COMMERCIAL SHRIMP PRODUCTION IN THE NORTHERN GULF OF MEXICO:

EFFECTS OF SHRIMP HABITAT ON COMMERCIAL SHRIMP FISHERY CATCH

A Thesis

by

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ABSTRACT

The Gulf of Mexico penaeid shrimp fishery is perennially one of the most productive fisheries in the southeast United States in terms of landings and value. Since 2007, a mandatory fishery observer program has been collecting data to characterize the catch and bycatch of the fishery. Factors affecting production of the fishery have been the subject of research for several decades. Linkages between the production of the shrimp fishery and environmental factors are of increased interest as stock assessment methods attempt to utilize environmental data as they become available. It is generally thought that juvenile growth and survival are the most important factors determining yield, as natural mortality of shrimp is very high. To substantiate this hypothesis, a generalized linear model is used to relate juvenile shrimp habitat factors and shrimp fishery production. The novelty of the model stems from its use of fishery dependent observer data to provide insight into coastal nutrient loading and sub-adult shrimp habitat in regard to commercial catch rates (CPUE). Distance weighted variables derived from juvenile shrimp habitat representing nutrient loads and proportional shrimp habitat were calculated and used to represent the influence of these habitat variables on commercial shrimp catch rates. The effects of environmental variables on shrimp CPUE generally agree with effects concluded in previous studies. Evidence is presented in support of the theory that high nutrient loads delivered to coastal areas can increase secondary production. Shrimp CPUE predictions are evaluated in simulated scenarios representing environmental regime shifts.

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Landcover and wetlands data were analyzed by Tom Minello, Phil Caldwell, and Lawrence Rozas. Nutrient load data used for the analysis were modeled by the United States Geological Survey Spatially Referenced Regression on Watershed attributes.

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NOMENCLATURE

AIC	Akaike’s information criterion
CAGES	Comparative Assessment of Gulf Estuarine Systems
C-CAP	Coastal Change Analysis Program
CPUE	Catch per Unit Effort
CTD	Conductivity, Temperature, Depth device
EDA	Estuarine Drainage Area
GAM	Generalized Additive Model
GIS	Geographic Information System
GMFMC	Gulf of Mexico Fishery Management Council
Gulf	Gulf of Mexico
NAWQA	National Water-Quality Assessment
NOAA	National Oceanographic and Atmospheric Administration
NWI	National Wetlands Inventory
QGIS	Quantum GIS
SEAMAP	Southeast Monitoring and Assessment Program
SPARROW	Spatially Referenced Regression on Watershed Attributes
SS3	Stock Synthesis
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

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1. INTRODUCTION

The Gulf of Mexico (Gulf) provides many natural resources that are exploited by commercial, industrial, and recreational users. Commercial fisheries exist for invertebrates and fish. Of interest to the research presented here is the commercial shrimp fishery found in nearly all coastal regions from Brownsville, Texas, to Key West, Florida. Commercial shrimping in the Gulf provides an economic boon for many coastal areas and also provides a sustainable domestic seafood product across the nation. At $413 million (NMFS, 2018), shrimp landings were reported to produce the highest revenue of any fishery in the Gulf. With landings of 161 million pounds from Louisiana and Texas alone, the fishery is second only to menhaden in terms of biomass (NMFS, 2018). There are currently approximately 1,000 active federal shrimp permits (GMFMC, 2017), and several thousand state issued commercial shrimp permits active across the Gulf. Shrimp provide for a portion of the nearly 51,000 individual jobs ranging from harvesters to processors to retailers in Louisiana and Texas (NMFS, 2018). The majority of shrimp species harvested by fishers in the Gulf are white shrimp (*Litopenaeus setiferus*) followed by brown shrimp (*Farfantapenaeus aztecus*) and pink shrimp (*Farfantepenaeus duorarum*).

The economically and societally important shrimp fishery is managed by the Gulf of Mexico Fishery Management Council (GMFMC) under the Shrimp Fishery Management Plan. Since coming into effect in 1981, 17 amendments to the management plan regarding the shrimp population and other species that are caught as bycatch have been implemented to ensure the fishery remains sustainable. Current population models use historical effort and catch data collected by state and federal agencies to parameterize stock assessment models (e.g., Hart, 2016).

The characteristics of the fishery across the Gulf differ by region, with densities of pink shrimp highest along the west coast of Florida and near the Dry Tortugas, and white and brown shrimp densities highest in waters extending from Mobile Bay to the U.S. – Mexico border (Scott-Denton et al., 2012). While pink shrimp are harvested throughout the Gulf, studies of penaeid shrimp in the western Gulf have primarily investigated white and brown shrimp, and they account for the majority of shrimp landings off the coasts of Louisiana and Texas. The geographic separation of species is reflected in Gulf shrimp stock assessments. Even though management practices are similar throughout the Gulf, the spatial extent of the pink shrimp assessment extends east only to the Mississippi River Delta. Thus, the study focuses primarily on brown and white shrimp.

To safeguard the continued success of the shrimp industry in the Gulf, it is important to consider what factors could have an effect on the commercial harvest of shrimp in the Gulf. White and brown shrimp spawn and are harvested in as short as one annual time step (Cook & Lindner, 1970; Lindner & Cooke, 1970) and are managed as an annual species despite evidence that brown shrimp may live for more than two years (Baxter, 1971). Like many short lived marine species, shrimp exhibit high fecundity, producing around 500,000 eggs per spawn (Lindner & Anderson, 1954), and high mortality during early life stages. The relationship between spawning adults and subsequent recruitment of new shrimp to the fishery is poorly defined, and understanding environmental factors that regulate success of juvenile shrimp is important to consider for fishery management (Belcher & Jennings, 2004; Baker et al., 2008).

Production in marine ecosystems is a product of both biotic and abiotic influences including habitat conditions and food availability. However, the mechanisms driving penaeid shrimp survival and recruitment to the fishery in the Gulf are unclear. It has been suggested that faster juvenile shrimp growth reduces overall mortality, and growth may be a product of food availability (Minello et al., 1989; Leo et al., 2018).

While studies have attempted to determine the most influential environmental dynamics, there are several approaches available to explore when analyzing environmental factors that influence shrimp survival and production. Age structured models and individual-based survival models have been built to assess how shrimp habitat affects survival; linear and generalized linear models, and non-linear models, have been used to predict abundance of shrimp on environmental covariates. In the Gulf, the abundance of juvenile brown shrimp in the bay during the spring and early summer has provided the most reliable estimate of brown shrimp production off the Texas and Louisiana coasts. It is clear there is a need for more research in creating a novel model capable of incorporating juvenile habitat characteristics and their effects on commercial shrimp catch.

As management moves toward more holistic goals, such as ecosystem-based fisheries management, it is becoming critically important to incorporate environmental conditions in scientific models and continue research on what drives estuarine ecosystem production (Turner, 2001). Although a study of all environmental factors is outside the scope of this research, the study will focus on two critical areas: nutrient loads effluent to the bays and estuaries of the western Gulf and the proportional areal coverage of suitable juvenile shrimp habitat of these same estuary systems.

Estuaries and coastal zones provide not only habitat for a plethora of species, but also more food production per unit area as an ecosystem service than all other biomes combined (Costanza, 1997). These coastal areas are dynamic and under immense pressure from factors that influence delivered nutrient flux and areal coverage of shrimp habitat: nutrient enrichment, hypoxia, coastal development, oil and gas exploration, land subsidence, sea level rise, and hurricanes (Turner, 1990; Austin, 2006).

