EFFECTS OF SEAGRASS HABITAT AND ENVIRONMENTAL STRESSORS ON BLUE CRAB POPULATIONS IN TEXAS

A Thesis

by

JESSICA C. CASILLAS

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Chair of Committee,	Meri Davlasheridze
Co-Chair of Committee,	Wesley Highfield
Committee Member,	Samuel D. Brody
Head of Department,	Kyeong Park

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ABSTRACT

Declining blue crab stocks in Texas coastal systems in the 1980s and most recently in the early 2000s have led scientists and policy makers to re-evaluate fishery management plans. A newer ecosystem-based approach to managing these fisheries has recently gained some traction from policy makers, termed Ecosystem Approach to Fisheries. An important component to understanding this approach, is to understand the relationship between a fishery and its ecosystem components. The goal of this study is to investigate the relationship between the blue crab fishery and its habitat of submerged aquatic vegetation (SAV). Alongside of this investigation, the study also examines environmental stressors (e.g. water temperature, salinity, dissolved oxygen, turbidity) that may lead to changes within a fishery.

The results of this research suggest relationships may exist between blue crab catch, seagrass habitat, and select environmental stressors. Environmental stressors, such as salinity, are found to be equally influencing drivers for blue crab populations along the coast of Texas. Although aimed to represent an ecosystem-based approach in the models, this study is limited to just a few interactions within the system. This work serves as a stepping stone for future work, where interactions between socioeconomic factors and additional ecological factors (e.g. freshwater inflow, tidal and wind influence, system morphology) should be taken into account. This level of adaptation is best to effectively manage ecosystems so that “bottom up”, “top down”, and mid - level interactions are recognized and managed accordingly.

DEDICATION

This humble work is dedicated to my parents, Salvador and Janie Casillas, for their never-ending love and support. I am truly honored and blessed to have them as my parents. Their dedication to my education is unfathomable. Through their hard work, sacrifices, and many prayers, I have been given opportunities that have made it possible to pursue a graduate degree and complete it successfully.

A special thank you is given to my mother, whose strength and courage has deeply inspired and motivated me to pursue my own dreams. Without her loving upbringing and nurturing, I would simply not be here today. God's love is truly shown through her in every action she takes. I am blessed to call her my rock, role model, and best friend.

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"And whatever you do, whether in word or deed, do it all in the name of the Lord Jesus, giving thanks to God the Father through him."

\- *Colossians 3:17*

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Contributors

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NOMENCLATURE

CPUE	Catch Per Unit Effort
DO	Dissolved Oxygen
EAF	Ecosystem Approach to Fisheries
GIS	Geographic Information Systems
G.U.L.F.	Gulf United for Lasting Fisheries
IDW	Inverse Distance Weighted
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometric Turbidity Units
OLS	Ordinary Least Squares
PPT	Parts Per Thousand
SAV	Submerged Aquatic Vegetation
SCPT	Seagrass Conservation Plan for Texas
TCEQ	Texas Commission on Environmental Quality
TGLO	Texas General Land Office
TNRCC	Texas National Resources Conservation Commission
TPWD	Texas Parks and Wildlife Department
TSMP	Texas Seagrass Monitoring Plan
USFWS	United States Fish and Wildlife Service

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1. INTRODUCTION

Ecosystems represent the linkages and dynamic relationships amongst species, species abundance, processes, and patterns (Costanza et al., 2006). They provide invaluable direct and indirect benefits to human systems and contribute to their long-term livelihood and welfare. About 44% of the world's population lives in coastal zones (Cohen et al., 1997), and their societies and economies strongly rely on the goods and services ecosystems provide. However, anthropogenic footprints on the coastal environment have compromised many valuable ecosystems and degraded the services they provide. If society is to utilize ecosystems in a prosperous and sustainable way, effective management practices are needed that accounts for the interconnectivity between processes taking place within an ecosystem, and the interactions between ecological, social, and economic systems (Barausse, 2011).

The focus of this work is to analyze the need for an ecosystem-based approach within the blue crab fishery of Texas. Management of Texas' fisheries has been of long concern, as the State produces a majority of the seafood for the United States, about 14.4 million pounds of seafood products (TCEQ, 2009). Texas fisheries alone are responsible for nearly 34% of total United States' harvest for blue crab commercial landings (GSMFC, 2015), generating about $40 million annually for Gulf of Mexico states and between $3 - 5 million annually for Texas alone.

A newer ecosystem-based approach to managing these fisheries has recently gained some traction from policy makers (Garcia and Cochrane, 2005), termed Ecosystem Approach to Fisheries (EAF). Ward et al. (2002) defines EAF as "an extension of conventional fisheries management recognizing more explicitly the interdependence between human well-being and ecosystem health and the need to maintain ecosystems productivity for present and future generations, e.g. conserving critical habitats, reducing pollution and degradation, minimizing waste, protecting endangered species" (p. 5). The most recent action plan of Texas developed by Audubon's Nature Institute's Gulf United for Lasting Fisheries (G.U.L.F.), shows evidence that an ecosystem-based approach is a valuable perspective to effectively manage the blue crab fishery in Texas. An important component to understanding the EAF, is to understand the relationship between a fishery and its ecosystem components. The goal of this study is to investigate the relationship between the blue crab fishery and its habitat of submerged aquatic vegetation (SAV), often described as seagrasses. Alongside of this investigation, the study also examines environmental stressors (e.g. water temperature, salinity, dissolved oxygen, turbidity) that may lead to changes within a fishery productivity, with the aim to determine if an impact to the fishery has occurred, either directly or indirectly. The term 'impact' here is defined as "consequences, caused by changes in ecosystem quality and state, for human welfare and for the social and economic benefits from an ecosystem" (Barausse, 2011). As an example, a decrease in the abundance of blue crabs, which then leads to decreased landings, and ultimately a negative economic consequence is a direct impact. An indirect impact may arise from a change in an environmental stressor so that it decreases habitat, thus leading to a decrease in a species abundance, and thus, a reduced economic welfare. We examine this relationship in five major bays in Texas.

The results of this research suggest that relationships may exist between blue crab catch per unit effort (CPUE), seagrass habitat, and select environmental stressors. While specific bays were not assessed according to their physical characteristics and morphology, this study provides a general analysis for factors that may contribute to the blue crab fishery.

Environmental stressors, such as salinity, are found to be equally influencing factors to blue crab populations along the coast of Texas.

Submerged Aquatic Vegetation

Seagrasses serve as an ecosystem in itself or may serve as a vital component within a larger ecosystem framework. Seagrass beds are recognized as being a unique subtropical habitat in many of Texas' bays and estuaries that provide several beneficial roles. One of the critical roles that SAV serves is providing habitat for coastal and pelagic species as their nursery and breeding grounds (Jackson et al., 2001). SAV also serves as a major source for organic biomass for coastal food webs, natural agents for stabilizing coastal erosion and sedimentation, and as a biological agent in the nutrient cycling process and filtration process for maintaining water quality (Pulich, 1999). Due to their positive impacts within the coastal environment, seagrass beds have increasingly become a conservation goal in Texas.

Due to recent declines in SAV within major bays along the coast, a coast-wide Seagrass Conservation Plan for Texas (SCPT) was developed in 1999 by three major sponsors which include, the Texas Parks and Wildlife Department (TPWD), the Texas General Land Office (TGLO), and the Texas Natural Resource Conservation Commission (TNRCC). Each agency is responsible for producing the plan due to their legislative authority or statutory jurisdiction to the seagrass beds or waters in which they occur. Determining the status and trends of seagrasses along the Texas coast is primarily handled by TPWD. In an effort to accurately assess the state of SAV within Texas coastal areas, protocols and policies were implemented within the plan that led to consistent sampling methods and analysis, which was the first step towards producing reliable data.

Table 1 depicts historical trends for many of Texas' major bays from the 1950/1960 to 2002. Many of these bays show a significant decline in SAV coverage over the past several decades. Seagrass losses occur globally and are considered the most threatened ecosystems on earth (Waycott et al., 2009). Declines are attributed to both natural and anthropogenic causes. Orth et al. (2006) found that of the 47 case studies of seagrass loss, 28 of them were attributed to human influence. Among natural causes, natural disasters commonly responsible for declines are hurricanes, earthquakes, disease, and grazing by herbivores. On the other hand, anthropogenic causes for declining SAV are those which affect water quality and clarity. These include nutrient and sediment loading from runoff and sewage disposal, dredging and filling, pollution, upland development, certain fishing practices, and boating activity (Short and Wyllie-Echeverria, 2000).

Table 1. Summary of total seagrass changes for Texas bay systems. Seagrass values are in hectares and acres in parenthesis. Reprinted from Dunton et al. (2011).

Bay System	[1]**Late 1950s or mid-1960s**	[2]**Mid-1970s**	[3]**1987 or early 1990s**	[4]**1998**
		Galveston Bay System		
Galveston/Christmas Bays	590[a] (1,457)	134[a]	113[b]	210[c]
		Midcoast Region		
Matagorda Bay System			1,099[b] (2,716)	
San Antonio Bay System		5,000[d] (12,350)	4,305[d] (10,683)	
		Coastal Bend Region		
Aransas/Copano Bays			2,871[e] (7,094)	
Redfish Bay and Harbor Island	5,380[e] (13,293)	6,200[e] (15,320)	5,710[e] (14,109)	
Corpus Christi Bay System			2,568[e] (6,342)	
		Laguna Madre System		
Upper Laguna Madre	12,321[f] (30,445)	20,255[g] (50,050)	22,903[h] (56,593)	22443[i] (55,456)
Lower Laguna Madre	59,153[f] (146,166)	46,558[g] (115,044)	46,624[h] (115,207)	46,174[i] (114,095)
Baffin Bay			2,200[j] (5,436)	

[1] Data for Galveston/Christmas Bays, Redfish Bay, and Harbor Island based on 1956/58 Tobin photography. Data for upper and lower Laguna Madre based on field surveys during mid-1960s. [2] Data for Galveston/Christmas and Redfish Bay/Harbor Island based on 1975 (National Aeronautics and Space Administration Johnson Space Center (NASA- JSC) photography; San Antonio Bay based on 1974 NASA-JSC photography. Data for upper and lower Laguna Madre based on 1974–75 field surveys. [3] Data for Christmas, Matagorda, and San Antonio Bay systems from 1987 NASA-Ames Research Center photography. Data for Aransas/Copano, Redfish, and Corpus Christi Bay systems based on 1994 TPWD photography. Data for upper and lower Laguna Madre based on 1988 field surveys. Data for Baffin Bay based on 1992 U.S. Fish and Wildlife Service National Wetlands Inventory photography. [4] Data for Christmas Bay from 1998 Galveston Bay National Estuary Program photography. Data for upper and lower Laguna Madre from 1998 field surveys. [a] From Pulich and White (1991). [b] From Adair and others (1994). [c] From Pulich (2001). [d] From Pulich (1991). [e] From Pulich and others (1997). [f] Areas computed for this review from McMahan (1965–67). See Laguna Madre vignette. [g] Areas computed for this review from Merkord (1978). [h] Areas computed for this review from Quammen and Onuf (1993). See Laguna Madre vignette. [i] Areas computed for this review. See Laguna Madre vignette. [j] Areas computed for this review by Texas Parks and Wildlife Department, Coastal Studies Program, Austin, Tex. (unpub. data)

A loss in SAV is suggested to lead to a loss of commercially and recreationally important fish species and subsequently reduced revenue from the commercial fishing sector to the State (Pulich, 1999). Seagrass beds serve as habitat for many important recreational and commercial fish species. A loss of recreational species contributes to a decline in ecotourism and a loss of commercial species contributes to a decline in their landings. Both losses ultimately affect economic activity of a region and result in welfare losses. Figure 1 depicts the linkages and factors contributing to seagrass declines and its threats to the region's economy. Natural processes (e.g. energy from the sun, precipitation) within a bay area are driven by the exchange with land and ocean. Human activity (e.g. boating, dredging, land development, and deposition of nutrients from farming practices) have the potential to negatively impact the bay, and thus lead to loss of resources and revenue.

For the Gulf of Mexico, it is estimated that 98% of all commercial landings are estuarine-dependent for at least part of their life cycle (Chambers, 1992). Pulich (1999) estimated the total value of seagrass habitat within Texas estuaries for recreational and commercial harvests at $12.6 million annually. However, seagrass beds provide other valuable services including protection against storm surges, which are hard to quantify monetarily. Using values for recreation and storm protection, Lipton et al. (1995) estimated the per acre value of seagrass beds to be between $9 million to $28 million.

