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2017 Coastal Master Plan

Attachment C3-13: Brown Shrimp, *Farfantepenaeus aztecus,* Habitat Suitability Index Model

DRAFT

Report: Version II

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Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every five years) and annual plans. CPRA's mandate is to develop, implement and enforce a comprehensive coastal protection and restoration master plan.

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Executive Summary

The 2012 Coastal Master Plan utilized Habitat Suitability Indices (HSIs) to evaluate potential project effects on wildlife, fish, and shellfish species. Even though HSIs quantify habitat condition, which may not directly correlate to species abundance, they remain a practical and tractable way to assess changes in habitat quality from various restoration actions. As part of the legislatively mandated 5-year update to the 2012 plan, the fish and shellfish habitat suitability indices were revised using existing field data, where available, to develop statistical models that relate fish and shellfish abundance to key environmental variables. The outcome of the analysis resulted in improved, or in some cases entirely new suitability indices containing both data-derived and theoretically-derived relationships. This report describes the development of the habitat suitability indices for juvenile brown shrimp, *Farfantepenaeus aztecus,* for use in the 2017 Coastal Master Plan modeling effort.

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List of Abbreviations

CPRA	Coastal Protection and Restoration Authority
CPUE	Catch per unit effort
DO	Dissolved oxygen
ICM	Integrated Compartment Model
LDWF	Louisiana Department of Wildlife and Fisheries
SAS	Statistical Analysis Software
SAV	Submerged aquatic vegetation
SI	Suitability Index
TL	Total length

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1.0 Species Profile

Brown shrimp are demersal omnivores that are distributed from Massachusetts to around the tip of Florida and throughout the Gulf of Mexico to the northwestern Yucatan Peninsula (Pattillo et al., 1997). Within the northern Gulf of Mexico, it is distributed throughout coastal waters and estuaries, although it is uncommon or absent along the western Florida coast. Its highest density occurs along the coasts of Louisiana as well as Texas and Mississippi (Allen et al., 1980; NOAA, 1985; Williams, 1984). Louisiana has the second highest abundance of brown shrimp landings and typically accounts for about 30% of the brown shrimp landings in the northern Gulf (http://www.st.nmfs.noaa.gov).

Environmental conditions, habitat degradation, food availability and substrate type are all related to brown shrimp abundance and distribution (Christmas & Etzold, 1977; Herke et al., 1987; Minello et al., 1990; Minello et al., 1989). Suitable estuarine habitat is critical to survival and recruitment of juveniles (Nance et al., 1989; Turner, 1977), and habitat loss may eventually result in declines in recruitment and harvest (Christmas & Etzold, 1977; Nance et al., 1989). Predation and disease (e.g., viral infection) can also reduce populations of brown shrimp (Couch, 1978). Other factors that affect penaeid shrimp population dynamics are nursery area productivity, prey availability, refuge from predation, amount of freshwater inflow, light intensity, tides, and rainfall (Christmas & Etzold, 1977; Pattillo et al., 1997). Changes in microhabitat conditions (e.g., salinity, turbidity, and light conditions) can cause brown shrimp to inhabit non-vegetated areas where early juveniles in particular may be more vulnerable to predation (Minello et al., 1990, 1989; Pattillo et al., 1997).