While a myriad of definitions of eutrophication exist, Nixon (1995) made the case for classifying eutrophication as the organic carbon supply that he tied to nutrient enrichment. Under Nixon's definition, eutrophication is an increase in the rate of supply of organic matter to an ecosystem. Nutrient delivery from inland areas to coastal margins has increased dramatically in the last century as the result of human activity, and, if there is an increase in the limiting nutrient, contributes to eutrophication. It is estimated annual nitrogen flux in the Mississippi river has increased 400% since the pre-industrial era (Howarth et al., 1996). Nutrient availability can limit production in marine systems, and primary production as well as secondary production tends to increase as more nutrient becomes available. However, the relationship between nutrient flux and marine species production is not straightforward or linear in nature.

There appears to be an ideal amount of eutrophication that increases fish biomass, but once the environment is delivered with excess nutrients, habitat regimes can shift. In the Gulf, a large annual hypoxic or ‘Dead Zone’ is enhanced by nutrient enrichment on a seasonal basis (Rabalais et al., 2002). Studying the balance between nutrient enrichment, hypoxic water formation, and production in fisheries of several semi-enclosed seas in Europe, Breitburg (2002) found that fishery production peaked in environments with a large seasonal, nutrient driven hypoxic area, similar to what has been observed in the Gulf. Rabalais (2002) noted an increase in production across trophic levels with increased nutrient flux in the northern Gulf, but remarked excess nutrient enrichment can cause severe and long lasting habitat degradation.

Shrimp have a unique lifecycle that starts from eggs in the open ocean. After several larval stages, the post-larval shrimp migrate into bays and estuaries. During this juvenile stage, salt marshes provide shrimp resources to grow and protection from predators (Zimmerman et al., 2000). While shrimp remain in the marsh, several factors influence growth and survival. Production of the shrimp fishery depends on juvenile shrimp recruiting to offshore waters, and may ultimately be driven by environmental conditions of juvenile shrimp habitat. Marsh edge appears to be used as predation grounds by brown and white shrimp, with increased shrimp production as more marsh edge becomes available to the shrimp (Zimmerman et al., 1992). For this study, scale is increased to account for the total areal coverage of habitat available to shrimp while they reside in estuarine areas.

To better understand the effects of nutrient enrichment and areal coverage of shrimp habitat on commercial shrimp production, I will analyze two hypotheses with a geostatistical nonlinear model.

Hypothesis 1: Nutrient flux effluent to estuaries and bays adjacent to the Gulf positively affects the production of commercial shrimp catch per unit effort (CPUE).

Hypothesis 2: Proportional areal coverage of suitable juvenile shrimp habitat will have a positive effect on commercial shrimp harvest.

This is a novel study, as it provides insight into coastal nutrient loading and sub-adult shrimp habitat that have not been thoroughly explored in regard to commercial catch rates and provides a tool to estimate changes in shrimp productivity under certain regional changes to shrimp habitat.

The objective of this study is determine if shrimp habitat parameters can be useful in predicting commercial shrimp CPUE across the northwestern Gulf. The current research expands on most common habitat suitability models by including variables that are proportional to the sum of distance weighted juvenile habitat characteristics and determining abundance as represented by CPUE. CPUE can be used as one indicator to assess the status of a stock. However, standardizing raw CPUE data can be problematic because several factors can affect the catchability of the target species including environmental factors and fleet efficiency (Maunder et al., 2006). The novelty of the study is highlighted by the use of high precision fishery dependent observer data that covers a broad geographic range and the exploration of the effects of environmental factors (e.g., coastal nutrient loading and quantity of sub-adult shrimp habitat) on commercial shrimp CPUE. While there may be some variation in shrimp catchability over the study period, the average catchability used to parameterize white and brown shrimp stock assessments models during the study period have remained relatively stable (see Hart, 2018a & 2018b). To illustrate the application of the model in a management framework, comparative analysis of simulated environmental regime changes are presented.

2. PREVIOUS RESEARCH

Predicting abundance of commercially important species occurs throughout the world, and the Gulf of Mexico shrimp fishery is no exception. Historically, the shrimp fishery has been managed using a stock-recruitment relationship. Due to the life history of shrimp and large annual variability of catch, parameterizing a stock-recruitment model can be difficult. The stock-recruitment relationship can be further obscured by environmental fluctuations. Current management utilizes Stock Synthesis (SS3) which has the ability to incorporate environmental parameters when estimating abundance (Methot & Wetzel, 2013). SS3 models derived from age-structured population analysis are used to determine the specific biological reference points, namely maximum amount of fishing mortality and spawning stock biomass at the maximum sustainable yield (Hart, 2016). Through these and other management measures, shrimp fishery management aims to keep the stock productive both economically and ecologically.

While the SS3 model provides a metric for maximum sustainable yield, the unpredictable nature of the shrimp population has caused researchers to rely on abundance indices that provide annual production estimates only weeks in advance of the peak shrimp season for an ‘in-season’ estimate of catch. The Galveston Bay Bait Index, developed in the 1960’s (Berry & Baxter, 1969), is an index of abundance of juvenile brown shrimp captured in the inshore bait shrimp fishery and used to predict the annual catch of shrimp off the Texas coast. Baxter and Sullivan (1986) later investigated several indices of abundance of shrimp at various life stages as an earlier predictor and concluded the bait shrimp index was the more accurate predictor available. Today, the Galveston Bay Bait Index continues to be used by NOAA Fisheries to predict annual catch along the Texas coast (NOAA Fisheries, 2018).

2.1. Shrimp Habitat

Physical and chemical characteristics of the environment play a large role in determining the distribution and success of many terrestrial and aquatic species. Salinity, temperature, depth, and the dissolved oxygen levels have all been used to study species distributions in marine environments (Tyberghein et al., 2012). In white and brown shrimp, growth and survival have been tied to a specific environmental que: intertidal marsh coverage (Boesch & Turner, 1984; Zimmerman et al., 2002; Minello et al., 2008).

Turner (1977) was one of the first researchers to study the relationship between commercial penaeid shrimp yield and intertidal vegetation. He developed an equation that showed a relationship between inshore yields and the area of estuarine vegetation. His work followed in the wake of Giles and Zamora (1973), who found substrate, food, and vegetative cover were important when developing habitat distribution models for brown and white shrimp. Giles and Zamora (1973) also found that brown shrimp will displace white shrimp in vegetative cover when the two species are introduced together, which was reinforced by the Minello and Zimmerman (1985) finding that brown shrimp more often utilized vegetative cover and were less likely to be preyed upon than white shrimp if the vegetative habitat was present. While both species of shrimp have been found to utilize the marsh edge (Minello, 1999), brown shrimp seem to prefer structure more than white shrimp. The affinity for marsh edge seen in brown shrimp could be attributed to white shrimp growing at a faster rate than brown shrimp, as size is thought to deter predation on penaeid shrimp and increase survival (Minello et al., 1989). More recently, Haas et al. (2004) and Leo et al. (2016) surmised that marsh edge increased brown shrimp survival, and these survivors grew faster than shrimp that did not utilize marsh edge.

Previous work comparing the production of several estuarine systems in the Gulf has been undertaken by the NOAA's Galveston lab. The project, a Comparative Assessment of Gulf Estuarine Systems (CAGES) compared biomass patterns of nekton among 24 estuaries in the northern Gulf (Brown et al., 2013). CAGES summarized the catch patterns from the Southeast Monitoring and Assessment Program (SEAMAP) that has been collecting physical and biological data since the 1980's. Additional CAGES work investigated the habitat characteristics of these same estuaries using remotely sensed datasets. Areal coverage of estuarine marsh and suitable habitat for estuarine-dependent species was calculated using geographic information systems (GIS). While the analyses rendered from the CAGES work provides a valuable perspective on characteristics, a clear relationship between areal habitat coverage and production was not found.