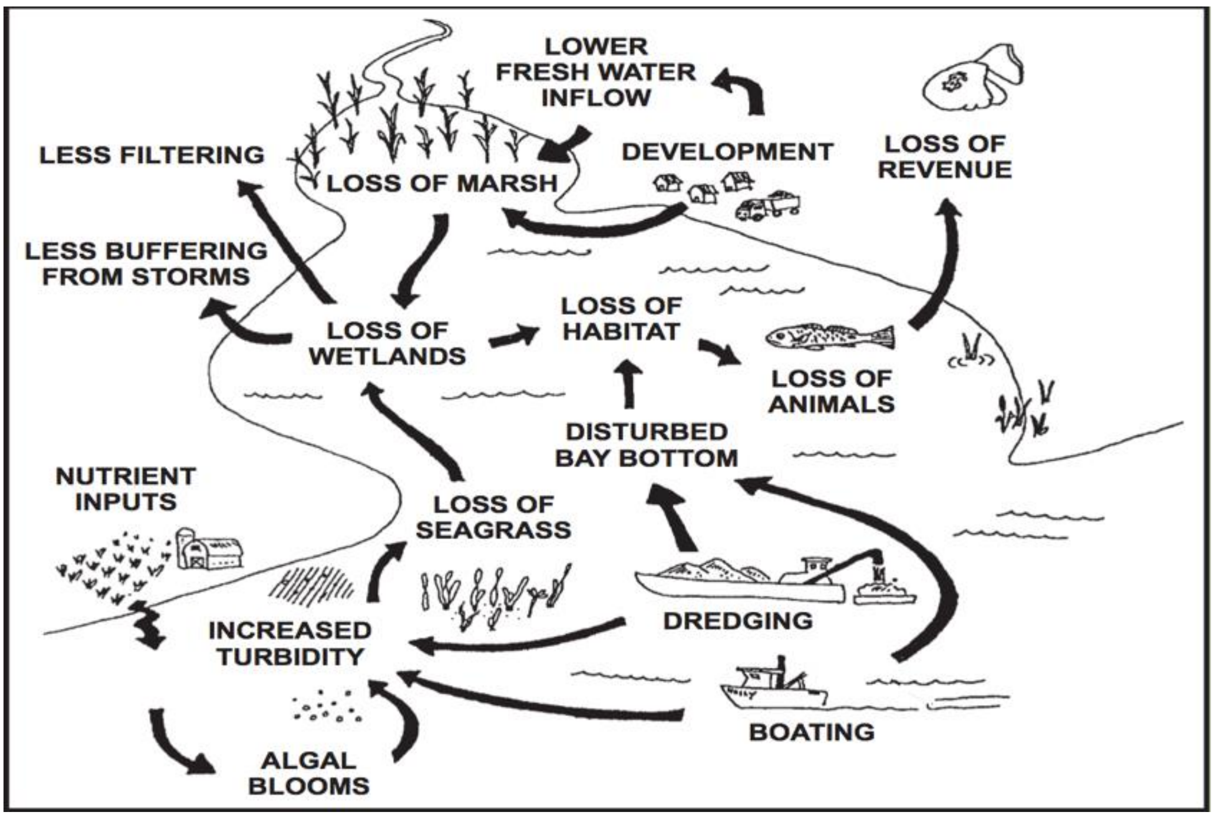

Figure 1. Factors contributing to SAV decline and revenue loss (adapted from Montagna, 1996)

Texas Blue Crab

Although several species depend on seagrasses for all or parts of their life cycle, the focus of this study will be on the adult blue crab (*Callinectes sapidus*) population within Texas. Seagrasses serve as a primary habitat that are linked to the blue crab survival and abundance (Hovel and Lipcius, 2002). Current trends indicate that blue crabs have significantly declined over the past several decades, leading to a period defined as "senescent" or declining from 1992 to 2005 (TPWD, 2007). Many problems that face the blue crab population include a reduction in freshwater flow to the estuary, over-harvesting, unsuitable water quality, and a loss of natural habitat.

According to TPWD, the blue crab hit its lowest ever recorded harvest in 2005 with 3.1 million pounds landed (TPWD, 2007). Historically, the average harvest for Texas was around 6.3 million pounds (TPWD, 2007). Most recent estimates from the National Oceanic and Atmospheric Administration (NOAA) indicate that 2016 harvests levels were recorded at 4.9 million pounds (NOAA, 2018). Figure 2 displays the historical trends from 1960 to 2016 for annual landings in pounds, where a maturity phase peaked in 1987 and has since been in steady decline. Figure 3 displays historical trends from 1960 to 2016 for the landing value of blue crabs in million dollars, which shows an inverse trend relative to landing weights which may be indicative of the scarcity of the resource.

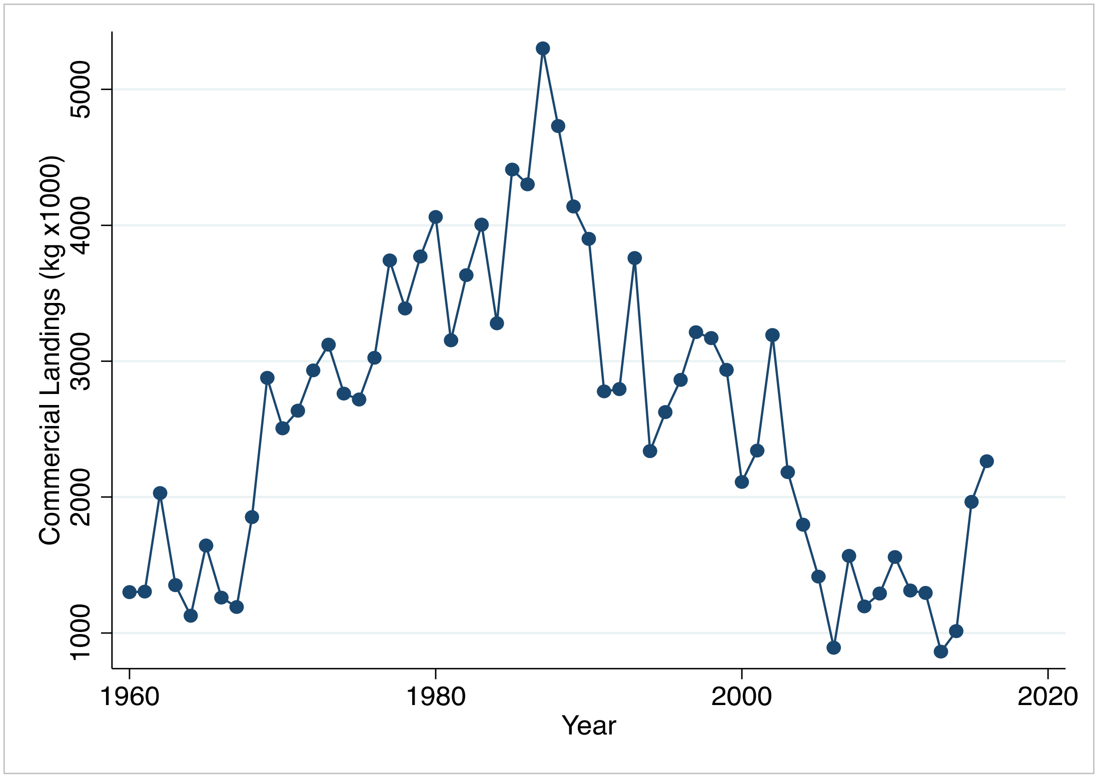

Figure 2. Blue crab annual commercial landings (kg x1000) from 1960-2016

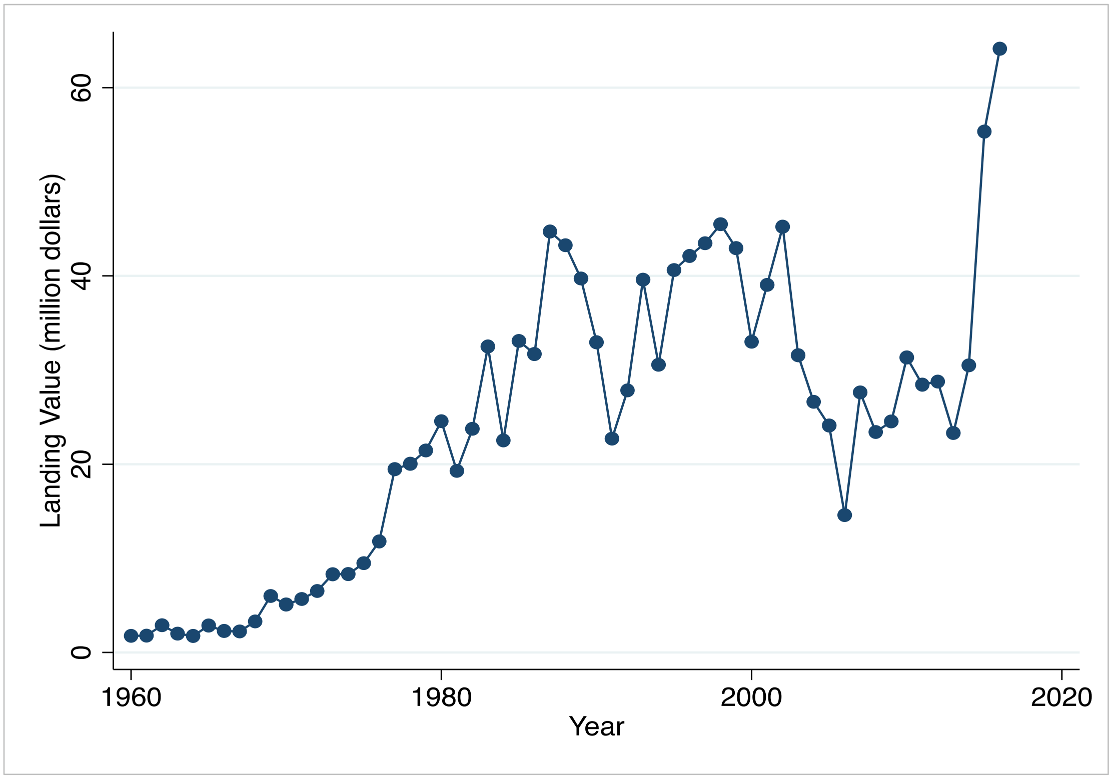

Figure 3. Blue crab annual landing value (million dollars) from 1960 -2016

From the above discussion, recent trends indicate that both seagrass beds and blue crab populations have steadily declined. To assess the relationship between the blue crab population and seagrass habitat, the first objective of this study is to quantify the importance of SAV in terms of blue crab productivity along the Texas coast. The analysis focuses on five highly productive bays within Texas: (1) San Antonio Bay, (2) Aransas Bay, (3) Corpus Christi Bay, (4), Upper Laguna Madre Bay, and (5) Lower Laguna Madre Bay. The second objective of this study is to assess the magnitude of importance of certain environmental stressors on the blue crabs' population in the aforementioned major bays in Texas. The work of this thesis aims to assess an ecosystem-based approach in the blue crab fishery management in Texas. This research contributes to the extent of literature that examines the linkages between species abundance and habitat along with environmental stressors (Read et al., 2011).

2. LITERATURE REVIEW

According to the Food and Agricultural Organization of the United Nations, an estimated 50% increase in current supply of fish and aquatic invertebrates is needed to meet the demands of the human population in 2050 (Bertelli et al., 2014). This significant increase places pressure on improving and sustaining aquatic ecosystems (e.g. seagrass beds) that support commercially valuable species. An ecosystem – based management approach recognizes the importance of all interactions within and between ecological, social, and economic systems and provides strategies for marine ecosystems to be effective and sustainable. The foundational roles of certain marine ecosystems have been well documented in literature, yet the understanding of specific linkages between ecosystem, habitat, and productivity of commercial species are needed in order to achieve sustainable fisheries.

Many studies investigating these relationships are concentrated around a specific commercially valuable species and habitat. Although extensive knowledge is needed to understand the dynamics between this relationship, it is also important to investigate relationships that expand beyond this traditional concept. The first part of this section reviews the traditional fishery - habitat model, while the second part explores associations outside the traditional relationship of habitat and fishery (i.e. environmental stressors affecting species production).

Habitat–Fishery Relationships

The first determination in understanding a habitat-fishery relationship is to analyze the habitat as being essential, facultative, or non-essential. Depending on the way a habitat is treated, a habitat may be defined as essential (species cannot survive without at least some of the habitat), facultative (more of the species because of the habitat, but if the habitat was lost the species could still survive as some levels), or non-essential (more habitat has no effect on species' levels) (Foley et al., 2012). Complexity of an ecosystems makes it difficult to categorize habitats into these three groups, but attempts have been made in the literature. However, it appears model design seems to determine whether the habitat qualifies as essential, facultative, or non-essential (Mykoniatis and Ready, 2013).

Barbier and Strand (1998) explored the value of mangrove habitat as breeding and nursery grounds for shrimp production in the State of Campeche, Mexico. The authors assumed an open access fishery and that mangrove area affected the carrying capacity of the shrimp fishery and its production. The results from this study suggested that while the mangroves were essential habitat for the shrimp, their contributions to shrimp productivity was relatively small. It was estimated that only 0.4% of annual harvest and revenues resulted from habitat decline, which was a considerably smaller decline relative to the decline attributed to resource over-exploitation.

An important aspect of the Barbier and Strand (1998) study was that the model assumed mangrove habitat to serve as essential habitat. Mykoniatis and Ready (2013) developed a more general framework for fishery-habitat interaction without assuming apriori that the habitat was essential, facultative, or even relevant. While their results of interaction between the SAV and blue crabs in Chesapeake Bay were consistent with Barbier and Strand (1988), authors also found contradicting evidence when they modeled the SAV as non-essential. It was found that assuming the habitat as essential led to potential model misspecification and biased regression estimates. The authors however did not account for ecological inputs or processes (e.g. water and nutrient cycling, energy flow) into the model.

To expand beyond the traditional habitat-fishery relationship, Seitz et al. (2004) investigated areas of an estuarine that are not usually viewed as important habitat to a commercially valuable species. In their study, they examined the importance of the blue crab population within various areas of the estuarine habitat, such as seagrass beds and included mudflats and sandflats.

