grounds, represented by gridded spatial bins of empirical harvest locations (Bastardie et al., 2010). The simulation of the Gulf Menhaden fishery reproduced several important patterns seen in the CDFRs data; most of the Moss Point vessels' harvests occur in Chandeleur Sound, Breton Sound, and the Mississippi Sound. Fishing for these vessels has several patterns as it develops seasonally, with harvests per net set reaching their maximum in July, and then decreasing throughout the rest of the season. A general pattern of reaching maximum efficiency around the middle of the season is mirrored in other measures, including the number of net-sets per vessel and the total number of vessel-days per month. Additionally, the distance traveled between harvests also decreases as the fishing season progresses, reaching its minimum in August. This increased exploitation as the Gulf Menhaden season develops leads to a reversal of the above trends during the latter part of the season, when the harvest amounts per net set, the number of net sets per vessel-day, and the number of vessel-days decreases while the distances between successive catches increases.

Understanding the movement dynamics of the fishery is necessary if managers are to make informed decisions about amending or instituting spatial fishing restrictions (Little et al., 2004). Previous spatial analyses on the Gulf Menhaden fishery have focused on the relationships between hypoxic zones in Louisiana waters and the catchability of Gulf Menhaden (Langseth et al., 2014; Smith, 2001) or the overlap between Gulf fisheries and the spatial extent of the Deepwater Horizon oil spill (McCrea-Strub et al., 2011). The patterns of harvest over the course of the fishing season in the IBM reproduced the observed decrease in the spatial extent of effort as the season reaches the second half in August. Clupeids, such as Gulf Menhaden, may become more vulnerable to purse-seine fisheries as their abundance and spatial extent decreases, complicating interpretations of catchability (Arreguín-Sánchez, 1996). Spatial and temporal variation in catchability may lead to inadequate estimates of fishing mortality and spawning stock biomass (Langseth et al., 2016), both of which are used to determine if the stock is overfished or if overfishing is occurring (SEDAR, 2013). Additionally, marine reserves can lead to “fishing the line,” as part of an optimal harvesting strategy for fishers, where effort is displaced towards the boundary of spatial restrictions, influencing CPUE (Kellner et al., 2007). Analogous concerns may apply to spatial restrictions on specific fisheries, such as the Gulf Menhaden fishery, which may lead to biased estimates of catchability or CPUE.

Like the IBM of Little et al. (2004), the bioeconomic IBM of Bastardie et al. (2010) experimented with different strategies, in their study to test hypotheses on possible fuel-use reduction. While I did not explicitly model fuel-use, I did examine other measures of efficiency, such as the distance from reduction plant of the last net set of the day, and the related distance-from-shore metric. The increased mean distance from shore with additional spatial restrictions around the Mississippi mainland was an expected result, though it was associated with a decrease in depth. This seemingly contrary result may be caused by the different geography of the waters of the Mississippi Sound as opposed those of south Louisiana. The general trend suggests that spatial restrictions will increase the distances and travel times for vessels fishing from Moss Point, Mississippi when examining the the mean distance of the last net set of the day from the reduction plant and the mean maximum distance from plant per vessel day (Table 7).

While no model can perfectly represent all aspects of a system (Box, 1976), the IBM in this project efficiently and effectively simulates several important features of the Gulf Menhaden fishery, such as the changing distribution of effort over the course of the fishing season. However, there are limitations and unanticipated results in this model and study. Some ad hoc simplifications were made during model design, which may have influenced model output. For example, when filtering and cleaning the empirical data prior to model parametrization, it was assumed that vessel-days with four or less hours on the fishing grounds were “bad fishing days” and not representative of the distribution of Gulf Menhaden. It is unknown if these short vessel days are indicative of days of bad weather, equipment failures, bad information, or early returns to port to offload harvest. I also assumed that vessels in this IBM have perfect knowledge of the historical distribution of catch, which is simultaneously used in the model as the distribution of fish schools. The increased distance from shore of harvests in the model compared to the CDFR data may be caused by the modeled vessels lacking any explicit strategy. Captains and crew in the Gulf Menhaden fishery may decide, given the choice, to fish closer to shore for ease of harvest, and may prefer to fish closer to the reduction plant if they soon plan to offload harvests. The vessels in my IBM were “unranked,” which may not capture the dynamics of competition (Helu et al., 1999), as they draw the number of net sets per day and the harvest amount per net set from the same monthly, plant-specific PDFs. Daily voyages by simulated vessels are essentially a random walk with unequal step lengths; only the starting point, or first net set of the day, is determined by the weighted random sampling of binned historical data. It was unexpected that the closure of all Mississippi waters to the fishery would also cause a reduction in fishing in the northern Chandeleur Sound. This may be caused by the occasional sampling of long distances from the gamma distribution, which would normally coincide with vessels changing fishing grounds between the Mississippi Sound and Chandeleur and Breton Sounds. As simulated vessels can no longer travel north of Chandeleur Sound, they now travel south near the mouth of the Mississippi River. This model also does not simulate the biomass of Gulf Menhaden, or make projections or predictions related to the population dynamics of Gulf Menhaden.