Much value has been placed on saltmarsh regarding shrimp production. As such, reports of estuarine habitat loss is a growing concern as more of the coastal regions of the world become developed, land subsides, and sea levels rise. In the northwestern Gulf, this is evidenced by the disappearance of 24% of the salt marsh in Texas

(Armitage et al., 2015) and the historical loss of 0.5% of land per year in the Mississippi River delta (Britsch & Dunbar, 1993). The cumulative effect of habitat loss is difficult to quantify, as there is new habitat created as well as deleterious effects. For example, when a saltmarsh subsides or becomes dominated by other vegetation, the existing habitats do not simply disappear, but rather provide a different habitat type (i.e., open water or mangroves). In the context of current shrimp habitat research, high production value has been associated with intertidal vegetation. However, due to the large areal extent of open water, there is evidence that open water supports a large portion (>50%) of the shrimp production in the region (Fry, 2008). The research presented here accounts for all estuarine habitat, inclusive of open water and vegetated marsh, to incorporate the entire nursery habitat available to shrimp in a distinct estuary or bay.

2.2. Nutrient Enrichment

Along with understanding how environmental factors affect species distributions and abundance, it is important to understand how anthropogenic influences can impact marine flora and fauna. Over the past 100 years, nutrient enrichment to coastal areas has increased substantially, and opinions regarding the effect of nutrient enrichment in coastal systems are conflicting. Rabalais et al. (2014) provide research demonstrating the detrimental effects of excess nutrient loads examining hypoxia as a result of increased eutrophication. Similarly, excess nitrogen loads delivered to the northern Gulf have been shown to be the primary driver of hypoxia in the region (Rabalais et al., 2007). Currently, the Gulf of Mexico Hypoxia Task Force is working with stakeholders to achieve the goal of reducing areal coverage of the annual hypoxic zone in the northern Gulf in part through decreased nutrient enrichment.

While the ill effects of hypoxia on marine habitat quality are clear, some studies have shown that nutrient enrichment increases primary and secondary production (Nixon et al., 1986; Nixon & Buckley, 2002). De Mutsert et al. (2016) found an increase in production of shrimp species associated with nutrient enrichment that outweighed hypoxic water impacts along the Louisiana coast when simulating conditions with an ecosystem-based fisheries model.

Predicting the effects of regulatory control on delivered nutrients is beyond the scope of this research. Regardless of the unknown fate of nutrient enrichment regulations, this research identifies the current impacts of nutrient enrichment, and can serve as a benchmark for analysis of these regulatory impacts. Considering the contradictory views weighing the benefits of nutrient enrichment and possible detriment to production associated with eutrophication induced hypoxia, continued research into the effects of nutrient enrichment on commercial shrimp production is necessary.

3. METHODS

3.1. Data Sources

To address the hypotheses posed herein, the research combined information from multiple data sets so the relationship between shrimp production and predictor variables could be examined. The descriptions of the data may not be comprehensive, but rather serves as a guide to how the data were used. Data used for this study have been the subject of scrutiny among the scientific community and continue to be used in peer reviewed publications.

3.1.1. Spatial and Temporal Range

The study spans a 9.5 year period (July 2007 – December 2016), matching the availability of the fishery observer data used to calculate commercial shrimp CPUE. While a shrimp fishery exists across the entire Gulf, the study area used for analysis is partitioned to the western Gulf, from Mobile Bay to the United States – Mexico border. A spatial constraint was used due to the difference in the fishery characteristics in the western and eastern Gulf. In the eastern Gulf, pink shrimp are primarily targeted and effort peaks in the winter, while along the coast of Louisiana and Texas, effort peaks in the summer and brown and white shrimp are the primary targets.

3.1.2. Environmental Variables

Environmental variables are available from SEAMAP, which compiles survey data in the Gulf of Mexico. SEAMAP collects fisheries independent data for shrimp, ground fish, plankton, and reef fish. These survey data are collected at randomly generated locations for selected strata each year. At each sampling location, a conductivity, temperature, depth (CTD) device is deployed to collect physical properties of the water column.

From these point data, the variables of dissolved oxygen (mg/L), temperature (℃), and salinity (ppt) from each sampling station that met the criteria of being both the deepest reading at the station and within 3 meters of the bottom depth recorded at the station were extracted from the dataset and imported to Quantum GIS (QGIS) (version 3.4.3; QGIS, 2019). The distribution of the sampling stations were fairly regular and with few extreme values throughout the study area. Multilevel b-spline interpolation was used to create a continuous surface of values for these three variables. Multilevel b-splines use a hierarchy of control lattices to generate a sequence of B-splines that are combined to one equivalent B-spline (Lee et al., 1997). B-splines allow for smooth surfaces that accurately portray local minima and maxima.

Interpolated surfaces were created for each season: winter (January – March), spring (April – June), summer (July – September), fall (October – December). An Albers Equal Area Conic projection and cell size of 1000 m x 1000 m was used for all environmental variables derived from SEAMAP data. After the surfaces were prepared, the environmental data were extracted to fishing set locations that occurred during the corresponding season.

3.1.3. Shrimp Catch Data

With authorization from the Magnuson-Steven Fishery Conservation Act (MSA), fishery observers are placed on board commercial shrimp vessels to collect fishery dependent data. While aboard vessels, observers collect a range of data pertaining to catch composition, gear measurements, locations fished, and the amount of fishing effort. (For a more comprehensive description of data collection methods, see Scott-Denton et al., [2012]). Trips that fished using skimmer trawl gear were omitted from the dataset, as this gear is fixed to frames on the vessel and may not necessarily fish the area of the water column the environmental data represent.

Effort, catch composition, gear characteristics, depth, and location data collected while at sea were extracted from the observer data. Shrimp total weights were recorded as whole or headed depending on the preferences of each fishing vessel. Conversion factors for head on and head off weights developed by Kutkuhn (1962) were used to convert shrimp weights to whole weight if the total shrimp catch was recorded as head off. To account for some trips retaining both brown and white shrimp, conversion factors were averaged. Observers collect data on a per net basis, including if the tow was completed successfully under normal fishing operations. Any nets that encountered problems such as snagging marine debris, digging into the benthos, or not being deployed correctly are coded as being problematic and were discarded prior to the final analysis. To standardize catch rates on a per net basis, area swept was calculated in hectares. Vessel speed (knots) was multiplied by the hours towed to calculate the total distance traveled, then multiplied by footrope length. The total weight of brown and white shrimp retained from that net was then divided by hectares swept to calculate CPUE as kg/ha swept. Interpolated CPUE values and tow locations are shown in Figure 1.

3.1.4. Shrimp Movement

The extent of shrimp movement from bays adjacent to Gulf waters was based upon previous studies and observed distances of shrimp tows from the observer data. A review of literature provided three similar data points from tag-recapture studies. Klima (1964) found that the majority of white and brown shrimp were captured within 30 miles of the location they from which they were released after being tagged, with some individual white shrimp traveling up to 120 miles. Lyon and Bodreaux (1983) concluded that distance traveled was related to time at large, with a maximum of 155 nautical miles traveled and majority of shrimp caught within 22 nautical miles of release point. Notably, Sheridan et al. (1987) recorded one shrimp traveling 385 miles, but found most shrimp were recaptured within 30 miles of release. QGIS’s measure tool showed the maximum distance of a tow location yielding shrimp to be around 115 miles away from the nearest effluent bay. Averaging the maximum (with exception of the 385 miles data point) and common distances from literature, and maximum observed in the commercial shrimp tows resulted in a distance traveled value of 78.67 miles. For the analysis, 75 miles was used as the search radius when calculating a distance matrix relating bays and fishing locations. At distances greater than 75 miles, it is likely the influence of each individual bay will have a greatly diminished effect.