The study sought to determine if structurally complex habitats (vegetated areas) were statistically different from structurally simple habitats (unvegetated areas) within Chesapeake Bay. The goal was to quantify abundance of blue crab juveniles and assess their survival in SAV areas and unvegetated areas (mudflats and sandflats). Results indicated that blue crab abundance was heavily concentrated in the seagrass areas (~50%) and in shallow unvegetated, up-river habitats (~40%). The remaining blue crab juveniles were found in unvegetated areas between the seagrass beds and up-river segments. Interestingly, they also found that larger juveniles and adults dispersed from seagrass areas to sand and mud flats, as they were now less vulnerable to predation. Seitz et al. (2004) concluded that conservation and restoration efforts should be equally focused on unvegetated areas (sand flats and mud flats) just as much as vegetated areas (seagrass beds).

Numerous studies have examined the linkages between habitat and commercially valuable species (Anderson, 1989; Bell and Pollard, 1989; Kikuchi, 1974; Shabmann and Capps, 1985). They all were consistent in finding that diminishing seagrass beds led to declining fish catches. Anderson (1989) and Shabmann and Capps (1985) expanded their studies to investigate the economic benefits of seagrass restoration. Anderson (1989) used a model that simulated catch and revenue values assuming seagrass beds within Chesapeake Bay were partially or fully restored. The study estimated that the net economic benefit to Virginia hard-shell blue crab fisherman of full SAV restoration to be about $1.8 million per year. Shabmann and Capps (1985) also concluded that seagrass restoration within Chesapeake Bay could improve the soft-shell crab fishery in Virginia. Bell and Pollard (1989) found slightly different results and concluded that fisheries are only likely to depend heavily on seagrass habitats when harvests are made in very enclosed bays and estuaries, where seagrasses provide the only form of shelter, and where a species spawns within the bay or estuary.

Contrary to these positive habitat-fishery relationship, other studies have demonstrated that fisheries are able to thrive during periods of significant seagrass habitat loss (Saenger et al., 2013; Heck et al., 2003). Rasmussen (1977) also found that despite a drastic decline in eelgrass *Zostera marina* habitat, the decline did not contribute to fishery collapse.

A study conducted in Florida Bay found significant decline in the pink shrimp *Farfantepenaeus duorarum* fishery coincided with the loss the seagrass *Thallasia testudinum*, which served as essential habitat for pink shrimp. The fishery was able to bounce back after just 5 years, but seagrass area had not been restored. Coincidently, when seagrasses drastically declined, South Florida experienced a drought that decreased freshwater inputs into the bay. It was likely the low freshwater inputs that played a major role in pink shrimp stock declines, rather than the loss of seagrass habitat (Rudnick et al., 2005).

Lastly, Lipcius and Van Engle (1990) investigated SAV loss, which served as nursery grounds for blue crab populations within Chesapeake Bay. Although a majority of the SAV habitat was lost in the upper part of the bay, the blue crab fishery was not substantially affected. The physical location of seagrass habitat within the bay appeared to serve as a more important component to the fishery. Juveniles remained unaffected as they utilized seagrass patches located in the lower part of the bay. The location of the seagrass habitat determined where they settled into the bay from offshore waters and thus, the fishery remained stable.

Environmental Stressors

Fisheries are able to sustain themselves when given the best water quality conditions as it improves the health and abundance of fish stocks (McConnell and Strand, 1989). Numerous biological studies have provided evidence of the most suitable water quality conditions for the adult blue crab. It is suggested that blue crabs are able to grow and develop well within certain ranges of common environmental stressors. The following studies provide well-researched examples of each environmental stressors including salinity, water temperature, dissolved oxygen, and turbidity, used in the following analysis.

Determining salinity preference of adult blue crabs has attracted many researchers over the past several decades. It is one of the most important environmental variables that influences the abundance and distribution of an organism. Studies that focused on adult blue crab populations demonstrate blue crabs are more abundant in estuaries with low salinity levels (Longley, 1994; Pulich et al., 1998; Greenwood et al., 2008). While the range of preferred salinity levels vary, studies consistently show that blue crabs favor areas with salinity levels less than 29 parts per thousand (ppt). For example, Longley (1994) found blue crabs were most abundant in salinities < 22 ppt. Pulich et al. (1998) found similar results, where peak adult blue crab abundance was found in large areas of water with salinities between 5-15 ppt. Hamlin (2004) found highest blue crab abundance in areas where salinity did not exceed 20 ppt and Greenwood et al. (2008) found highest abundance in areas that ranged from 5-29 ppt in salinity levels.

Another important environmental variable that has been documented to influence adult blue crab distribution and abundance is water temperature. Blue crabs are a ubiquitous species and are able to tolerate a wide variety of temperature ranges. The species is normally found in a wide range of climates where temperatures range below 10 ºC in the winter to 30 ºC in the summer. Populations in colder regions (Atlantic blue crabs) thrive in colder climates by overwintering in the muddy bottoms (Schaffner et al, 1988). However, blue crabs in Texas have not been documented to overwinter and continue growth in all seasons as temperatures rarely drop below 15 ºC (GSMFC, 2015). Perry (1975) found higher adult blue crab catch rates were associated with water temperatures between 20 – 25 ºC. Buskey et al. (2015) found that although adults were able to tolerate a wide variety of temperatures, growth did not occur when temperatures dropped below 9-11 ºC. Copeland and Bechtel (1974) found the optimum temperatures for adult blue crabs to be between 10-35 ºC for populations in the Gulf of Mexico and on the Atlantic coast.

Adequate levels of dissolved oxygen (DO) are known to be a requirement for any organism using oxygen to survive. The studies that focus on identifying threshold levels for blue crabs have found blue crabs are a tolerant species, but do not survive in hypoxic areas (i.e. in areas where DO < 2 $mg \cdot L^{-1}$). Rabalais et al. (2001) and Eby and Crowder (2002) found that adult blue crabs avoided or migrated from areas with oxygen concentrations lower than 2 $mg \cdot L^{-1}$. With 2 $mg \cdot L^{-1}$ being the minimum threshold for blue crab observations, Eby and Crowder (2002) also found that values above 6 $mg \cdot L^{-1}$ were associated with higher adult blue crab abundance.

Lastly, there have been very few studies that have investigated the influence of turbidity on adult blue crab populations. However, Lunt and Smee (2014) found that blue crabs and similar invertebrates were most abundance in areas where turbidity was greater than 30 nephelo-metric turbidity units (NTU). Abundances were compared above and below 30 NTU because that level is known to effect vision of marine organisms (Minello et al. 1987; Sweka and Hartman 2003). Similar studies for comparison to this threshold are not well documented; the analysis for this study will be dependent on the results provided by Lunt and Smee (2014).

Studies investigating the interaction between a habitat and a commercially valuable species generally suggest that the habitat has a positive impact on the abundance and distribution of a species, but many suspect environmental and unique spatial characteristics of the region have important contributions towards the relationship. The information provided in this section is aimed to frame the following analysis for the goal of allowing scientists and managers to maintain the ecological health of a fishery and to provide information to allow for adaptive management strategies. The model proposed in this thesis will be built upon suggested relationships of blue crabs with environmental factors and the habitat with the aim to determine the relationships within economically valuable bays and species in Texas.

3. THEORETICAL FRAMEWORK

Following the habitat-fishery model described in Barbier and Strand (1998), a modified standard open access fishery model is used to account for the production of blue crabs and the seagrass as nursery and habitat. This model defines X_t as the stock of blue crab in the fishery measured as biomass, therefore changes over time in the stock of blue crabs can be represented as

(1) $$X_{t-1} – X_t = F(X_t, S_t) – h(X_t, E_t),\ F_X > 0,\ F_S > 0$$

where $F(X_t, S_t)$ describes the biological growth for the blue crab stock and $h(X_t,E_t)$ captures the annual harvest, which is assumed to be a function of the blue crab stock and the fishing effort, E_t. In the modified biological growth function, habitat (i.e. seagrass) enters the growth function and assumes to represent a positive component for the fishery, given that seagrass serves as habitat, breeding, and nursery grounds for the blue crabs (Jackson et al., 2001). It is thus assumed that the influence of the seagrass on growth is positive (i.e. $\partial F/\partial S_t = F_S > 0$).

Similar to Barbier and Strand (1998), we also assume that this model follows the Schaefer – Gordon bioeconomic model. Hence, harvest can then be represented by the following equation:

(2) $$h_t = qX_tE_t,$$

where q is the constant catchability coefficient. Assuming the logistic growth function for the blue crabs and $h(X_t,E_t)$ with equation 2, yields the following expression for the change in blue crab stock:

(3) $$X_{t+1} – X_t = [r(K(S_t) – X_t) – qE_t]X_t\,,$$

where r is the intrinsic growth of blue crab at each period, K is the environmental carrying capacity and the S_t is the seagrass (i.e.) habitat area, which has a positive influence on the carrying capacity ($K_S > 0$). Adjustment in fishing efforts between the two periods can be specified as in equation 4:

(4) $$E_{t+1} - E_t = ø[ph(X_t,E_t) - cE_t],$$

where ø represents the adjustment coefficient, p represents constant blue prices per unit of blue crab harvested, and c is the unit cost of effort. Equation 4 suggests that fishing effort for the next period of time will adjust based on a net profit made during the current time period.

In a standard open access fishery, the long-run equilibrium is achieved when fishing effort and blue crab stock do not change over time (i.e., $X_t = X_{t+1} = X;\ E_t = E_{t+1} = E$). In addition, it is assumed that the seagrass is also in long-term steady-state equilibrium (i.e. $S_t = S_{t+1} = S$). Also, the steady-state open access fishery implies economic profits are fully dissipated and fishers make zero profits. Using these assumptions, equations (3) and (4) can be solved for the steady state stock (X) and effort level (E) as follow:

(5a) $$X = \frac{c}{pq}, \text{ for } E_{t+1} = E_t = E.$$

(5b) $$E = \frac{r(K(S) - X)}{q}, \text{ for } X_{t+1} = X_t = X.$$

An important objective for this study is to determine the effect of the seagrass on blue crab productivity. By assuming the seagrass area to have a proportional relationship with carrying capacity (i.e. $K(S) = \alpha S$, $\alpha > 0$), Barbier and Strand (1998) show that the steady-steady relationship between the harvest and the seagrass can be represented by the following equation (6)

$$h = qEK(S) - \frac{q^2}{r}E^2 = (q\alpha)(E \times S) - \left(\frac{q^2}{r}\right)E^2,$$

where the harvest is the function of the interaction between effort and seagrass ($E \times S$) and effort squared (E^2). Since parameters q, α and r are constant they can be recovered from the empirical estimation of this model specified as:

(7) $$h = \beta_0 + \beta_1 (E \times S) + \beta_2 E^2 + u,$$

where β_0 is the intercept, β_1 is the slope coefficient such that $\beta_1 = q\alpha$ and $\beta_2 = \frac{q^2}{r}$, and u is an error term. Estimating this model requires the data on fishing effort (E), total harvest and the area of seagrass.

Fishing effort data for the study area were not available and in order to quantify the relationship between the seagrass and the catch levels, the equation (7) was modified in a way that the dependent variable represents the catch per unit effort (CPUE), which depends on the area of the seagrass and various environmental variables identified in the literature (e.g. temperature, salinity, dissolved oxygen, and turbidity). The final model is thus given as:

(8) $$CPUE_{it} = \beta_0 + \beta_1 (\mathrm{SAV}_{it}) + \beta_2 (\mathrm{Temp}_{it}) + \beta_3 (\mathrm{Sali}_{it}) + \beta_4 (\mathrm{DO}_{it}) + \beta_5 (\mathrm{Turb}_{it}) + \mu_t + e_{it},$$

where $CPUE_{it}$ represents the catch per unit effort in location i at time t, β_0 is an intercept, β_1 captures the effect of SAV on $CPUE_{it}$, β_2 captures the effect of temperature on $CPUE_{it}$, β_3 captures the effect of salinity on $CPUE_{it}$, β_4 captures the effect of dissolved oxygen on $CPUE_{it}$, β_5 captures the effect of turbidity on $CPUE_{it}$, μ_t is the time specific unobservables that are common across areas such as state-wide policy change related to habitat conservation or catch regulation, and e_{it} is the random error term.

It is expected that blue crabs would prefer lower salinities (5-15 ppt), thus increased levels of salinity is expected to having a negative effect on the average CPUE. Blue crabs have a preference for warmer waters; its effect is hypothesized to be positive on average CPUE. Turbidity is expected to first have positive effects, as blue crab prefers turbid environments, but then expected to have a negative effect once it reaches a threshold that would diminish water quality. Lastly, SAV and DO are expected to have positive effects on average CPUE, as increases in these variables provides more seagrass habitat and higher amounts of oxygen in the aquatic environment.

4. STUDY AREA AND DATA

Study Area

The study area expands along the southern coast of Texas, covering five highly productive bays in the State (Figure 4). Nearly 95% of the total area of seagrasses are found within these selected bays (TPWD, 1999). Of the approximately 235,000 acres (1994 estimates), 4.6% is found in San Antonio Bay, 3.4% is found in Aransas Bay/Copano Bay, 11.2% is found in Corpus Christi Bay, 28.6% is found in the Upper Laguna Madre Bay, and 50.5% is found in the Lower Laguna Madre Bay (TPWD, 1999).