Future research would benefit from fishery-independent estimations of the spatial distribution of Gulf Menhaden schools in the northern GOM. Remote sensing using spotter planes, drones, or satellites could be used to determine schools' locations, extents, approximate population size, or simply their probable aggregation locations (Santos, 2000). The above remote-sensing data of school locations could be ground-truthed with data from commercial fishing vessels, or with fishery-independent vessels equipped with sonar (Gerlotto et al., 1999; Misund et al., 1996). The addition of explicit and varied strategies to modeled vessels, acquired by further examining the fishery dependent data and interviewing those who work in the industry, may improve some metrics of model output such as distance from shore and reduction plant of harvests. Integrating the IBM with a model of population biomass of Gulf Menhaden, or an estimation of the spatial extent of biomass based on biotic and abiotic factors–such as chlorophyll a, dissolved oxygen, and salinity–would free the determination the location of initial net sets from being solely dependent on fisheries-dependent data.

This project confirms the feasibility of creating a spatially-explicit IBM to examine the effects of spatial restrictions on the movement dynamics of the Gulf Menhaden fishery. The general structure of this project, (1) determining movement and harvest PDFs from datasets and (2) using those PDFs to create a model embedded in a spatial network over the range of interest, could be applied to many other phenomena. The related software for the creation of spatial networks is also beneficial for the creation of models using such networks, whether in fisheries or other fields. The concentration of the spatial distribution of effort as the fishery reaches its peak confirms concerns about the assumptions, calculation, and use of catchability in purse-seine fisheries' stock assessments (Arreguín-Sánchez, 1996).

APPENDIX A – Overview, Design Concepts, and Details

A standardized description of IBMs facilitates the communication and reproducibility of these models, and Grimm et al. (2006) created the Overview, Design concepts, and Details (ODD) protocol for this purpose. The ODD protocol also provides a unifying framework for the creation IBMs, independent of the implementation language (Grimm et al., 2006, 2010). In the following description of the ODD, the sections and subsection titles of the ODD for the Gulf Menhaden Fishery IBM are capitalized. The Overview section of an ODD contains the Purpose of the model, it's State Variable and Scales, and the Processes and Scheduling of the source code. Design Concepts are a list of features common in IBMs, such as Stochasticity and Observation. Describing what agents "know," what groups agents belong to, what is random in the model, and which data from the model are recorded allows the reader to understand the creation and functionality of the model. The Details section provides all of the necessary information to program and run a model, including the Initialization, Input Data, and Submodels. Here the Initialization section includes the spatial network's creation, the state variables' values, and the spatial restriction regimes. Explicit exposition of the model setup and parameter values allows the recreation of models and the reproduction of results (Grimm et al., 2006). Time-varying environmental variables make up the Input Data section. The Submodels Section of this ODD includes the inner workings of the model, providing more detail of the algorithms and mathematics mentioned previously in the Overview. This specification of model design elements facilitates the communication, reuse, and modification of IBMs. Creating any model requires an unambiguous formulation of assumptions, which is beneficial for the scientific process (Hilborn and Walters, 1987), and the ODD protocol encourages the explicit statement of assumptions.

Overview

Purpose: The purpose of this model is to examine the effect of spatial fishing restrictions or closures on the Gulf Menhaden vessel's movement dynamics. This spatially-explicit model aims to simulate vessel movements and fishing dynamics and determine the effects of alternative spatial restriction scenarios on the fishery. Changes in the patterns observed in the fishery, such as depth at harvest and mean distance to the reduction of the last harvest of each vessel day, will be examined for each of the alternative spatial restriction scenarios.

Entities, State Variables, and Scales: This model simulates vessels in the Gulf Menhaden purse-seine fishery with a focus on vessels with their home plant in Moss Point, Mississippi. The modeled fishing vessels move through a spatial network which represents the waters of the northern Gulf of Mexico. Each vessel has associated net-set, movement, and harvest parameters, derived from fishery-dependent Captain's Daily Fishing Reports (CDFRs). Variation in parameter values for modeled vessels corresponds to monthly, plant-specific, differences in vessels for efficiency and strategy. The net-set parameter, λ of the Poisson probability mass function (PMF), represents the mean number of net sets per vessel day. The movement parameters, α and β, of the gamma probability distribution function (PDF), determine how far vessels move between harvest events (km), with long distances representing movement to new fishing grounds. The harvest parameters, μ and σ, of the log-normal PDF, determine the amount of harvest (mt) of each net set. Each simulated vessel is processed on a daily time step.