3.1.5. Nutrient Data

Data for total phosphorus and nitrogen loads in coastal bays and estuaries were provided by United States Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Project. Nutrient loads were estimated using the Spatially Referenced Regression on Watershed attribute (SPARROW) models developed by the USGS. These estimates represent average annual excess amounts of nutrients (in metric tons per year) beyond the assimilative capacity of their respective water bodies. Loads of total nitrogen and total phosphorus delivered to each bay system were highly correlated (>0.99). In the northern Gulf, nitrogen appears to be the limiting nutrient in biomass accumulation, and is tied more closely to hypoxic area formation (Rabalais et al., 2002). For this reason and concerns of multicollinearity in model specification, only delivered nitrogen was used to represent nutrient loading in analysis. A summary of bay and estuarine drainage area (EDA) characteristics is shown in Table 1.

To create a variable capable of capturing the effect of nutrient loadings on shrimp CPUE, a spatially weighted variable for nitrogen loads was calculated ($D_{nutrient}$). Using the point of effluence of each coastal waterbody and the fishing set locations, a distance matrix was calculated limited to associating each tow location with the three closest bays within a 75 mile radius. For each fishing location, the inverse distance weighted value of the nutrient enrichment variable is calculated following the general form from Shepard (1968):

$$D = \sum \frac{1/d_i}{d_{total}} V_i$$

where D is the inverse distance weighted variable, d_i is the distance in meters from the i^{th} closest effluent bay or estuary, V_i is the nutrient load for the bay or estuary, and d_{total} is the sum of the inverse distance to each of the bays within the search radius: $(\frac{1}{d_1} + \frac{1}{d_2} + \frac{1}{d_3})$.

3.1.6. Habitat Areal Coverage

Areal coverage of estuarine habitat in EDAs along the western Gulf coast was the product of an extensive analysis by Minello et al. (2017) in an effort to describe variation between coastal bays and estuaries in the Gulf. Their research employed the United States Fish and Wildlife Service’s (USFWS) National Wetlands Inventory (NWI) and NOAA’s Coastal Change Analysis Program (C-CAP) data to calculate the areal coverage of marsh in each bay system. For the current research project, their results from 2010 C-CAP data are used as these data matched most closely the temporal range of the shrimp fishery observations.

The C-CAP land cover data are categorized into classes representing different land cover types. In their study, categories of interest were Estuarine Aquatic Bed, Estuarine Emergent Wetland, Estuarine Scrub-Shrub, and Estuarine Forested Wetland. Open water was also considered as estuarine habitat, and the area of water in each EDA was multiplied by the ratio of saltwater to freshwater to calculate estuarine water area that was included in the total estuarine area.

Further, their study provided areal estuarine coverage from each EDA in the western Gulf with the exception of three EDAs used for analysis: Mermentau River, Mississippi River, and the Brazos River. For these EDAs, total estuarine area was calculated using the same C-CAP land cover data and analysis. The C-CAP data is provided at a resolution of 30 m x 30 m. The ratio of saline to freshwater was calculated using salinity zone coverage from NOAA's Coastal Assessment Framework (Nelson, 2015) and applied to total open water area in the three EDAs. Total estuarine area was divided by the total area of each respective EDA to calculate the proportion of EDA considered suitable habitat for shrimp.

The final resulting group of 19 EDAs were labeled by the estuary to which they drain: Aransas Bay, Atchafalaya/Vermilion Bays, Barataria Bay, Brazos River, Breton/Chandeleur Sound, Calcasieu Lake, Corpus Christi Bay, East Mississippi Sound, Galveston Bay, Lower Laguna Madre, Matagorda Bay, Mermentau River, Mississippi River, Mobile Bay, Sabine Lake, San Antonio Bay, Terrebonne/Timbalier Bays, Upper Laguna Madre, and West Mississippi Sound. EDAs, the study area, and the effluent bay locations used to calculate the distance weighted variables are shown in Figure 2.

An inverse distance weighted variable ($D_{estuarine}$) capable of capturing the effect of estuarine habitat on commercial shrimp CPUE was calculated using methods described in section 3.1.5 for $D_{nutrient}$.

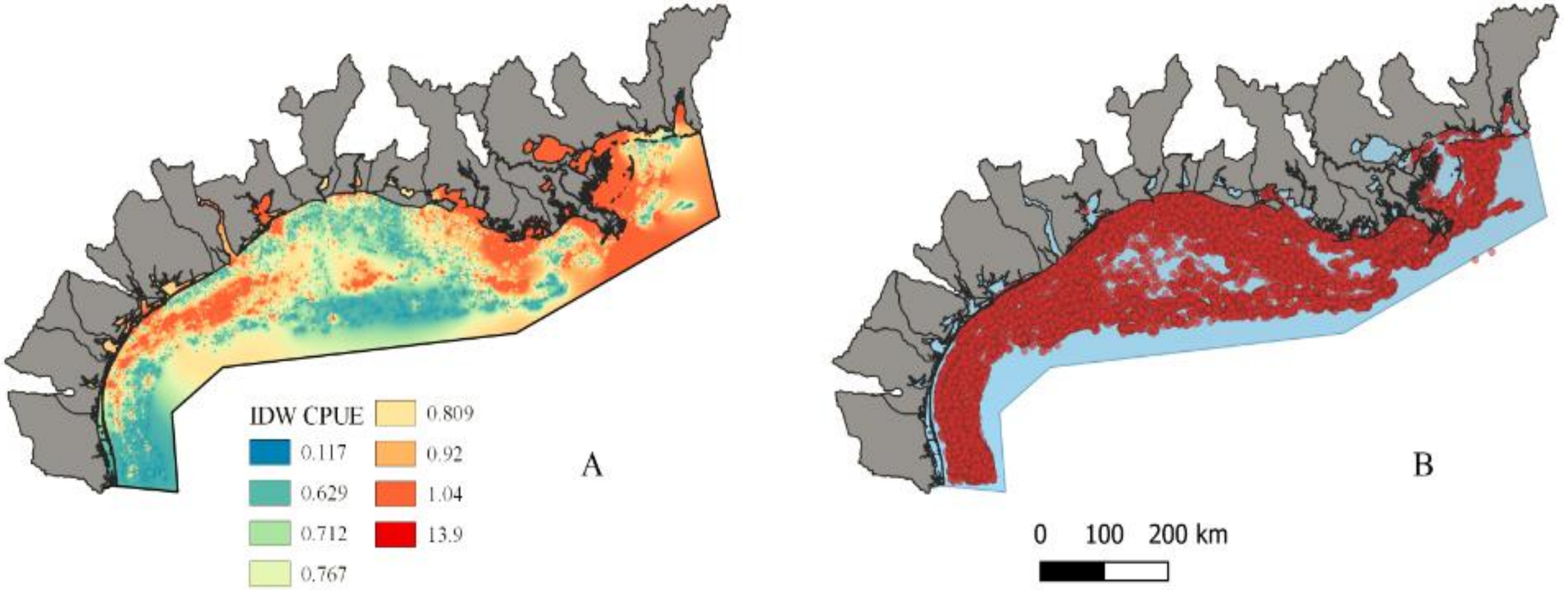

Figure 1. The interpolated surface of CPUE (kg/ha swept) values in the study area is shown on the left (A) and fishing set location are on the right (B).