The northern of the five bays, San Antonio Bay, Aransas Bay, and Corpus Christi Bay are supplied with freshwater inflow coming from large rivers (Guadalupe and San Antonio Rivers) (USGS, 2001). However, the southern bays, Upper Laguna and Lower Laguna Madre Bays are supplied with limited amounts of freshwater from Arroyo-Colorado River (Tunnell, 2002).

Average depth within Texas bays range between 1-3 meters, with exceptions from dredged inlets and Gulf Intracoastal Waterway. Due to their shallow depths, most mixing occurs primarily through wind, except for tidal mixing that occurs near inlets (Solis and Powell, 1999). The average salinity within the bays are around 35 ppt, but increase > 50 ppt in areas of the Laguna Madre Bay Systems (hypersaline environments). This is due to a strong precipitation gradient and higher freshwater inputs in the northern parts of Texas and decreasing in the southern parts of Texas (Texas Aquatic Science, 2013).

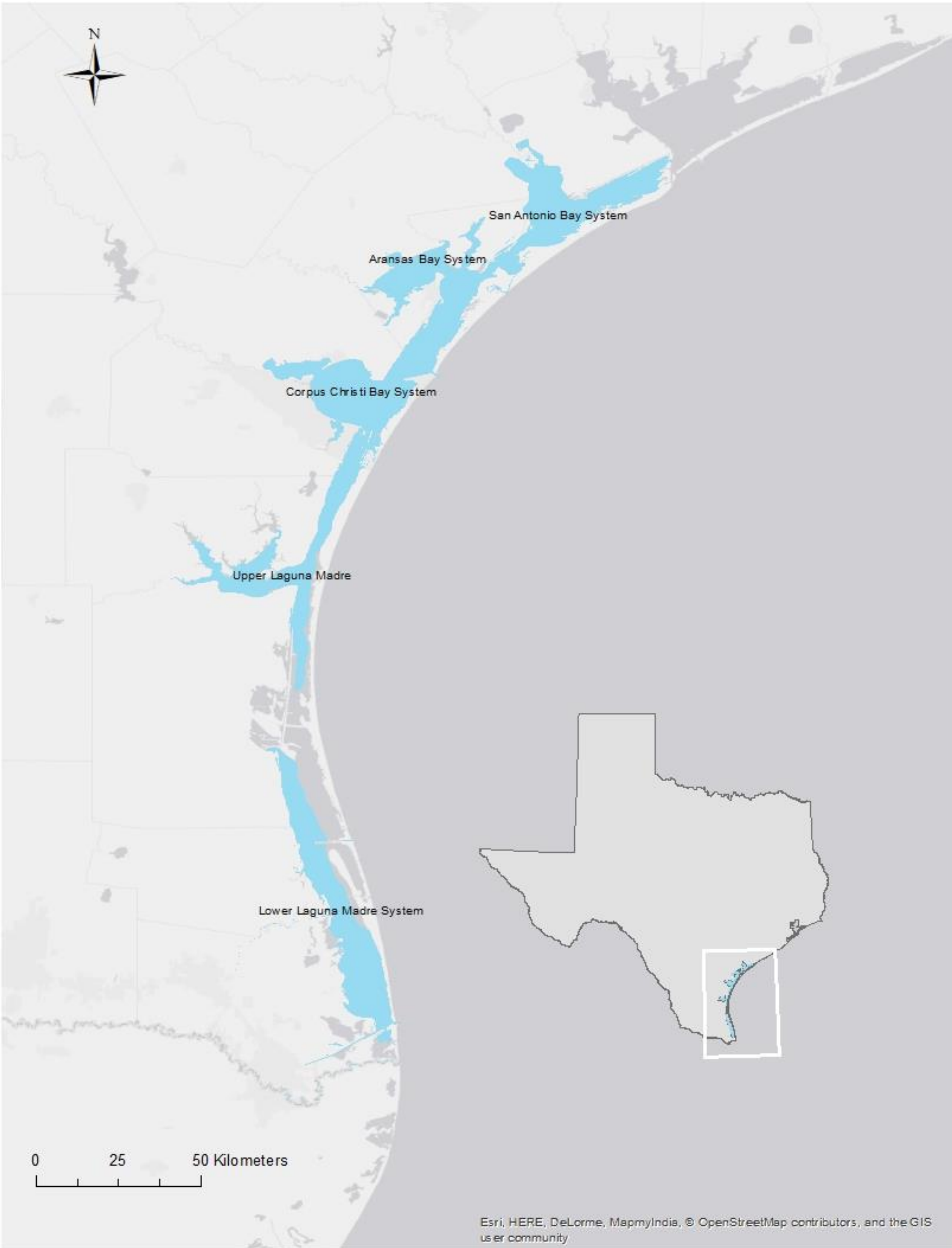

Figure 4. Study area along the Texas coastline

Data Description – Submerged Aquatic Vegetation

Five subtropical species of seagrass is found in Texas coastal waters, (1) *Halodule wrightii* (shoal grass), (2) *Thalassia testudinum* (turtle grass), (3) *Syringodium filiforme* (manatee grass), (4) *Halophila engelmannii* (star grass), and (5) *Ruppia maritima* (widgeon grass). All of these species are perennial; growth occurs during late spring and early summer with dormancy occurring in the winter. These species were annually monitored based on recommendations of the Texas Seagrass Monitoring Plan (TSMP). Using methods described in Neckles et al. (2012), seagrass coverage data was collected using rapid assessment sampling techniques (i.e., using semiquantitative metrics and best professional judgement to classify a condition based on field observations).

Data collection took place in fixed stations within each bay, which were originally created from NOAA's program, 2004/2007 Benthic Habitat Mapping. The 2004/2007 Benthic Habitat Mapping program overlaid areas with tessellated hexagons. Seagrass sampling stations were selected within hexagons that contained > 50% seagrass. Once a hexagon was selected, a random number generator was used to determine latitude and longitude coordinates of the sampling station. A total of 567 permanent stations were assigned using this design method.

Sampling was conducted during peak biomass times, from late summer to early fall. Once at a sampling station, an experienced technician would visually assess seagrass percent cover within a 25 m^2 quadrat frame. Four replicates were taken around the boat as Neckles et al. (2012) found that using a 25 m^2 quadrat frame was sufficient in order to obtain mean percent cover ± 5% of the true mean 80% of the time and ± 10% of the true mean > 99% of the time.

Data Description – Texas Blue Crab

Blue crab collections were conducted by the TPWD Coastal Fisheries Division using a 6.1-m trawl with a mesh size of 38 mm. Monthly samples were taken during the first and second half of each month. Larger bays (San Antonio Bay, Aransas Bay, and Corpus Christi Bay) were divided into two zones and smaller bays (Upper Laguna Madre and Lower Laguna Madre) were left as a single zone. Grids of one minute latitude and one minute longitude were created within each zone. Ten randomly selected grids were selected for sampling each month. A grid that was not accessible by boat (< 1 m of water) or contained obstructions were not sampled; instead an adjoining grid selected at random was selected. Grids were not duplicated within each month.

Once on site, environmental variables were collected first. A datasonde (YSI or equivalent) collected water temperature (ºC), salinity (ppt), dissolved oxygen ($mg \cdot L^{-1}$), and turbidity (NTU). Trawls were towed at 3 mph in a circular pattern for a targeted 10-minute period (actual duration was recorded) in order to keep prop-wash out of the tow and to stay within the selected grid. Organisms caught were identified to the lowest possible taxonomic level and were measured. Up to 35 blue crabs were measured (mm) from tip to tip of lateral spines. Using catch number and tow times, CPUE was collected for each trawl.

Ideally, commercial harvest and effort data would have been a preferred dataset for this analysis, but effort data was not available for all bays due to confidentiality constraints. However, in the absence or limitations of commercial datasets, it is common in the literature to use fishery-independent data as it provides good abundance estimates (Pennino et al., 2016).

5. METHODS

Spatial Analysis Using GIS Software

In order to determine the relationships presented in this thesis, datasets from TPWD and TSMP were organized first within Microsoft Excel and then entered into Geographic Information System (GIS) software. ArcMap 10.5 was used to spatially reference the point locations for seagrass percent cover and trawl locations; both datasets provided latitude and longitude coordinates where collections occurred. Using the Project Tool, the layers were projected into the NAD 1983 Texas State Mapping System, as the study area expanded across much of the Texas coastline. Shapefiles were created for each year (2011-2015) for SAV and catch data.

A shapefile obtained from TPWD containing all the major bays of Texas was used as a mask for the analysis. This layer was also projected to NAD 1983 Texas State Mapping System.

Since the SAV point data was used to represent percent cover as a snapshot of seagrass around the surrounding area, predictions of the surrounding areas were needed. Various interpolations techniques were explored to determine the most consistent and reliable method. Rasters using inverse distance weighted (IDW), spline, and Kriging techniques were first compared with the real SAV data points. Seagrass habitats are characterized as having high natural variation; its distribution can be altered by changes in the biological, chemical, and physical environment (Greve and Benzer, 2004). Therefore, spline interpolations would not be appropriate as is best used for smooth datasets (Childs, 2004). An IDW method was also not deemed appropriate for this dataset as points were not dense enough to capture local variation (Childs, 2004).

In order to determine if Kriging interpolation was an appropriate method for the SAV dataset, certain conditions were evaluated using the Explore Data function within Geostatistical Analysis. Although violations of the Kriging assumptions were apparent, they were addressed using a Universal Kriging technique. A Kriging interpolation was found to be most appropriate for this dataset as it assumes that the distance and direction between points reflects spatial correlation (Childs, 2004).

The Extract by Mask Tool was used to extract the interpolated SAV values using the major bays shapefile. The resulting layer was overlaid with a "grid" in order to assess changes over time using the defined and spatially fixed zones. The zones were created to span the study area, with each zone covering 625 km^2 (Figure 5). Zones were selected only if seagrass collections were taken within the defined area, therefore years 2011-2014 contain less zones. Efforts during 2015 were increased so that additional collections were taken in the San Antonio Bay System. The SAV and catch shapefiles were then spatially joined to the grid shapefile by summarizing the attributes so that each zone contained the average SAV percent cover, catch, CPUE, and the averages of select environmental variables. This approach was taken to best represent the average SAV habitat within each zone and identify relationships between catch and CPUE within the same zones. Figure 6 provides an example of approximating average SAV percent cover from interpolated values. Lastly, the attribute table of the combined average SAV and average catch data was converted into a Microsoft Excel file using the Table to Excel Tool.