The spatial extent of the model ranges from -95° to -87.5° W and from 28° N to the coast of the Gulf of Mexico. To create the spatial network, a set of locations, or vertices, with a grid size of 0.01° longitude by 0.01° latitude were created over the spatial extent of the model. Uniform random deviations ranging from -0.001° to 0.001° were added to the latitude and longitude vertex attributes. Distances between each node and its eight neighbors were calculated on the WGS84 ellipsoid (Hijmans et al., 2016); these distances become the weights of the edges, or the connections, between the neighboring vertices in the spatial network. A depth attribute was added to each vertex using nearest neighbor selection from a Digital Elevation Model (DEM) (Love et al., 2012) and a Coastal Relief Model (CRM) (NGDC, 2001). To provide starting locations for each vessel-day, monthly historical harvest data was binned using a grid of 0.05° longitude by 0.05° latitude.

Process Overview and Scheduling: Pseudocode is a way of describing a program using human-readable language along with a few basic programming constructs, such as loops and if-then statements. Below is an example, in psuedocode, of a description of the processes in a simulated season of fishing in the IBM.

```
FOR each day of the fishing season
  FOR each vessel
    net-sets = sample Poisson PDF for number of harvests
    intial-location = sample a grid square from binned historical data
                      for general location
    start-vertices = list of vertices in intial-location grid square
    destination = random vertex in start-vertices where depth < 10 m
                  and which isn't in an area of spatial fishing
                  restrictions
    WHILE net-sets > 0
```

```
        net-sets = net-sets - 1
        travel-distance = sample vessel's gamma PDF (km)
        potential-locations = all vertices which are about
                              travel-distance (km) away
        destination = randomly sample a vertex from potential-locations
                      where depth < 10 m and which are not in an area
                      of spatial fishing restrictions
    harvest-amounts = sample log-normal PDF for each harvest event (mt)
WRITE vessel, date, harvest-amounts and destinations to log-file
```

Each vessels' fishing day is simulated for each day in the fishing season. The monthly number of vessel days is determined by multiplying the mean number of active vessels by the mean number of fishing days per vessel for that specific month from the fishery-dependent data. Each of the eight Moss Point, Mississippi vessels have their daily harvests written to a log for later analysis. The number of harvest events per vessel-day, *n*, is sampled from a Poisson distribution (Figure 1) fit to days in the fishery-dependent data where fishing occurred for four hours or more.

The general fishing area for each vessel is determined by a random weighted sample of the binned historical data (Figure 6). The first harvest of the day occurs at a random node within the sampled grid square whose depth is 10 m or less. Each selected grid square is reduced by a value of 20 each time it is selected for the initial harvest location for a vessel day. After the first harvest, a random distance *d* (km) is sampled from a gamma function's probability distribution function (PDF) (Figure 2) to determine the distance to the next harvest event for that vessel. The parameters α and β of the gamma distribution vary for each month, and for each plant or collective of vessels.

These gamma PDF parameters are derived from fishery-dependent data using the method of moments. A random node, whose depth is 10 m or less is and which is within ε of distance *d* (km), where

$$\varepsilon = 1 + (d/10),$$

is chosen for the next harvest location; this process repeats for all *n* sets of the vessel-day. The harvest amount for each set is sampled from a log-normal distribution fit to empirical harvest amounts (Figure 3) using the method of moments.

Design Concepts

Basic Principles: This individual-based model simulates the Gulf Menhaden fishery using fishery-dependent data, random samples from probability distribution functions derived from the fishery-dependent data, and a spatial network in northern Gulf of Mexico waters. In the absence of available fishery-independent data on the distribution of Gulf Menhaden schools, the historical harvest locations in the fishery-dependent data are used as a proxy for the density and distribution of Gulf Menhaden schools. Each location in the fishery-dependent data is associated with the closest vertex in the spatial network. These vertex locations are used to calculate the distances (km) real vessels travel between schools, using the spatial network; this allows paths which travel around islands. Gamma distribution PDFs fit to the distances traveled by real vessels are used to create a parameter space which can be sampled from for use in the model. The number of schools caught per vessel day simulated with a Poisson PMF, and as with the distances traveled, this provides the monthly parameter values used in the model. By randomly sampling the PDFs defined by real world data, simulated vessels travel to and between schools in a manner which mimics the locations chosen and distances traveled by real-world vessels. These simulated vessels are then placed in situations future vessels may face to examine changes in patterns in the fishery, such as mean depth-at-harvest (m) and proportion of harvest events in Mississippi waters, with regard to 1.6 km (one mile) and 3.2 km (two mile) nearshore fishing restrictions and also a complete closure of the Mississippi Sound to fishing. Unlike many models in fisheries, this is not a population or individual growth model of fish, it is a simulation of the movement patterns of fishing vessels.