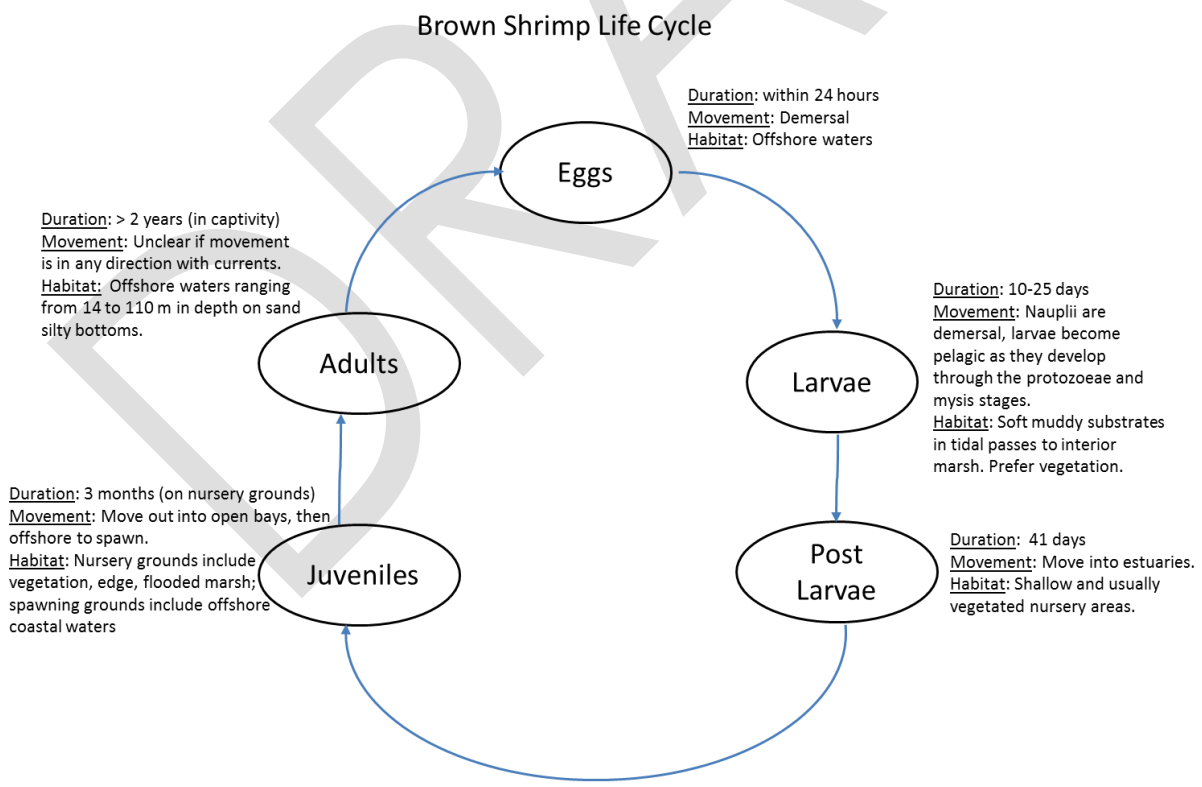

Figure 1: Brown Shrimp Life Cycle Diagram (Pattillo et al., 1997 and references therein).

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Eggs (0.26 mm diameter and demersal; Kutkuhn, 1966) are spawned from spring through fall in off-shore waters, where they hatch and develop into larvae (Christmas and Etzold, 1977; Klima et al., 1982; Figure 1). Larval stages (0.3-4.3 mm) consist of 5 naupliar stages, 3 protozoeal stages, and 3 mysis stages. Shrimp nauplii are demersal and become pelagic as they develop through the protozoeae and mysis stages (Lassuy, 1983). While planktonic, time of day, temperature, and water clarity determine their position in the water column (Kutkuhn et al., 1969; Temple & Fischer, 1965, 1967).

Brown shrimp postlarvae are 4.6 mm – 25 mm total length (TL). At 10-15 mm TL, they are carried into estuaries by tidal currents and migrate to shallow, usually vegetated nurseries (Copeland & Truitt, 1966; King, 1971) from January to June (Zein-Eldin & Renaud, 1986). In the northern Gulf of Mexico, recruitment into estuaries may occur all year (Rogers et al., 1993). Postlarvae can control their recruitment to the estuaries by moving lower in the water column when northerly cold fronts push water out of the estuaries, followed by movement up in the water column during return flow after frontal passage (Rogers et al., 1993). Juveniles (25-90 mm TL) inhabit estuaries, preferring higher saline, flooded marsh and edge habitats where they prey upon infauna. When juveniles are larger than 55-60 mm they move out into open bays and at sizes from 80-100 mm (as sub-adults) they migrate into the coastal waters (Minello et al., 1989). They emigrate to off-shore spawning grounds from May through August, coincident with full moons and ebb tides (Copeland, 1965). It is not clear if there is a net movement of adults in any direction with currents (Cook & Lindner, 1970; Hollaway & Baxter, 1981; Pattillo et al., 1997; Sheridan et al., 1989). Adults (140 mm TL for females) generally inhabit off-shore waters ranging from 14 to 110 m in depth (Renfro & Brusher, 1982).