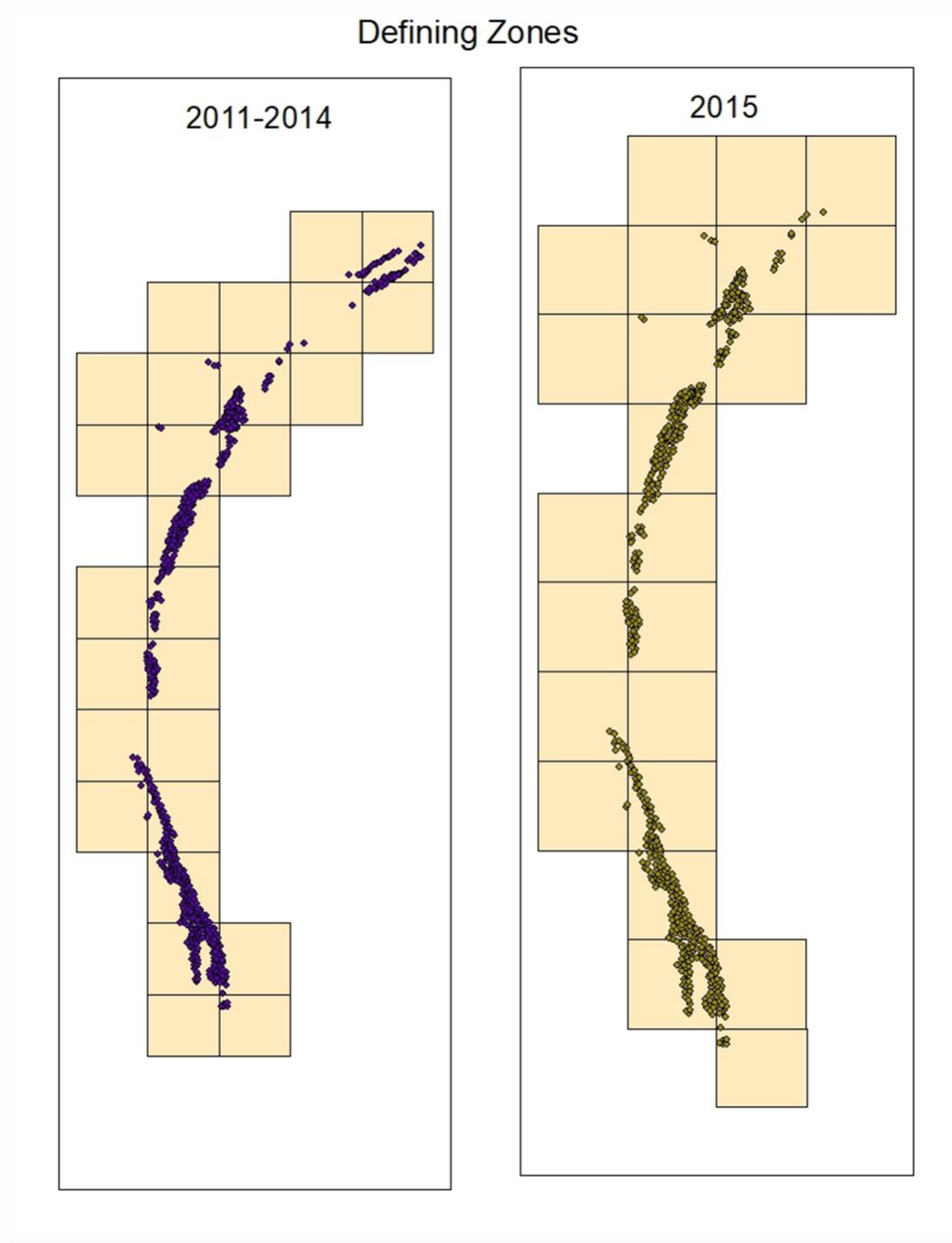

Figure 5. Zones overlaying the study area for 2011- 2014 and 2015

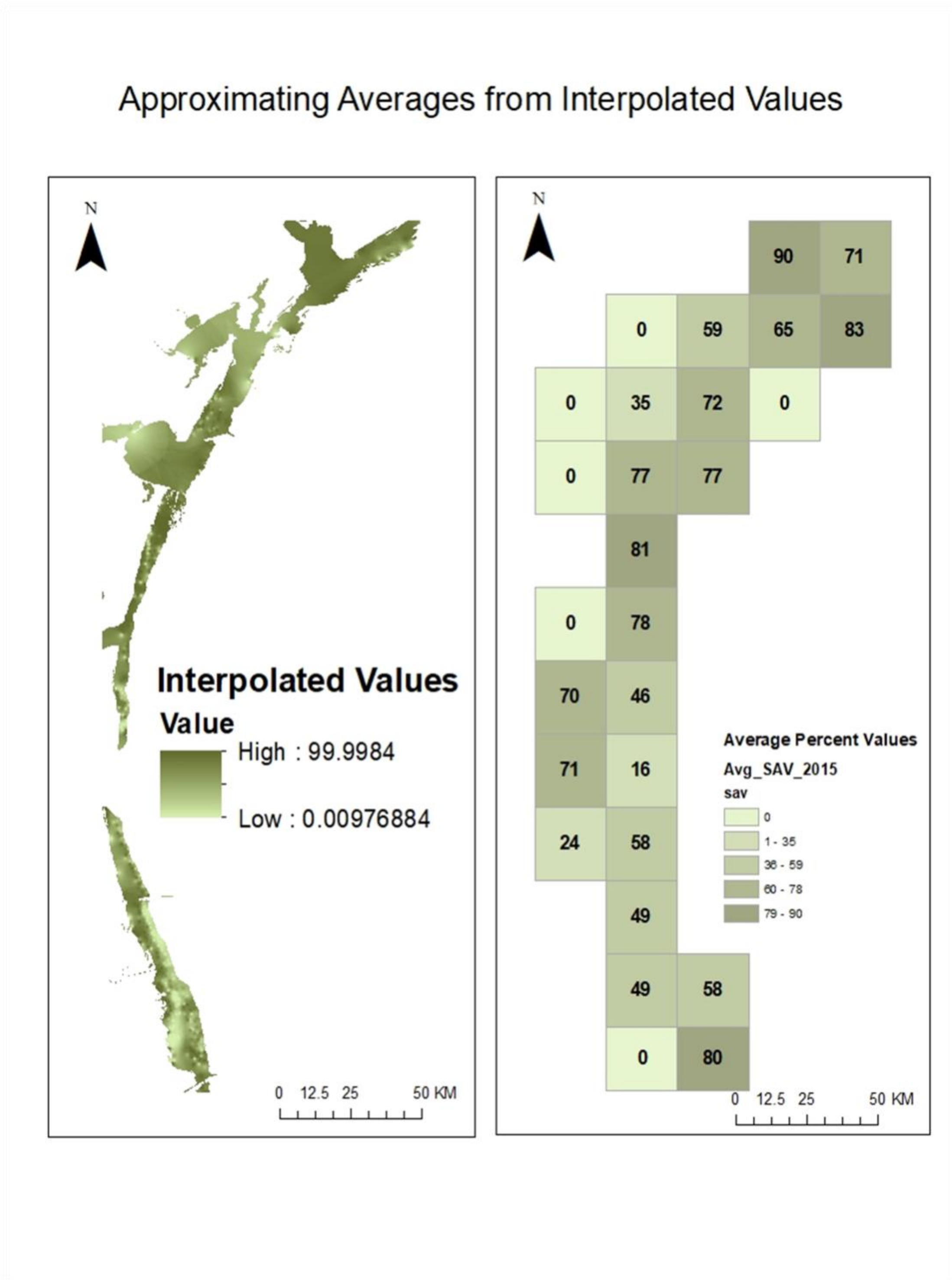

Figure 6. Estimated average SAV percent cover from interpolated values

Statistical Analysis

Stata 14.2 software was used to estimate the effects of seagrass habitat and environmental stressors on blue crab CPUE (equation 8). An ordinary least squares (OLS) regression was estimated on the combined years panel dataset. This method allowed for the estimation of linear and nonlinear relationships between the independent variable (CPUE) and explanatory variables (SAV habitat and environmental stressors), assuming the variables are uncorrelated with the error term (exogenous) and errors are uncorrelated across observations.

To capture nonlinear effects from the environmental variables square terms were created for those that were assumed to contain diminishing effects with a one-unit increase of the independent variable. The environmental attributes that may exhibit diminishing effects include temperature, salinity, and turbidity; these variables may indicate a change in sign once a threshold is met. An additional model including these squared terms was estimated to address potential effects.

Last, dummy variables for year controls for any potential time varying effects that could affect catch in all in a similar fashion such as state-wide habitat and catch regulation. In a separate specification, we also include bay-specific fixed effects to account for time invariant differences across bays. To ensure variables were not highly correlated, checks for correlation and multicollinearity were also performed.

6. RESULTS

Table 2 reports the summary statistics for each variable used in the analysis, along with their hypothesized effects. The time trend for the average CPUE indicates that years 2011 and 2015 of the study time frame have outlier CPUE observations while average CPUE did not show much variability from 2012-2014 (Figure 7). The distribution of the average CPUE (avg_CPUE) over the study time frame (2011-2015) is presented in Figure 8. As shown, CPUE is highly skewed to the right with, which is also indicated by a positive skewness coefficient of 3.04 and a kurtosis of 14.33. The mean for the average CPUE for all years is 5.44 with a standard deviation of 8.2 and a median of 3.1.

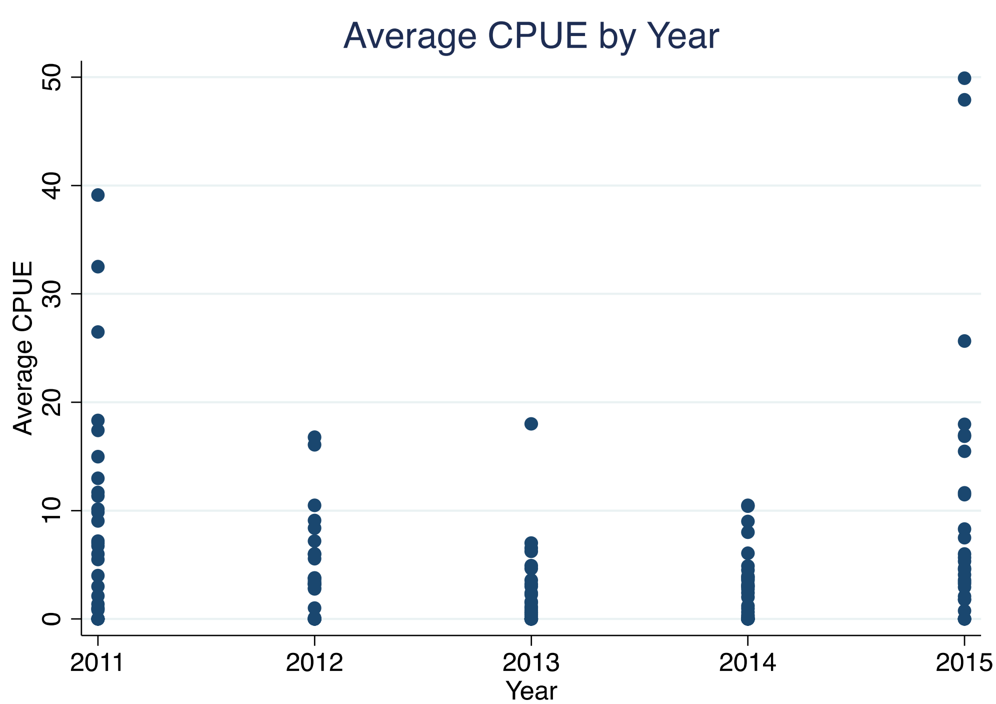

Figure 7. Average CPUE within the study time frame, 2011 - 2015

Table 2. Summary statistics and hypothesized direction of effects

Variable	**Definition**	**Effect**	**Mean**	**Std. Dev.**	**Min**	**Max**
Avg_CPUE	Average #catch/hour (CPUE) within zone	NA	5.44	8.20	0	49.90
Avg_SAV (%)	Percent average SAV within zone	+	36.19	34.47	0	96
Avg_Temp (ºC)	Average temperature within zone, Celsius	+	18.99	9.26	0	28.5
Avg_Sali (ppt)	Average salinity within zone, parts per thousand	–	25.96	14.26	0	61.01
Avg_DO ($mg \cdot L^{-1}$)	Average dissolved oxygen within zone, milligrams/liter	+	5.55	2.74	0	8.18
Avg_Turb (NTU)	Average turbidity within zone, Nephelometric turbidity unit	+/-	13.90	15.50	0	158.67
Avg_Catch	Average blue crab catch within zone	NA	.91	1.37	0	8.33

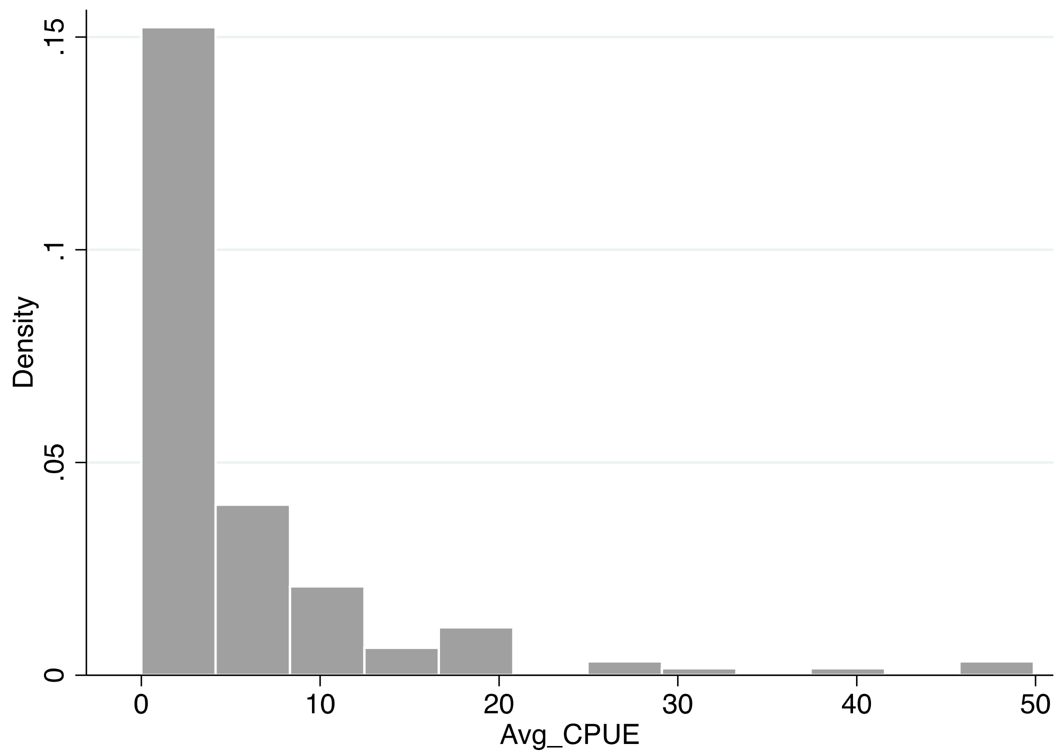

Figure 8. Distribution of average CPUE for all years (2011-2015)

To assess differences in average CPUE throughout the sample time frame, Table 3 reports the means of average CPUE by year and are displayed graphically in Figure 9. The lowest mean average CPUE corresponds to year 2013, where mean average CPUE is 2.33. The highest mean average CPUE corresponds to year 2015, where mean average CPUE is 9.32. A oneway ANOVA model, testing for the difference between the means of each year, appeared to be significant at a 1% level (see Appendix).