Sensing: Vessels are aware of the distribution of historical harvest, and this information is used to choose the initial location for the day. In this version of the model, vessels are not aware of the location or harvest of other vessels on a given day.

Interaction: Direct interaction between vessels does not occur, however indirect interaction occurs through local depletion of fish, represented by altering the binned historical data, changing the distribution of initial fishing grounds.

Stochasticity: The directions vessels travel are random. The number of net-sets per vessel-day and the distances traveled between harvest events are randomly selected from the Poisson and gamma distributions, respectively. The harvest amount (mt) per net-set is randomly sampled from the log-normal distribution.

Collectives: Vessels belong to one of four different reduction plants. This project focuses on the vessels with Moss Point, Mississippi, as their home plant.

Observation: The IBM generates a simulated fishery-dependent data for each simulated fishing season. The output data contains information for each harvest: vessel id number, date, location (vertex ids and their associated geographic coordinates), depth at harvest (m), harvest amount (mt), movement parameters (α and β of the gamma PDF), harvest-frequency parameter (λ of the Poisson PMF), harvest-amount parameters (μ and σ of the log-normal PDF), and spatial-restriction scenario.

Details

Initialization: The model space is a large spatial network grid over the northern Gulf of Mexico. The random deviates of the nodes of the spatial network are reproducible via a seed number. There are 130,148 vertices and 512,192 edges in the model. The weights or distances associated with the edges range from 0.77 km to 1.76 km. The depths at each location, and the distances between neighboring locations were calculated and added as attributes of the spatial network, which was saved in an Rdata file and reloaded for each spatial restriction regime and/or fishing season. Monthly movement, harvest, and harvest amount parameters are set at the model start and change each month. These parameters are shared by all vessels from the same reduction plant. Current spatial restrictions in Mississippi include a ban on fishing 1.6 km (one mile) from the mainland of Hancock and Harrison Counties and from the Mississippi Barrier Islands. The mainland of Jackson County currently has no such restrictions. The alternative spatial restriction regimes are (1) a 1.6 km (one mile) zone off the Jackson County mainland, in addition to currently existing restrictions, (2) 3.2 km (two miles) of restrictions around all coastlines of Mississippi, and (3) a complete closure of all Mississippi waters to Gulf Menhaden fishing. Separate lists of vertex ids where fishing is allowed were loaded into the programming environment for each scenario.

Input Data: Time-varying environmental processes include monthly gridded historical data which determines the initial general harvest area for each vessel day. Parameter values for the Poisson, gamma, and log-normal distributions also change each month and are derived from fisheries-dependent data.

Submodels: The frequency of distances (*d*) traveled by real world vessels are fit to the gamma distribution, using the α and β parameterization:

$$Pr(d_i|\alpha,\beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} d_i^{\alpha-1} e^{-\beta d}$$

$$\Gamma(a) = \int_0^{\infty} t^{\alpha-1}\, e^{-t} dt$$

The parameters of the gamma distribution are calculated using the method of moments (Pearson, 1894). The moments of the gamma distribution are:

$$\mu = \frac{\alpha}{\beta}$$

and

$$\sigma^2 = \frac{\alpha}{\beta^2}$$

Assuming that the empirical distribution of between-harvest distances can be modeled by a gamma distribution, and thus that the mean, $\overline{d}$, and variance, $Var(d)$, of the observed data are equal to the mean and variance of the gamma distribution, α and β are:

$$\overline{d} = \frac{\alpha}{\beta}$$

$$Var(d) = \frac{\alpha}{\beta^2}$$

Solving for β:

$$Var(d) = \frac{\overline{d}}{\beta}$$

$$\beta = \frac{\overline{d}}{Var(d)}$$

Now solving for α:

$$\alpha = \overline{d}\beta$$

$$\alpha = \frac{\overline{d}^2}{Var(d)}$$

The number of net-sets per vessel-day is calculated using the Poisson PMF:

$$Pr(n|\lambda) = \frac{\lambda^n}{n!}e^{-\lambda}$$

where λ represents the mean number of net-sets per vessel-day. The harvest amounts (mt) for each net sets were described using a log-normal PDF, based on historical harvest data for each plant-month. The log-normal PDF is:

$$Pr(x|\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}}e^{-\frac{(ln(x)-\mu)^2}{2\sigma^2}}$$

where σ is the standard deviation of the log-transformed data, and μ is the mean of the log-transformed data.

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