The spatial and temporal distribution of brown shrimp life stages within the estuary is summarized by a space-time plot (Figure 2), which indicates the relative abundance of each life stage throughout the year for each region: upper, mid, and lower estuary, and inner and outer shelf. These regions are characterized by similar habitats and environmental conditions (Table 1). Generally, the upper estuary is primarily comprised of shallow creeks and ponds with the greatest freshwater input, lowest average salinities, and densest fresh and intermediate marsh and submerged aquatic vegetation. The mid estuary is comprised of more fragmented intermediate and brackish marsh vegetation with salinities usually between 5 and 20 ppt. The lower estuary is comprised mainly of open water habitats with very little marsh, deeper channels and canals and barrier islands with salinities generally above 20 ppt. The inner and outer shelf regions are defined as the open marine waters divided by the 20 meter isobath.

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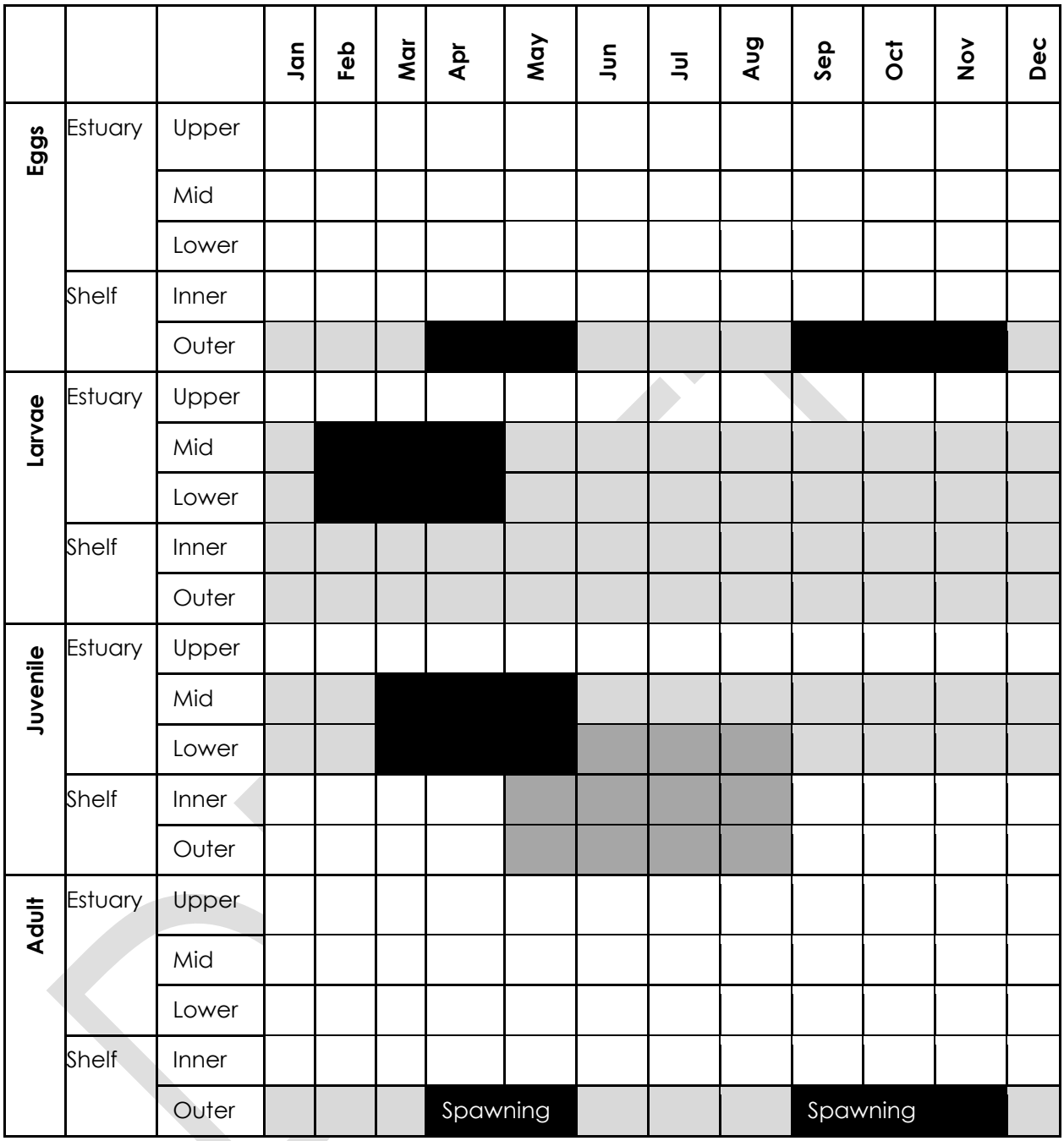