Table 3. Mean average CPUE by year

	2011	2012	2013	2014	2015
Mean Avg_CPUE	8.65	4.00	2.33	2.93	9.32

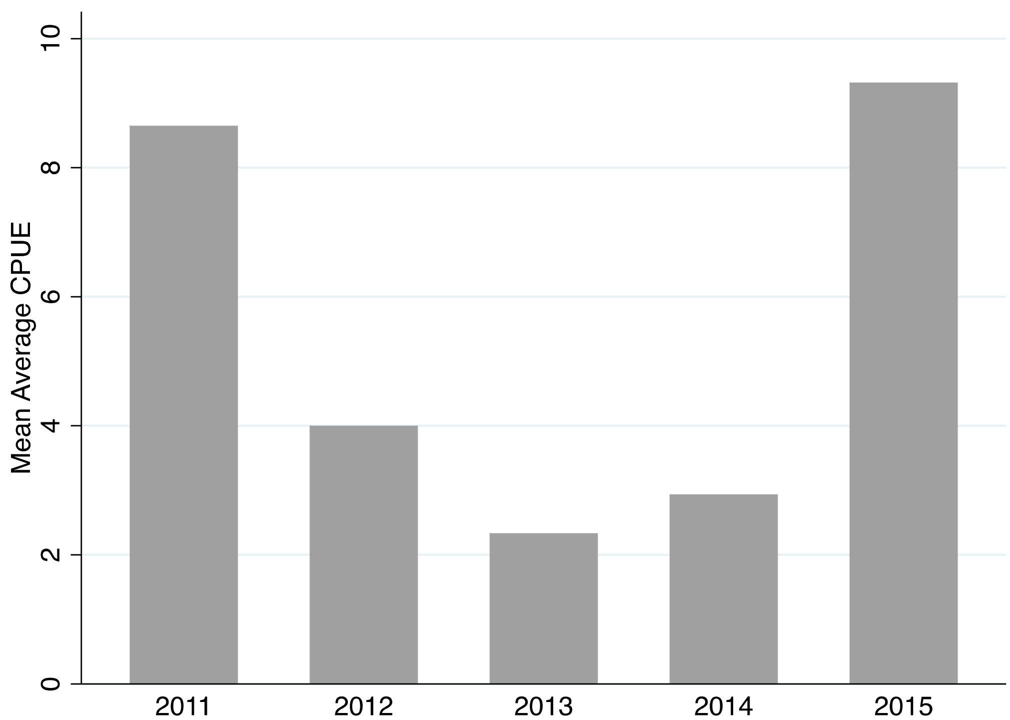

Figure 9. Mean average CPUE for 2011 - 2015

Trends for each dependent variable were compared with average CPUE that resulted in high values of average salinity associated with low values of average CPUE. Table 4 reports the means of the average salinity levels for all years. For comparison, Figure 10 displays the years with the lowest mean average CPUE (2013 and 2014) are also found to have the highest mean average salinity.

Table 4. Mean average salinity by year

	2011	2012	2013	2014	2015
Mean Avg_Sali	25.72	26.73	28.58	27.96	20.80

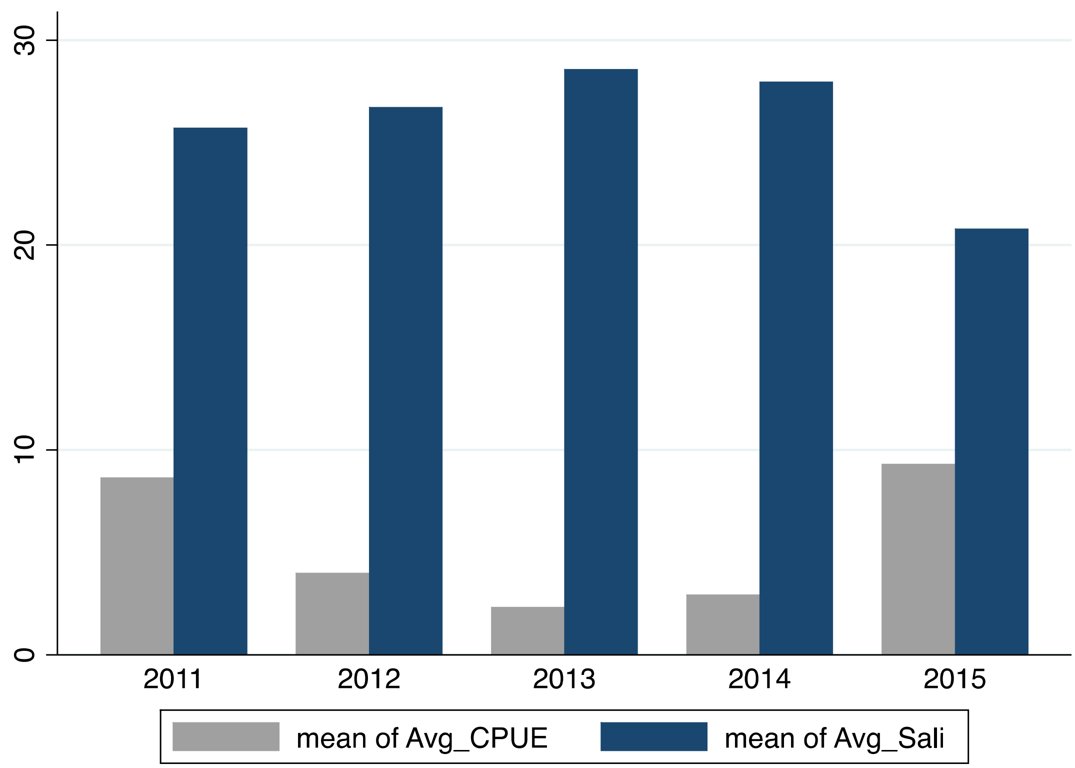

Figure 10. Mean average CPUE and mean average salinity for 2011 - 2015

To assess for visual relationships between environmental stressors and the average CPUE, Figure 11 was generated. The only variable that showed a relationship with average CPUE was average SAV. Although weak, the graph shows a slight increase in average CPUE with an increase in seagrass habitat.

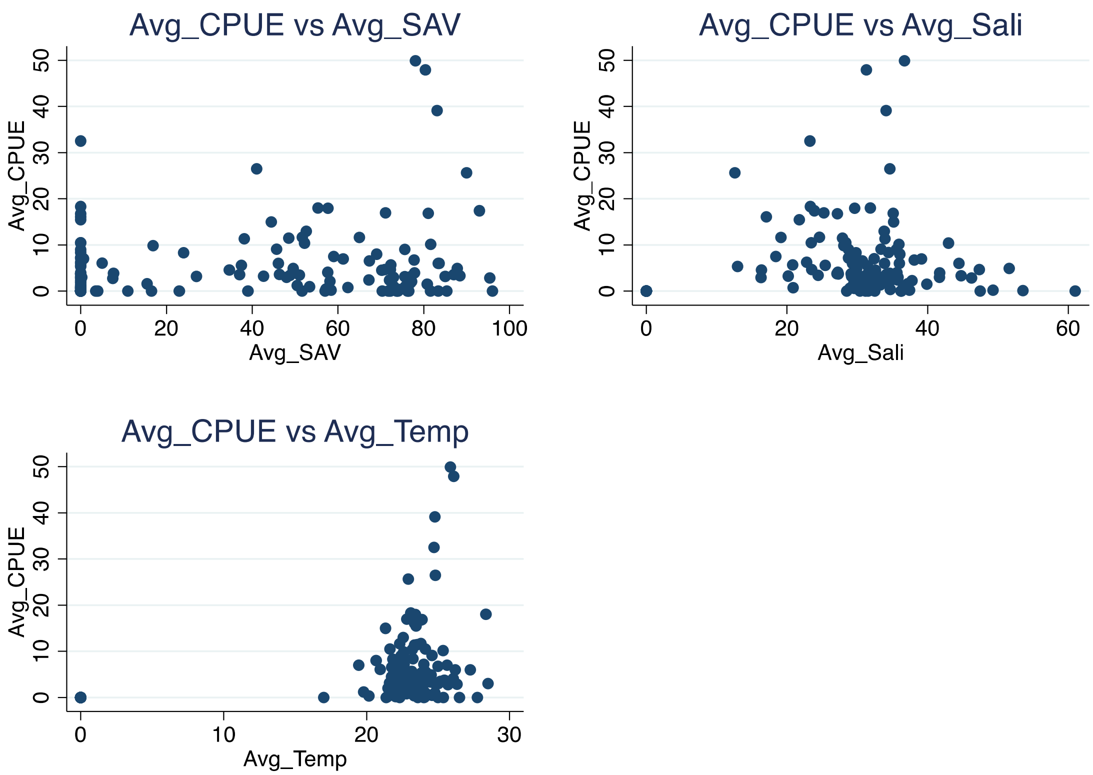

Figure 11. Assessing visual trends of average CPUE with average SAV, salinity, and temperature

Table 5 reports OLS regression results, with one, two and three asterisks indicating statistical significance at 10%, 5% and 1% significance levels, respectively. In parenthesis are also reported standard errors which are heteroscedasticity robust standard errors. In column (1) results are reported from the model in which average CPUE is the function of the average SAV habitat, salinity, and turbidity. Model results reported in column (2) in addition to main model variables specified in column (1) also includes year dummy variables, with the year 2011 being the omitted category. Column (3) also controls for bay-specific dummies, we omit San Antonio Bay and the coefficient estimates show the effects relative to that category.

Results from collinearity reports indicate three explanatory variables to be highly correlated to one another (see Appendix). Temperature and DO were found to be highly correlated (0.94) and had VIF values > 10. Temperature and salinity were also found to be highly correlated (0.87) and had VIF values > 10. These correlations are not a surprising factor as DO, temperature, and salinity are biologically dependent upon one another (Davis, 1975). Therefore, Table 5 displays results with DO and temperature excluded from the models.

The results from column (1) show that average SAV and average salinity have statistically significant effects on average CPUE with expected signs. Specifically, the coefficient associated with the average SAV was found to be significant at the 10% level and indicates a positive effect on the average CPUE. Average salinity was also significant at the 10% level as having a negative effect on the average CPUE.

In model (2), after controlling for year-specific dummy variables, the effect of SAV habitat on CPUE remained positive and continues to indicate its effects as statistically significant at the 10% significant level. While maintaining a negative effect on average CPUE, average salinity is reported as highly significant at a 1% significance level. As for year fixed effects, estimated effects show that on average CPUE has declined overtime relative to 2011, however only years 2012, 2013, and 2014 were statistically significant.

Results from the 3rd model, with additional bay-specific fixed effects show that SAV while remains positive loses statistical significance. This is not surprising given that we employ average SAV measures, which are less variable across bays, making identification challenging with bay-specific dummy variables in the model. Importantly, the effects of salinity on CPUE remains highly significant at less than 1% significance level with an expected sign. CPUE exhibits overall decline over year with years 2012, 2013, and 2014 associated with statistically lower ($p<0.01$) catch levels relative to 2011. All else held constant, CPUE was statistically high (however, significance was marginal at 10% level) in the Corpus Christi Bay system relative to San Antonio Bay.

Even with slight differences in the models, the results remain consistent. Results suggest habitat and salinity as having important contributions on the average CPUE in five major bays of Texas. The magnitudes of the coefficients reported for each variable's effects also remain fairly consistent. These results are further discussed in the following section.

Table 5. OLS model results (DO and temperature excluded due to collinearity)

	Model 1	Model 2	Model 3
	Avg_CPUE	**Avg_CPUE**	**Avg_CPUE**
Avg_SAV	0.0432*	0.0276*	0.0306
	(0.0225)	(0.0188)	(0.0204)
Avg_Sali	-0.0557*	-0.1266***	-0.1324***
	(0.0405)	(0.0435)	(0.0440)
Avg_Turb	0.0661	0.0102	0.0053
	(0.0547)	(0.0408)	(0.0381)
2012.Year		-4.7950**	-4.8475**
		(2.0147)	(1.9913)
2013.Year		-6.6092***	-6.6525***
		(1.9130)	(1.8987)
2014.Year		-5.8676***	-5.8928***
		(1.8508)	(1.8602)
2015.Year		1.0528	1.0445
		(2.7612)	(2.7653)
Aransas Bay			0.0464
			(1.8828)
Corpus Christi Bay			-3.4334*
			(1.7449)
Upper Laguna Madre Bay			-1.1191
			(2.3793)
Lower Laguna Madre Bay			-0.3869
			(1.7042)
_cons	1.5194*	4.2648**	4.8504**
	(0.8661)	(1.8919)	(2.1523)
R^2	0.18	0.27	0.31
N	120	120	120

* p<0.1; ** p<0.05; *** p<0.01. Robust standard errors reported in parenthesis

Statistical Diagnostics

An OLS regression was determined to be appropriate for this analysis, as tests for violations of OLS assumptions were determined to be not severe enough to warrant concern. In a test for linearity of model parameters, the resulting observed predicted values indicated symmetrical distribution around the fitted line (see Appendix). A visual inspection of residuals plotted against fitted values of CPUE determined that robust standard errors were needed in order to correct for heteroscedasticity (see Appendix). In addition, a test for spatial autocorrelation was conducted using GeoDa software to examine a spatial autocorrelation of errors across zones. Moran's I value and a visual graph were generated to indicate possible types of spatial autocorrelation if it exists. A value near -1 or +1 indicates spatial autocorrelation in the dataset. The Moran's I value calculated for this analysis was found to be near 0 for combined years and for individual years, indicating no violations or independence of errors in the OLS models. Lastly, inspections for collinearity and multicollinearity (previously discussed) resulted in high correlation among select environmental factors, which were ultimately dropped in the OLS regression analysis.

However, there is evidence in the results that the models did not account for a key variable in the estimation. A Ramsey reset test resulted in an F-statistic of 2.79 and a p-value of 0.04, which led to rejection of the null hypothesis that the model contained no omitted variables. The Ramsey reset test again led to the rejection of the null hypothesis when the temperature variable was included in the regression. One important variable currently missing in the model is effort level due to data confidentiality discussed in data section. Therefore, the results from this analysis should be interpreted with caution.