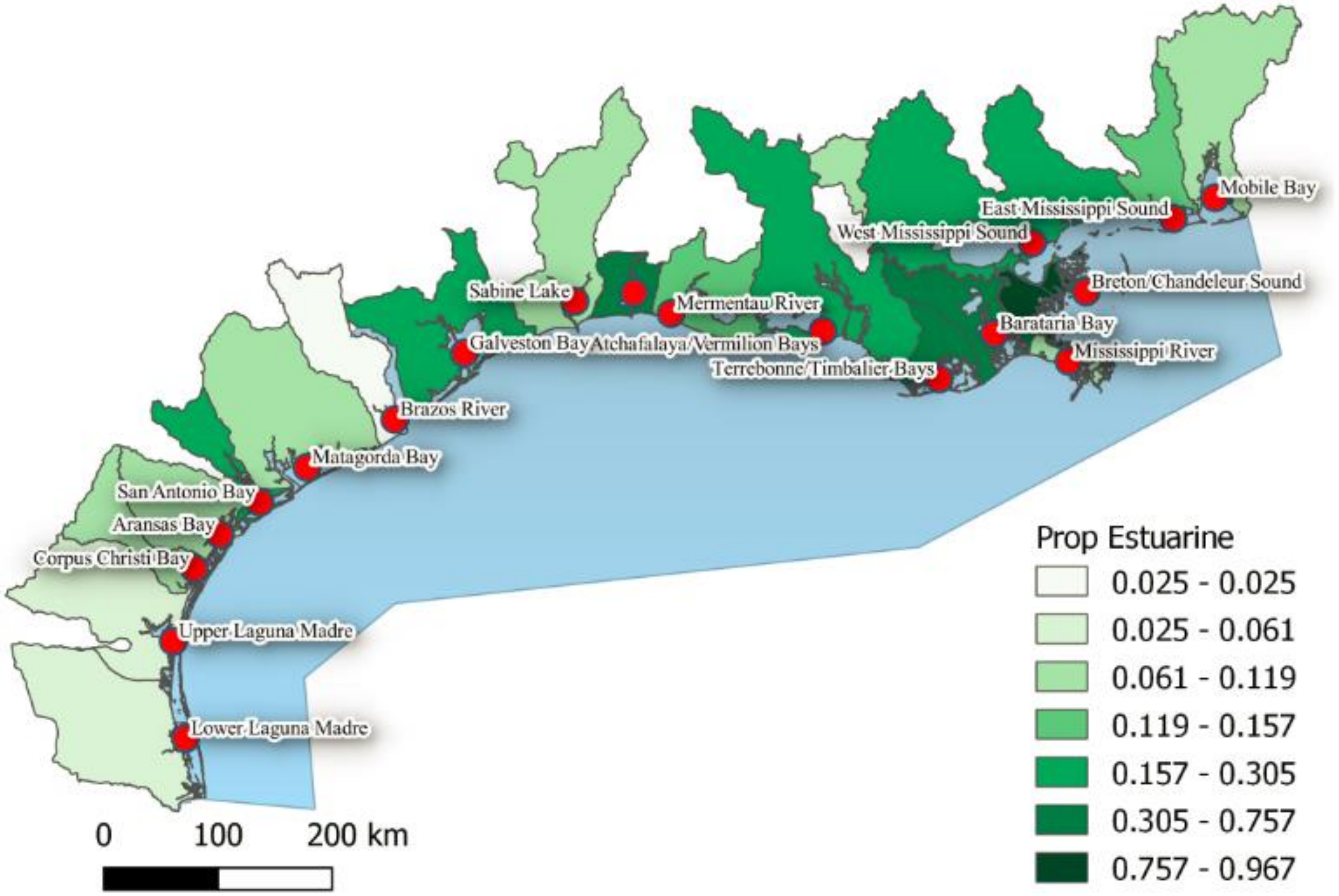

Figure 2. Bays and estuaries effluent to the western Gulf of Mexico used in this study. The study area is shown in light blue. Estuarine drainage areas are shown in shades of green, with darker colors representing higher proportional coverage of juvenile shrimp habitat.

Bay	Estuarine Area (ha)	Total Area (ha)	Prop. Estuarine	N Load	P Load
Aransas Bay	70,570	694,463	0.102	8,300	1,249
Atchafalaya/Vermilion Bays	356,364	1,889,235	0.189	184,083	24,665
Barataria Bay	258,661	563,568	0.459	4,761	2,386
Brazos River	27,297	727,348	0.038	609,949	93,633
Breton/Chandeleur Sound	623,987	645,170	0.967	319	20
Calcasieu Lake	125,186	267,532	0.468	72,149	14,453
Corpus Christi Bay	60,478	506,253	0.119	10,577	2,151
East Mississippi Sound	83,215	528,669	0.157	11,212	1,176
Galveston Bay	217,194	1,150,509	0.189	862,260	140,905
Lower Laguna Madre	87,615	1,447,379	0.061	5,042	604
Matagorda Bay	123,279	1,332,243	0.093	167,842	22,080
Mermentau River	85,419	557,327	0.153	41,758	13,184
Mississippi River	100,779	377,110	0.267	999,375	127,250
Mobile Bay	118,492	1,258,620	0.094	47,058	3,709
Sabine Lake	120,367	1,244,463	0.097	338,309	35,186
San Antonio Bay	82,522	401,332	0.206	180,941	20,482
Terrebonne/Timbalier Bays	294,944	389,541	0.757	17,669	3,134
Upper Laguna Madre	56,162	1,141,146	0.049	301	10
West Mississippi Sound	172,018	563,092	0.305	2,756	360

Table 1. Summary of bays and associated nutrient loads (metric tons year^{-1}), total area (ha), estuarine area (ha), and proportion of each EDA that is estuarine area.

3.2. Statistical Modeling

Environmental data were extracted from grid surfaces to fishing locations to prepare the final dataset used in model selection. Summary statistics of continuous variables are presented in Table 2. All statistical analysis were performed using R statistical software (version 3.5.2; R Core Team, 2018).

Variable	Min	Mean	Std. Deviation	Median	Max
$D_{nutrient}$	2,242	243,269	218,150	141,771	873,766
$D_{estuarine}$	0.054	0.259	0.173	0.239	0.835
CPUE	0.001	0.816	0.916	0.573	25.191
Temperature (℃)	13.400	24.200	3.384	24.430	30.760
Salinity (ppt)	12.830	35.620	3.744	33.950	37.550
Depth (m)	0.853	29.459	23.456	23.774	183.398

N = 18024

Table 2. Summary statistics of numerical variables used in analysis.

To assess the effects of coastal nutrient loads and estuarine area on commercial shrimp CPUE, generalized additive model (GAM) methods provided by the R package ‘mgcv’ (Wood, 2017) were used to predict CPUE. GAMs have the advantage of flexibility in the linear predictor and automatic control of parameter complexity (Venables & Dichmont, 2004). Calculated CPUE was used as the dependent variable; $D_{nutrient}$, $D_{estuarine}$, dissolved oxygen (mg/L), salinity (ppt), and temperature (˚C) were included as independent variables. A seasonal variable that split the year into 4 periods as winter (January – March), spring (April – June), summer (July – September), and fall (October – December) and year were included to account for any seasonal or annual differences in catch rates. Ten records with 0 CPUE were omitted from analysis leaving 18,024 data points available for final model selection.