Figure 2: Space-Time Plot by Life Stage for Brown Shrimp Showing Relative Abundance in the Upper, Mid, and Lower Region of the Estuary, and In-Shore and Off-Shore Shelf Regions by Month. White cells indicate the life stage is not present, light grey cells indicate the life stage is at moderate abundance, dark grey cells indicate abundant, and black indicates highly abundant.

Table 1: Habitat Requirements for Brown Shrimp Life Stages. Pattillo et al., (1997), Pattillo et al. (1995), and Zein-Eldin and Renaud (1986) were the primary source used to construct the table and the reader should refer to references therein.

Life Stage: Process	Salinity (ppt) Optimum (Range)	Temperature (°C) Optimum (Range)	Depth (m)	Preferred Substrate	Turbidity	DO (mg/L)
Egg	30-35 (24.1-38)	>24	Demersal	-	-	-
Larvae/ Post-larvae	2-40 (24.1-36; (0.1-69)	(12.6-30.6; Burrow <18)	Planktonic -Pelagic	Soft muddy substrates in tidal passes to interior marsh; prefer vegetation over non-vegetated but do not select vegetation from Dec-Mar	-	-
Juvenile	10-20 (0-45)	(2-38); stressed >32 and <10; growth slow <18	Positively related to depth[a;] Flooded marsh[b,c]	Mostly vegetated area [d,e,f,j] 25-80% of area covered by marsh vegetation[d]	Abundance is reduced in habitats with vegetative structure when turbidity is high because turbidity reduces underwater light levels (i.e., shrimp cannot see vegetation)	1.5 and 2.0 avoided by 65-86 mm juv. mean lethal DO is 0.8 ppm
Adults: Spawning	24-38.9 (0.5-45) 30-35 (24.1-36)	10-37, if acclimated	- 18-137 (46-91)	Do not use vegetation; found off-shore on sandy-silt clay bottoms	- -	< 2.0 ppm = stress; Hypoxia force shrimp in-shore where there is little hypoxia[h,i]

[a] Minello and Webb, 1997; [b] Rozas and Reed, 1993; [c] Minello et al., 2011; [d] Minello and Rozas, 2002; [e] Peterson and Turner, 1994; [f] Minello et al., 1994; [g] Rozas and Minello, 1998; [h] Zimmerman et al., 1997; [I] Craig et al., 2005; [j] Zimmerman and Minello, 1984

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2.0 Approach

The statistical analyses used the data collected by the Louisiana Department of Wildlife and Fisheries (LDWF) long-term Fisheries-Independent Monitoring program conducted for coastal marine fish and shellfish species. The program employs a variety of gear types intended to target particular groups of fish and shellfish; although all species caught, regardless if they are targeted, are recorded in the database. Due to the variable catch efficiency of the gear types, catch per unit effort (CPUE) for key species was estimated as total catch per sample event for each gear type separately. LDWF gears that caught consistent and relatively high abundances of the species of interest over time were used for the statistical analysis.