7. DISCUSSION

The analysis performed in this thesis suggest relationships may exist between blue crab catch, seagrass habitat, and select environmental stressors. Results demonstrate environmental factors, such as salinity, may equally contribute to SAV habitat when estimating their effects on blue crabs along the southern coast of Texas. The results are found to be similar to literature that suggest seagrass habitats may be essential to the blue crab fishery.

Although SAV was found to be significant in Models 1 and 2 (10% significant in both models), the significance was lost when bay effects were included in Model 3. This is most likely attributed to less variation of average SAV habitat when evaluating across several bays; average SAV may thus be correlated with bay-specific fixed effects. It also may be possible that while SAV habitat is utilized by blue crabs, it is not their only habitat. Blue crabs have been documented to occupy a wide variety of habitats, such as intertidal marshes and rocky shores, sandflats, mudflats, and in rivers and creeks that flow into a bay. Since many of these are found along the coast of Texas, it is possible that blue crabs, for at least parts of their life cycles, reside in areas outside of seagrass beds. Whether blue crabs are utilizing seagrasses or an outside habitat, we can draw one very important conclusion: some form of habitat(s) are an essential component to the blue crab fishery in Texas and efforts for restoration and conservation should be taken in order to maintain stocks. Primarily efforts should be concentrated towards seagrass beds as results from this analysis suggest SAV qualifies predominantly as essential habitat to the species.

Efforts towards conservation and seagrass restoration would not only increase blue crab productivity in Texas, but would also enhance commercial and recreational fisheries elsewhere, where stock abundances are linked to SAV habitats. To evaluate welfare implication of seagrass beds, Table 6 reports total revenue loss for the blue crab fishery as a result of declining seagrass beds. Using the SAV coefficient from Model 2 (0.0276), current and historical seagrass coverage estimates, ex-vessel price of crab, and number of fisherman, Table 6 reports the revenue losses from 2011-2015 associated with the annual percent decline of seagrass beds in 4 major regions in Texas (see Appendix for detailed assumptions). However, these calculations should be taken with caution as the economic contributions are accounted as the maximum potential of effort from fisherman throughout the year. In reality, fishermen are constrained to the natural spatial variations of blue crab presence in a bay, which is unfeasible to determine given the data.

Table 6. Total revenue loss associated with SAV loss

Region	% Decline (Historical - Current Estimates)	% Annual Decline	Total Revenue Loss (2011-2015)
Galveston Bay	64.4	1.69	$98,612
San Antonio Bay	14	0.93	$54,101
Coastal Bend Region	8	0.53	$30,749
Lower Laguna Madre	22	1.73	$100,997

Anthropogenic causes are the most commonly attributed to affect seagrasses along the Texas coast (Table 7). These include dredging and its ongoing impacts, nutrient loading, waterfront construction, shoreline development, and propeller scarring. Overall, seagrasses have fluctuated in many of Texas' bays, where they have increased in some areas (Upper Laguna Madre), but have severely diminished in others (Galveston Bay). Impacts have been especially severe in Galveston Bay, where over 95% of the historic seagrass beds have been lost in the bay.

Table 7. Historic and current estimates of SAV

Bay	Historic Estimates (hectares)	Current Estimates (hectares)	Cause
Galveston/Christmas	2,000	210	shoreline development, habitat alteration, nutrient loading, and tropical storms
San Antonio	5,000	4,305	Nutrient loading, dredging impacts, waterfront construction
Aransas	2,871	3,107	N/A
Corpus Christi	2,568	2,570	N/A
Upper Laguna Madre	12,321	22,444	N/A
Lower Laguna Madre	59,153	46,174	Construction of the Gulf Intracoastal Waterway and turbidity resulting from dredge deposits

A drawback to this work is that it only accounts for select life stages of blue crabs. Trawling, the sampling method used in this study, has the capabilities of only collected crabs of a certain size. The mesh sized used by the trawling gear is 38 mm, therefore excluding blue crabs of smaller sizes. Researchers have found that 30 times more juvenile blue crabs are found in areas of grasses than in areas without grasses (Chesapeake Bay Program, 2007). Therefore, juveniles < 38 mm, are not accounted for, which may modify results of the models. However, blue crabs are not allowed to be caught at certain juvenile stage and the model set-up presented in this thesis will not be able to accommodate for age-specific effects. Current regulations allow crabs measured 127+ mm for commercial harvesting and juveniles are commonly classified as <127 mm (Texas Commercial Fishing Guide 2017-2018). Orth and van Montfrans (1987) and Pile et al. (1996) found that blue crab juveniles appeared mostly in grass beds, until they reached a size of 7.5 – 11 mm and then migrated to areas outside the beds. Perhaps if juveniles were included in the analysis and over a time-lag to account for their development, the effect of SAV habitat would increase in magnitude, thus suggesting the habitat's importance mostly during the early life stages of the blue crab.

An important conclusion from this work addresses an ongoing debate among many researchers, whether using fishery – independent data is a good estimation of commercial stocks of a species (Wallace et al, 1998; Murray and Seed, 2010; Beckmann and Hooper, 2015). At least for blue crabs in Texas, CPUE appears to be a reliable index for abundance. Figure 12 shows NOAA commercial landings (pounds) and landing value for blue crabs within Texas during the sample time frame. The lowest mean landings correspond with year 2013 and the highest mean landing corresponds with year 2015. Similar trends were observed (Figure 8) using CPUE as an index in this analysis.

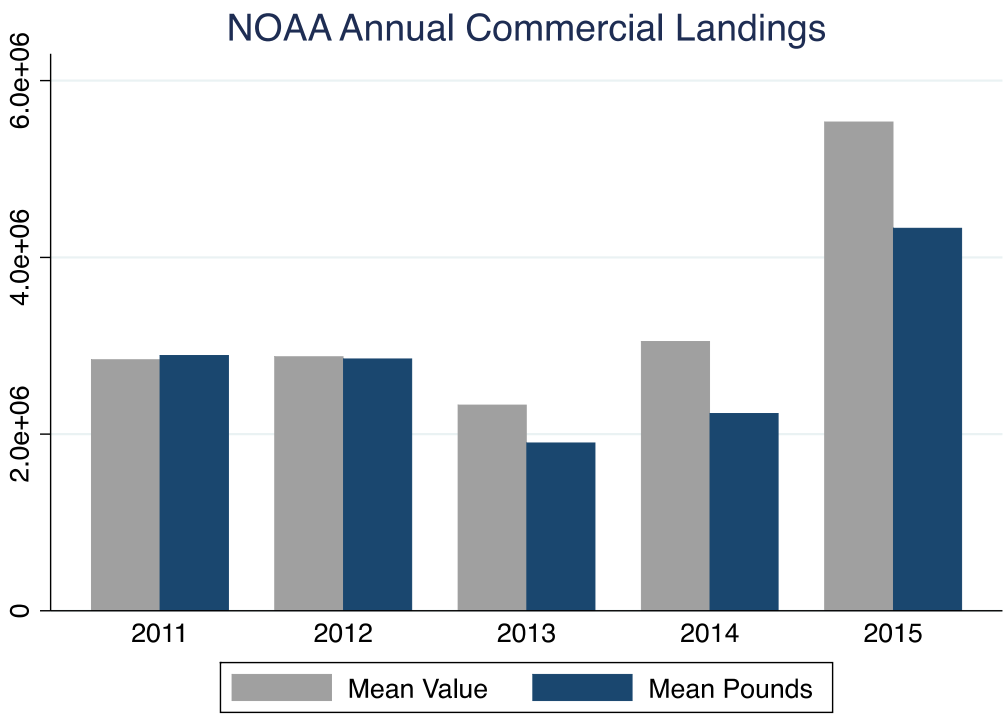

Figure 12. NOAA commercial landings in pounds and value (2011 – 2015)

Perhaps the most valuable finding of this work is the interaction of environmental stressors such as temperature and salinity, which are dependent upon freshwater inflow into Texas bays. Although this study does not directly assess freshwater inflow, the relationship is assumed to be accounted for in salinity's effects on blue crabs. Therefore, it is assumed controlling for freshwater inflow would not alter the direction of the effect of salinity, but would only change the magnitude of salinity's coefficients in the models. This assumption is based on fundamental knowledge that salinity is an indication of the amount of dissolved salts in a system. Therefore, high salinity levels indicate low freshwater supplies and low salinity levels indicate high freshwater supplies. This relationship may attribute to results seen in Figure 9, where in years of low CPUE, salinity was highest (28.58 ppt) and in years of high CPUE, salinity was lowest (20.80 ppt). Within the sample time frame, 2013 corresponded with the lowest blue crab CPUE (mean $CPUE_{avg} = 2.33$). This finding may be attributed to Texas experiencing a particularly dry year from drought conditions (USDM, 2013) (see Appendix for year drought conditions). During episodes of droughts, impacts are predominantly seen in freshwater inflow supplied to bay areas. As the drought ended in 2014 (TWDB, 2017), average CPUE is found to be the highest within the study time frame (mean $CPUE_{avg} = 9.32$). This finding also corresponds to the lowest average salinity (20.80 ppt), where it is assumed freshwater supplies were the highest.

It should be noted that over-fishing was not a factor considered in this work. To remedy historical declines, Texas created a commercial license buyback program in 1998 that limited entry to new crabbers. The success of the program has stabilized effort and has limited concerns of over-fishing blue crabs in Texas.

8. RESEARCH LIMITATIONS

The most notable limitation in this study was absence of information regarding seagrass coverage in areas throughout the bay region. First, sampling methods were concentrated on areas of a bay that were identified as possible restoration sites. Once a site was selected, random sampling in the vicinity was conducted. Therefore, the dataset used for seagrass coverage could have led to misinterpretation of coverage within a bay. In an effort to limit uncertainty, interpolations were conducted using the best interpolation method, Kriging, that was appropriate for the type of dataset. This method allowed for estimations of unknown areas, which were then organized by spatially fixed zones so that observations could be made over time (years).

The outcome from the model design allowed for us to assess the average of the variables within a zone. Therefore, it is essential to acknowledge that variation within the dataset was restricted as variables were reported based on averages over an annual scale.

A second limitation in this study was the use of CPUE as an assessment for blue crab abundance. The alternative approach for estimating abundance is using commercial datasets that contain harvests and effort data. However, effort data was not available for all bays within the study area due to confidentiality purposes. Whenever 3 or few fishermen are licensed within a bay for a single year, TPWD will not release the associated data. Therefore, estimations of abundance were dependent upon trawl collections by TPWD, where CPUE was recorded as catch per hour (tow time of trawl). Since the trawls were consistent in tow times (10 minutes), effort could not be calculated, as it was a fixed time. However, we found that for our dataset, CPUE was a good abundance index as it displayed similar trends with commercial datasets over the same time frame.

Lastly, catch size was a limiting factor, as crabs smaller than 38 mm were unaccounted for due to the mesh size of the sampling gear. Therefore, results and estimates are biased towards blue crabs greater than 38 mm. As a result, we are unable to determine the abundance of juvenile blue crabs that may be utilizing the seagrasses at the larval stage, where literature suggests may be the most important stage for seagrass use.

9. FUTURE RESEARCH

Due to the constraints of this study, future research is recommended to identify habitat-fishery relationships at a smaller spatial scale, where bay characteristics and processes can be examined comprehensively. However, to do this, habitat assessments must be conducted at this same spatial level, where natural variations can be detected spatially and temporally. A disadvantage to this study was that it provided estimates along much of the Texas coastline. These estimates were designed to be snapshots of the annual variation, thereby, providing general coverage in bays where seagrasses are currently found. Although this work was able to suggest that relationships do exists at larger spatial levels, an assessment at smaller spatial levels (e.g. bay level or sub-bays) would further strengthen those relationships and provide necessary information for policy makers for that specific bay region.

To determine the level at which juvenile blue crabs utilize seagrass habitats, I would also recommend future research to conduct assessments on the abundance of juveniles in seagrass areas compared with areas outside this habitat. A study as such would demonstrate the importance of seagrass beds along the Texas coast and how they are utilized as nursery grounds. Although this doesn’t initially provide estimates for harvests levels in the fishery, over a lagged period of one-year time (More, 1965), these juveniles will reach commercial size.

In this study we determined seagrass beds are an essential habitat for blue crabs in Texas. However, blue crabs may also utilize other habitat types found within estuaries in Texas. Identification of these habitats and their use to the blue crab would provide additional knowledge to the degree and life stage at which habitats were most important to the species.

10. CONCLUSIONS

As demonstrated from this study, simply relating a commercially valuable species to its habitat may not be sufficient for maintaining stocks. While seagrasses are regarded as important habitat to blue crabs, and our results show some evidence for that, they are not the only drivers in maintaining populations. Blue crab management plans have been established for several decades, especially in the State of Texas, where blue crabs have remained a valuable economic resource. The most influential management plan for Texas blue crab stocks (G.U.L.F. Texas Blue Crab Action Plan) is comparable to the well-known Chesapeake Bay Blue Crab Management Plan, where the fundamental framework for blue crab fishery management has developed. Similarities between the plan include thorough studies that examine factors which influence blue crab survival, such as predator-prey abundance, environmental parameters (i.e. salinity and temperature), habitat use, hypoxia, disease, and climate change. Current policy measures set forth in the most recent blue crab management plan for Texas point towards regulations regarding commercial and recreational catch limitations, impacts from human activity (i.e. pollution, eutrophication, and alterations in freshwater and sediment flow), and protective measures for habitat loss.