Variable selection was conducted with backward elimination, and an ANOVA was used to check for variable significance. Concurvity was assessed to ensure fitted smooths did not occupy the same space. To assess model fit, several model diagnostic tools were examined including histograms of Pearson and deviance residual and the quantile-quantile (Q-Q) plots. Models using Gaussian and Gamma distributions and log, inverse and identity links were assessed during model selection. The final model specified to assess the hypotheses is shown below, where s represents a smoothed spline term:

$$CPUE \sim s(D_{nutrient}) + s(D_{estuarine}) + s(Temp) + s(DO) + s(Salinity) + s(Depth) \\ + Year + Month$$

3.3. Simulating Environmental Changes

Simulated scenarios are presented to explore the utility of the model and gauge the sensitivity of shrimp production to changes in environmental conditions. Two scenarios are presented representing potential alterations to shrimp habitat as a result of environmental regime changes.

Current land use and management goals of several watersheds throughout the country include reduction in nutrient flux delivered to coastal waterbodies. The Gulf of

Mexico Hypoxia Task Force is working with stakeholders to achieve the goal of reducing the areal coverage of the annual hypoxic zone in the northern Gulf. Hypoxia in the Gulf is caused in part by eutrophication of coastal waters from the Mississippi River Basin. One of the goals put forth in the 2008 Action Plan is to reduce riverine total nitrogen levels by 45% (Gulf Hypoxia Action Plan, 2008). Accordingly, a 45% reduction of delivered nitrogen loads was applied across the board to coastal nutrient loads to evaluate how a large scale decrease in nutrient load could affect CPUE.

As noted previously, some coastal areas of the United States are disappearing at an alarming rate. Additional habitat loss occurs in the Gulf when one habitat type is converted to another through development, mitigation, and conservation. While the methods employed and data available do not allow for a long time series analysis of the effects of habitat loss or gain on commercial shrimp CPUE, the model does allow predicting effects of habitat regime shifts. Allowing for the strong assumptions that the proportion of estuarine habitat in each bay system reacts in a similar fashion and total juvenile shrimp habitat is reduced by 25%, estimated effects on the shrimp fishery are provided.

The change in commercial shrimp production in the northwestern Gulf was calculated for both scenarios by predicting the change in shrimp CPUE on a simulated dataset. In each simulation, one variable was adjusted to account for the change in environmental conditions in isolation. The difference between the mean CPUE predicted from the original model and the mean CPUE predicted from the simulated scenario was applied to the mean area swept per trip resulting in a calculated gain or loss of shrimp in kg/trip.

4. RESULTS

Modeled effects of annual nutrient loads to Gulf adjacent bays and proportion of the respective EDA that was suitable habitat for shrimp provide support for the hypotheses posed previously. Iteratively reducing the model (e.g., omitting variables and comparing AIC scores and deviance explained) indicated the best model fit was inclusive of $D_{estuarine}$, $D_{nutrient}$, temperature, dissolved oxygen, depth, salinity, year, and season. ANOVA was used to test significance of parametric variables in comparison with the null model, and both year and season were significant in the model. Parameter estimates are shown in Tables 3 and 4. Fitted smooths of the additive effects of the model terms are shown in Figure 3 and model diagnostics (histograms of residuals and QQ plot) are shown in Figure 4.

Overall model fit explained 29.5% of the deviance. The final model also had the lowest generalized cross validation (GVC) score and Akaike's information criterion (AIC) from various model fits while altering the smoothness term for each variable. A Gamma distribution with log link provided the highest amount of deviance explained. Alternative smoothness selection criterion were used (Restricted Maximum Likelihood, "REML" and "GCV") to check for robustness in the smooth selection, as GCV tends to over-smooth linear predictors. Comparing plots of residuals and smooth terms in relation to CPUE were nearly identical between the smoothing methods. Estimated degrees of freedom, AIC values and deviance explained were also similar between models, with slightly lower AIC and higher adjusted R^2 (0.165) using GCV methods; thus, the GVC smoothing methods were used in final model fitting.

The lowest dissolved oxygen levels corresponded with the lowest predicted CPUE and increased as dissolved oxygen increased to 6 mg/L. Predicted CPUE values were highest once dissolved oxygen exceeded 8 mg/L. CPUE was predicted to increase with temperature from the minimum with a peak around 20˚C and decline steadily until dropping rapidly around 30˚C.

Low salinities (< 20 ppt) were not common, but the predicted CPUE showed a steady climb from its minimum at ~13 ppt to its maximum at 20 ppt. CPUE rates remained stable across the rest of the salinity range, with a slight increase at salinity over 35 ppt.

The smooth term of depth showed the highest predicted CPUE values at the shallowest depths. There were very few observations at the deepest depths (> 100 m), as participants in the commercial fishery rarely target penaeid shrimp that deep, but there was a local peak in fitted CPUE around these depths.

The smoothed distance weighted nutrient variable was relatively flat throughout the range of the predictor, with the exception of a sharp increase at extremely high values (>700,000).

Response to the distance weighted proportion estuarine variable had a local maximum and minimum at 0.15 and 0.2, respectively. The fitted smooth then generally increased with increased proportion estuarine habitat. Interestingly, there is a downward trend in predicted CPUE as proportion estuarine habitat approached the maximum of its range.

Predicted effects of inter-annual variability indicate a decrease in CPUE from 2008 to 2014 where it stabilizes for 2015 and 2016. The annual trend roughly matches the index provided by Hart (2016). Seasonal variation showed fall and spring being similar, and a large increase in CPUE in the summer. The lowest CPUE values were predicted to occur in winter.