Data from the 6 and 16 ft trawl and 50 ft seine were evaluated for statistical relationships among the associated environmental data and brown shrimp CPUE. The 6 ft trawls were historically sampled weekly during April through the closing of the spring shrimp season at fixed stations to sample juvenile penaeid shrimp populations in shallow edge habitats in the interior marshes (LDWF, 2002). The current sampling program limits 6 ft trawl sampling to April and June (LDWF, personal communication). The body of the 6 ft trawl is constructed of 3/8 in bar mesh No. 6 nylon mesh while the tail is constructed of 1/4 in bar mesh knotted 35 lb tensile strength nylon and is 40 in long. The 16 ft trawls historically were sampled bi-weekly during November through February and weekly from March through October at fixed stations to provide abundance indices and size distributions for penaeid shrimps, crabs and finfish (bottom fish) in the larger in-shore bays and Louisiana's territorial waters. The body of the trawl is constructed of 3/4 in bar mesh No. 9 nylon mesh while the tail is constructed of 1/4 in bar mesh knotted 35 lb tensile strength nylon and is 54-60 in long. The 50 ft seines have historically been sampled once or twice per month at fixed stations within each coastal basin by LDWF to provide abundance indices and size distributions of the small fishes and invertebrates using the shallow shoreline habitats of the estuaries. The seine is 6 ft in depth and has a 6 ft by 6 ft bag in the middle of the net and a mesh size of 1/4 in bar.

LDWF also measures temperature, conductivity, salinity, turbidity (secchi depth), dissolved oxygen (DO) and station depth in concurrence with the biological (catch) samples. Conductivity and salinity were highly correlated, so for this analysis only salinity was used. Station depth was not used in the analysis as it characterizes the station and is not measured to serve as an independent variable for CPUE. DO has only been measured consistently since 2010, so DO was not included in the analyses since the minimal sample size greatly limits the ability to statistically test for significant species-environment relationships. Turbidity measurements collected with the trawl samples were not used because trawling disturbs the sediment and thus greatly affects turbidity and species catchability. For the analyses, the associated turbidity (seine only), salinity and temperature measurements were evaluated with the CPUE from the seine and trawl station samples. Salinity and temperature are measured at top and bottom of the water column and averages of their measurements were used for the analyses. Examination of the top and bottom measurements usually showed no or little difference between the two, and often only top or bottom salinity was collected such that the mean value was the result from the single measurement.

Other important variables such as vegetated/non-vegetated habitat and substrate type are not available from LDWF datasets. However, a comparison of the HSIs developed from those gears that are associated with non-vegetated habitat (trawls) with those that are associated with vegetation (seine) was made to see if optimum values for variables were similar between habitats and if they roughly supported previous findings (Minello & Rozas, 2002). Thus, the primary

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focus of the statistical analysis was on the water quality data collected by LDWF, and then a theoretical, literature-based relationship for wetland vegetation was incorporated.

Length distributions of the species were plotted by each gear type to determine if the catch was comprised of primarily juveniles, adults or a combination of the life stages. Mean monthly CPUE by year was also estimated and plotted for the species in each gear to determine which months had the highest consistent catch over time and which months had variable and low or no catch over time. These plots allowed for subsetting the data by the months of highest species catch in order to reduce the amount of zeroes in the dataset. In this way, the analysis was not focused on describing environmental effects on species catch when the species typically are not in the estuaries or else at very low numbers.

2.1 Seines

The length distribution of brown shrimp caught in the seine samples indicated that nearly all were small juveniles (median TL=53 mm; Figure 3). Brown shrimp typically mature at around 140 mm TL (Turner and Brody, 1983). Sizes above 140 mm TL constituted less than 1% of the total brown shrimp catch. Therefore, it was assumed that the estimated CPUE from the 50 ft seines samples were representative of small juvenile brown shrimp.