Due to the concern of seagrass habitat loss to the blue crab and several other estuarine-dependent species, a management plan for seagrass beds has recently emerged, the Seagrass Conservation Plan for Texas (SCPT). The Plan was created in 1999 and updated in 2012 with changes and recommendations necessary to the ongoing efforts of seagrass restoration and conservation. A policy recommendation resulted from the 2012 review which led to a Texas law prohibiting the uprooting of seagrasses with an onboard motor propeller. Studies conducted over the past decade saw an alarmingly trend, where motorboat propellers made contact with submerged vegetation that led to damaged areas in the beds. Recovery of the seagrass bed damage from prop scarring is found to take several years. Martin et al. (2008) found *Halodule wrightii* beds recovered in less than 3 years, but *Thalassia testudiunum* experienced recovery up to 10 years (Dawes et al., 1997, Kenworthy et al., 2002). As a result, the law was put into action in September of 2013 and continues to be enforced in all coastal areas of Texas.

Beyond protecting vegetation from boating activity, several agencies in Texas are leading efforts toward seagrass restoration, conservation, and education. Primary stakeholders involved in these projects include TPWD, TGLO, TNRCC, NOAA, TCEQ, United States Fish and Wildlife Services (USFWS), and the Coastal Bend Bays and Estuary Program. Projects led by these entities include monitoring research, establishing protective actions, education, and outreach. The efforts by these leading agencies and non-governmental organizations (NGOs) providing valuable knowledge where proactive solutions appear to be the most appropriate. As stated in SPCT, the highest priority for effective seagrass conservation stems from integrated management actions through research, education, and stakeholder involvement (SCPT, 1999).

With these management plans in mind, the most prominent conclusion from this thesis are the contributing factors identified that effect blue crab populations in Texas. Although this study aimed to represent an ecosystem-based approach in the models, it is limited to just a few interactions within the system. This work serves as a stepping stone for future work, where interactions between socioeconomic factors and additional ecological factors (e.g. freshwater inflow, tidal and wind influence, morphology of the system) should be taken into account. This level of adaptation is best to effectively manage ecosystems so that “bottom up”, “top down”, and mid - level interactions are recognized and managed accordingly.

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APPENDIX A

TABLES

Table A-1. Oneway ANOVA of Avg_CPUE by Year

Summary					
	Number of obs = 120		R-squared = 0.1298		
	Root MSE = 7.7517		Adj R-squared = 0.1058		
ANOVA					
Source	Partial SS	df	MS	F	Prob > F
Model	1299.8569	4	324.96422	5.41	0.0004
Year	1299.8569	4	324.96422	5.41	0.0004
Residual	8712.8926	115	60.088915		
Total	10012.75	119	67.199661		

Table A-2. Correlation Matrix

	Avg_CPUE	Avg_SAV	Avg_Temp	Avg_Sali	Avg_DO	Avg_Turb
Avg_CPUE	1.0000					
Avg_SAV	0.2008	1.0000				
Avg_Temp	0.3504	0.2122	1.0000			
Avg_Sali	0.1903	0.2462	0.8770	1.0000		
Avg_DO	0.3129	0.1186	0.9437	0.8015	1.0000	
Avg_Turb	0.1562	-0.0363	0.4214	0.3901	0.4585	1.0000

Table A-3. Variance Inflation Factors

Variable	VIF	1/VIF
Avg_Temp	15.19	0.065838
Avg_Sali	10.31	0.096989
Avg_DO	4.53	0.220883
Avg_Turb	1.29	0.774660
Avg_SAV	1.14	0.876978
Mean VIF	6.49	

Table A-4. Welfare Loss from Declining SAV

Region	[1]Loss over Time Period (%)	SAV Annual Loss (%)	[2]Annual Decline in CPUE	[3]Annual Total Hours Fished	Year	[4]# Fisherman	[5]Total Catch Loss	[6]Revenue Loss ($)	CPI	Adjusted Revenue ($)	Total Welfare Loss ($)
Galveston Bay	64.4	1.69	0.046644	2631.125	2011	125	15340.77	20,403.23	224.9	21,500.96	98,611.82
				2631.125	2012	118	14481.69	19,260.65	229.6	19,881.42	
				2631.125	2013	103	12640.80	16,812.26	233	17,100.88	
				2631.125	2014	121	14849.87	19,750.33	236.7	19,725.33	
				2631.125	2015	125	15340.77	20,403.23	237	20,403.23	
San Antonio Bay	13.9	0.9267	0.02557692	2631.125	2011	125	8412.01	11,187.97	224.9	11,789.90	54,100.55
				2631.125	2012	118	7940.94	10,561.45	229.6	10,901.84	
				2631.125	2013	103	6931.50	9,218.89	233	9,377.15	
				2631.125	2014	121	8142.82	10,829.96	236.7	10,843.68	
				2631.125	2015	125	8412.01	11,187.97	237	11,187.97	
Coastal Bend Region	7.9	0.5267	0.01453692	2631.125	2011	125	4781.06	6,358.81	224.9	6,700.92	30,748.64
				2631.125	2012	118	4513.32	6,002.71	229.6	6,196.18	
				2631.125	2013	103	3939.59	5,239.66	233	5,329.61	
				2631.125	2014	121	4628.06	6,155.32	236.7	6,163.13	
				2631.125	2015	125	4781.06	6,358.81	237	6,358.81	
Laguna Madre (Lower)	21.94	1.73	0.047748	2631.125	2011	125	15703.87	20,886.15	224.9	22,009.86	100,997.04
				2631.125	2012	118	14824.45	19,716.52	229.6	20,351.99	
				2631.125	2013	103	12939.99	17,210.18	233	17,505.64	
				2631.125	2014	121	15201.35	20,217.79	236.7	20,243.41	
				2631.125	2015	125	15703.87	20,886.15	237	20,886.15	

[1] Data was derived from historical and most current estimates from Table 1. [2] Value was obtained from the SAV coefficient in Model 2 reported in Table 5. [3] Annual total hours fished was calculated from Miller and Nichols (1985), who reported the average number of days crabbed in Texas by season. The number of days in a season was multiplied by the average daylight hours, plus an additional hour since commercial crabbing is allowed 30 minutes before sunrise and 30 minutes after sunrise. [4] The number of fisherman each year was provided by TPWD Coastal Fisheries Division through personal communication. [5] Total catch loss was calculated by multiplying the annual decline in CPUE and the number of fishermen in a given year. [6] Revenue loss was calculated by multiplying the total catch loss and the average price per pound of crab ($1.33).

APPENDIX B

FIGURES

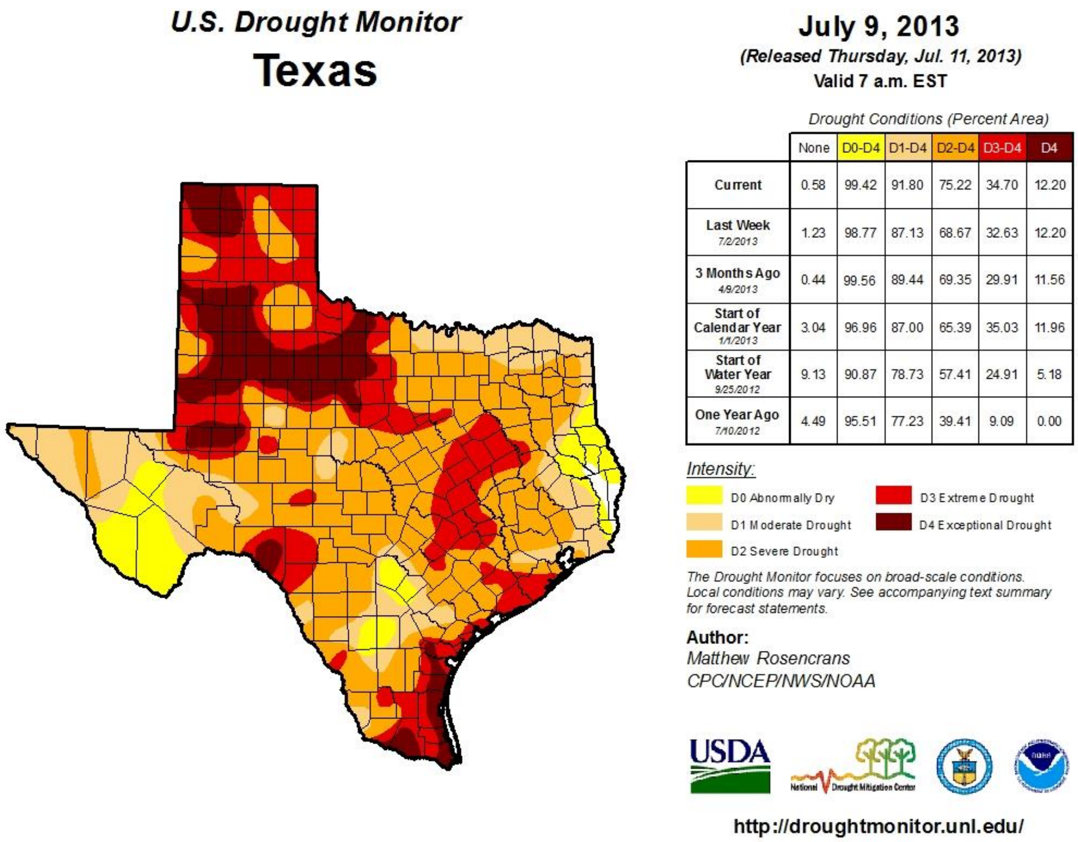

Figure A-1. Texas drought conditions during 2013 (taken from United States Drought Monitor)

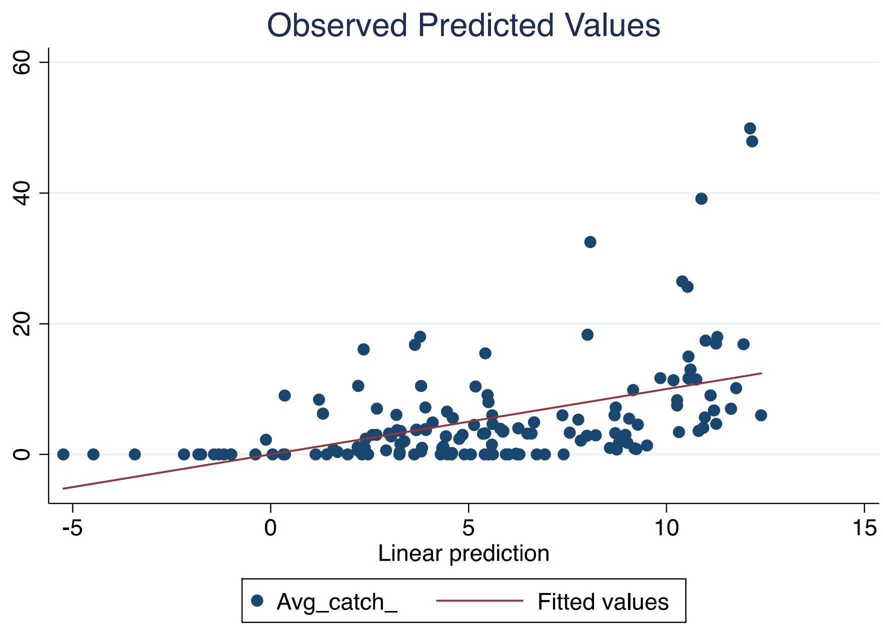

Figure A-2. Plotting observed predicted values

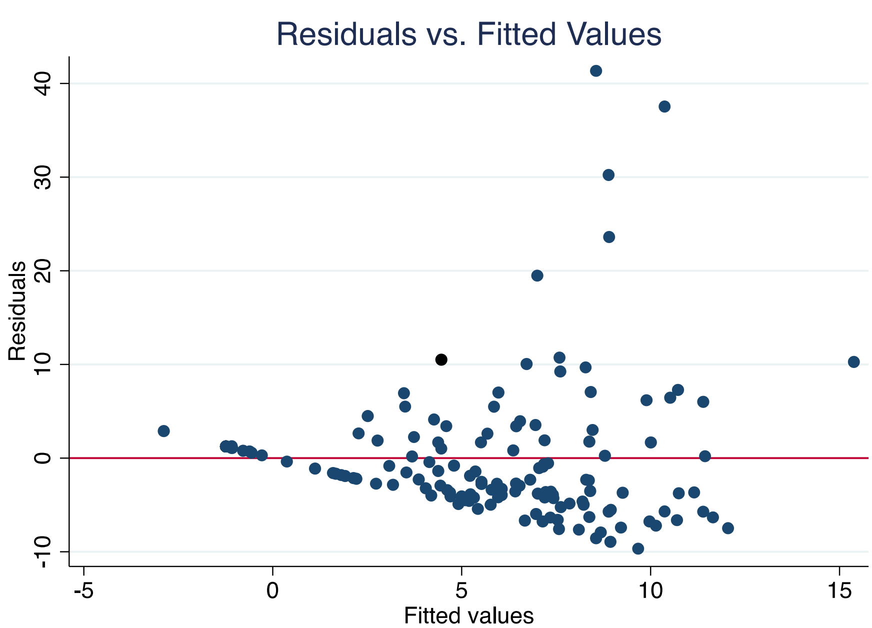

Figure A-3. Plotting residuals vs. fitted values