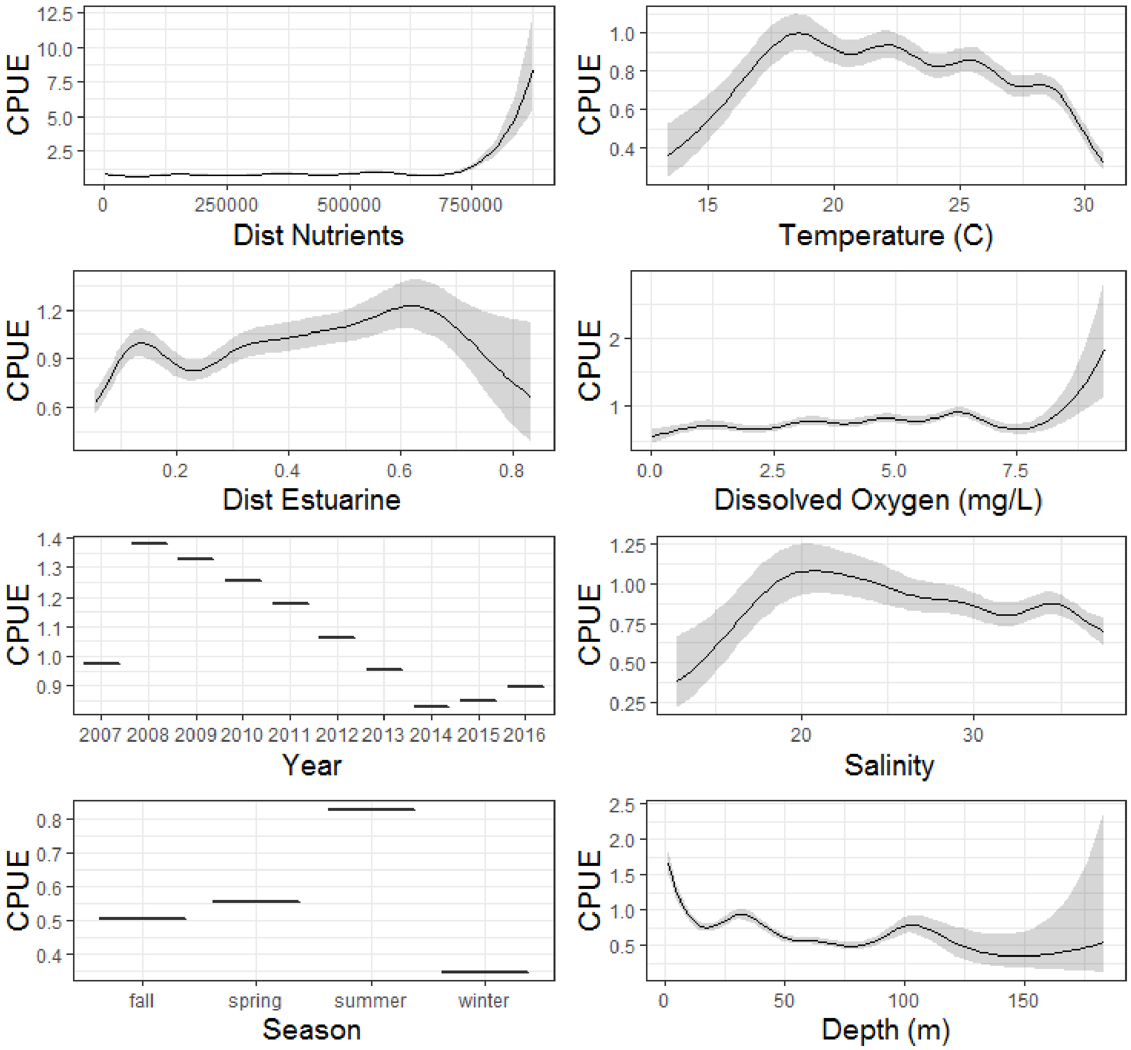

Figure 3. Fitted smooth terms on the response scale predicted by the model. Factored variables year and season are also shown.

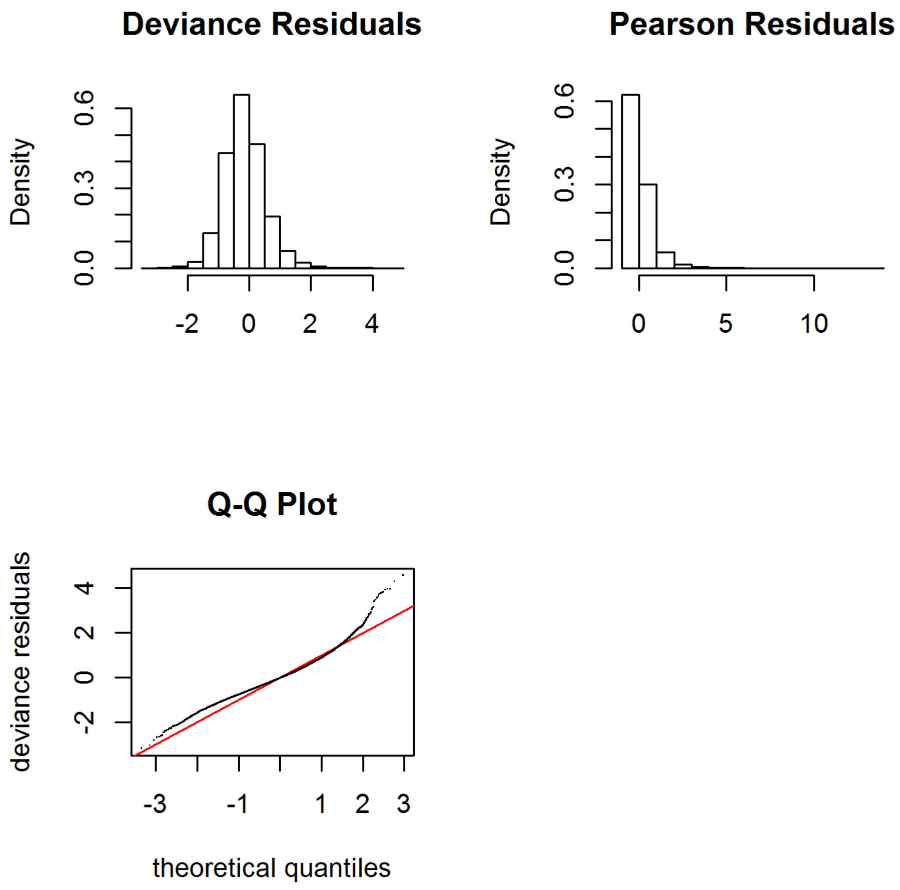

Figure 4. Histograms of deviance and Pearson residuals (top left and right respectively) and Q-Q Plot.

	Estimate	Std. Error	t-value	Pr(>|t|)	
Year					
2008	0.34980	0.03382	10.343	<0.0001	***
2009	0.31171	0.03400	9.168	<0.0001	***
2010	0.24061	0.03559	6.760	<0.0001	***
2011	0.19713	0.03367	5.856	<0.0001	***
2012	0.09204	0.03322	2.771	0.00560	**
2013	-0.01925	0.03243	-0.594	0.55271	
2014	-0.15938	0.03220	-4.949	<0.0001	***
2015	-0.13678	0.03299	-4.146	<0.0001	***
2016	-0.09078	0.03255	-2.789	0.00529	**
Season					
Spring	0.09941	0.02085	4.769	<0.0001	***
Summer	0.49654	0.01928	25.751	<0.0001	***
Winter	-0.37927	0.03374	-11.242	<0.0001	***
(Intercept)	-0.50468	0.02903	-17.385	<0.0001	***

Table 3. Parameter estimates of parametric variables used in the model. Year "2007" and Season "Fall" omitted as reference levels. Significance codes: "*" = $p < 0.001$, "**" = $p < 0.01$, “*" = $p < 0.05$.**

	Estimated DF	F	p-value	
s(distwtN)	8.872	24.174	<0.0001	***
s(distwtEst)	8.871	41.109	<0.0001	***
s(temp)	8.873	32.463	<0.0001	***
s(oxy)	8.971	13.911	<0.0001	***
s(salinity)	8.122	6.477	<0.0001	***
s(depthm)	8.835	98.910	<0.0001	***

Table 4. Approximate significance of smooth terms. Significance codes: "*" = $p < 0.001$, "**" = $p < 0.01$, “*" = $p < 0.05$.**

5. DISCUSSION AND APPLICATIONS

Results from the modeled effects of salinity, temperature, and dissolved oxygen are in general agreement with results from historical and contemporary research methods investigating the effects that influence shrimp survival and production of the shrimp fishery. The current research expands on common habitat suitability models by including variables that are proportional to the sum of distance weighted juvenile habitat characteristics and determining abundance as represented by CPUE.

5.1. Modeling

Determining the optimum conditions and habitat suitability for white and brown shrimp has been an undertaking of the scientific community for many decades. More recently, several different modeling approaches have been used explain environmental effects on shrimp growth, survival, and abundance. Using population models, Baker et al. (2014) concluded that juvenile shrimp survival may be the strongest driver in adult stock size, but the factors affecting juvenile growth are not clearly understood. The current study attempts to contribute to research exploring the interplay between juvenile habitat and growth in that it includes two factors that directly impact juvenile shrimp habitat: nutrient loadings and areal estuarine coverage of shrimp habitat. Modeled annual variability from a study using spatially explicit individual-based model representing the cumulative effects of salinity, temperature, and access to emergent marsh to model shrimp production found a significant correlation to survey data from the northern Gulf

(Leo et al., 2016). Diop, et al. (2007) used recursive linear models, combining life stage counts and environmental parameters, to estimate adult white shrimp abundance in Louisiana. Their study showed a positive relationship between temperature and salinity on CPUE and a negative relationship between river discharge rates and wetland loss. Two studies of pink shrimp abundance using delta-GAM models provide evidence for using non-linear smooths to describe the relationship between environmental covariates and CPUE (Drexler & Ainsworth, 2013; Rubec et al., 2016). Generally, there is an optimum range in which the modeled environmental condition suggests maximum positive effect on CPUE. The use of fishery dependent observer data from the Gulf precludes the use of the nested binomial models and allows for prediction of variable effects directly related to the commercial fishery.

Drawing inferences from the GAM results provides insights into how environmental conditions affect the distribution and abundance of penaeid shrimp in the western Gulf. The gear used by commercial fishers in this fishery trawl the benthos, and bottom temperature tends to fluctuate less than sea surface temperature. However, seasonal fluctuations in bottom temperature are still prevalent along the coastal shelf. Predicted CPUE shows a relationship with temperature that is consistent with a review of white shrimp and brown shrimp habitat suitability by Turner and Brody (1983). Their study indicated temperatures above 20˚C produce the highest catches of brown shrimp and above 32˚C can severely stress shrimp. Minimum average catch rates are seen during winter, when it could be expected that benthic temperature in the Gulf would be lowest. A seasonal high CPUE is seen in the summer, when brown shrimp are emigrating from bays to offshore waters. Brown shrimp emigration from bays to the Gulf peaks in May, June and July (Klima et al., 1982) and the increase in CPUE may be attributed partially to the annual closure in the shrimp fishery in Texas state waters and the federal waters extending to 200 nm from the Texas coast. The closure is used as a management tool to prevent growth overfishing and allow shrimp to emigrate from bays and grow to a more marketable size. Extremely high catch rates were observed in the data during weeks following the opening of these fishing grounds.

The fitted smooth term for depth shows three distinct depth ranges that predict higher CPUE. The highest effect is at the shallowest depths, and there are two local maxima near 30 m and 100 m. These maxima may represent a spatial segregation between shrimp species. Personal field observations on commercial shrimp vessels revealed that fishery participants targeting white shrimp fish in shallower water and those targeting brown shrimp fish deeper offshore waters. Particularly large and numerous brown shrimp have also been observed at depths around 100 m, which could account for the local maximum seen in the fitted smooth. Areas of high predicted CPUE values are in general agreement with gridded CPUE values for brown and white shrimp from Scott-Denton et al. (2012). The large variation in the smoothed estimate at the maximum depths could be attributed to fishers targeting brown shrimp overwintering grounds where CPUE can be generally very high or very low.

Median and mean salinity at fishing sites were at concentrations considered to be normal seawater (35.62 and 33.95 ppt, respectively). However, predicted shrimp abundance was highest under conditions that are thought to encourage shrimp growth (around 20 ppt). The peak predicted CPUE in response to salinity provides further evidence that 20ppt is an optimal salinity for shrimp production, and may represent fishing locations that are near or in estuaries.

The modeled CPUE over the time period 2008 – 2014 shows a downward trend and predicted CPUE stays low for 2015 and 2016. Interestingly, the low predicted CPUE in 2015 and 2016 coincides with a one of the strongest El Niño Southern Oscillation (ENSO) cycles in recent history. Future research should examine long-term environment drivers such as ENSO and their effect on shrimp production as it is an interesting avenue and has had effects on other fisheries (Mysak, 1986; Peterson, 2003).

While the trend of the fitted smooth of CPUE is upward as $D_{estuarine}$ increases, the sharp decline in CPUE above ~0.7 is difficult to resolve. However, the sparsity of the data at upper end of $D_{estuarine}$ greatly increases the uncertainty of the estimate. The smooth term also indicates a dip in predicted CPUE near the $D_{estuarine}$ value of 0.25. Comparing interpolated surfaces of $D_{estuarine}$ and CPUE reveals the water south of Sabine Lake, Calcaseiu Lake, and the Mermentau River share the common thread of having lower than average CPUE and $D_{estuarine}$ values around 0.25. In terms of the model fit, the area may have other unmodeled characteristics such as benthic sediment distributions that that influence the shrimp distribution and abundance.

While the inclusion of $D_{nutrient}$ was significant to the model, and provided ~ 2% of deviance explained, the smoothed effect remained relatively flat throughout its range, with exception to the higher end of the range. The increase in predicted CPUE in the upper range lends some support to the notion that bottom up production fueled by nutrient enrichment outweighs the negative effects of eutrophication induced hypoxia for overall shrimp fishery production.

5.2. Applications

The results presented demonstrate how juvenile shrimp habitat and environmental parameters can be useful in predicting shrimp catch rates across the western Gulf. This is a novel study, as it uses fishery dependent observer data to provide insight into coastal nutrient loading and sub-adult shrimp habitat that have not been thoroughly explored in regard to commercial catch rates and provides a tool to estimate changes in shrimp productivity under certain regional changes to shrimp habitat. Simulated scenarios are presented to display the utility of the model that may be useful to gauge the effect and estimate how changes to the environmental landscape could affect participants in the shrimp fishery in the northern Gulf.

The first scenario explored a change in the nutrient landscape present in shrimp habitat as a result of changes in the nutrient loads delivered to the Gulf. The second scenario address the question of how shrimp production would be predicted to change in response to habitat loss. These estimates provide examples of how the model could be useful for sensitivity analyses for a number of environmental regime shifts. For instance, coastal managers and planners could better evaluate economic impacts or focus habitat conservation and restoration efforts based on predicted outcomes from the model.

For example, Table 5 shows the resulting change to the mean shrimp CPUE (kg/ha), mean change in shrimp weight (kg) per trip, and estimated increase or decrease in vessel revenue assuming an optimistic ex-vessel price of $6/lb of shrimp.

Condition	Δ Mean CPUE (kg/ha)	Δ Shrimp Weight (kg)	Revenue loss at $6/lb per Average Trip
Reduced N	-0.049	-63.749	$841.49
Reduced Est	-0.055	-71.555	$944.53

Table 5. Estimated change in mean catch per unit effort (CPUE), shrimp weight (kg), and revenue loss ($US) under simulated scenarios.

6. CONCLUSION

The objective of this research is to determine if juvenile shrimp habitat parameters can be useful in predicting commercial shrimp CPUE across the western Gulf of Mexico. There is a need for insight into coastal nutrient loading and sub-adult shrimp habitat that has not been thoroughly explored that may affect commercial catch. Additionally, this research investigates factors that have been determined to affect shrimp production on a larger scale than previously applied, e.g. applying assumptions that have been made at the single estuary level to a regional scale.

Ultimately, methods employed here could be used by resource managers to better predict and assess how different environmental conditions could affect the ecology and economics of the shrimp fishery in the western Gulf. For instance, changing land use policy upstream of the rivers and estuaries effluent to the Gulf can affect a vast portion of the country and many stakeholders. Climatologic change in the form of increased temperature and sea level rise pose a challenge to coastal community planning, and this research could provide estimated effects on the shrimp fishery. In addition, with no clear stock-recruitment relationship in Gulf shrimp species, a better understanding of environmental factors could provide a more precise estimate of annual shrimp production.

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