The plot of mean CPUE by month for each year indicated the catch of juvenile brown shrimp in the 50 ft seines was consistently highest during April through June (Figure 4). This seasonality of juvenile brown shrimp catch in the seine samples coincides with their life history information of peak spawning on the shelf from spring through fall with juveniles occurring in the estuaries in the following March through May then gradually emigrating to off-shore spawning grounds from May through August (Copeland, 1965; Minello et al., 1989). Therefore, the seine data from April through June were used for the statistical evaluation of the juvenile brown shrimp CPUE-environment relationships, and the remaining months were dropped from the analysis as those months showed low and inconsistent catch of brown shrimp in the seines (Figure 4).

The seine data collected in April through June over all available years of record (1986 – 2013) across the Louisiana coastline were evaluated to determine if the averaged salinity, averaged water temperature, and/or turbidity data were related to the juvenile brown shrimp CPUE. The environmental variables were examined along with their squared terms and their interactions. Day of year and its squared term were also included in the model to explain any seasonal variation in brown shrimp within the estuaries.

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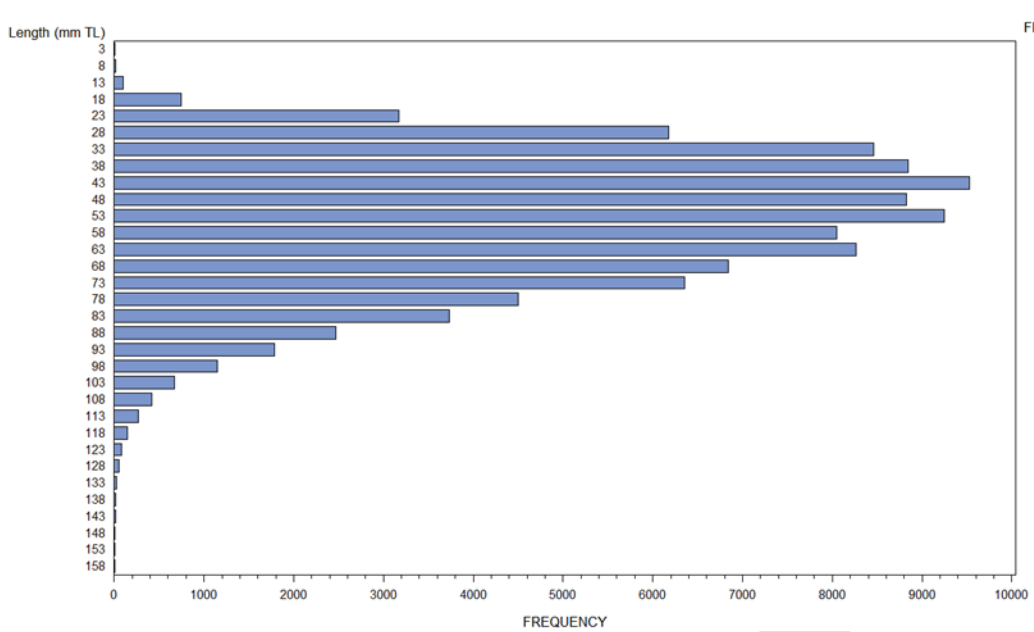


Length (mm TL)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
3	4	4	0.00	0.00
8	15	19	0.02	0.02
13	104	123	0.10	0.12
18	748	871	0.75	0.87
23	3175	4046	3.18	4.05
28	6180	10226	6.18	10.23
33	8458	18684	8.46	18.69
38	8841	27525	8.84	27.53
43	9527	37052	9.53	37.06
48	8829	45881	8.83	45.90
53	9245	55126	9.25	55.14
58	8049	63175	8.05	63.19
63	8261	71436	8.26	71.46
68	6839	78275	6.84	78.30
73	6354	84629	6.36	84.66
78	4501	89130	4.50	89.16
83	3734	92864	3.74	92.89
88	2464	95328	2.46	95.36
93	1786	97114	1.79	97.14
98	1149	98263	1.15	98.29
103	672	98935	0.67	98.97
108	415	99350	0.42	99.38
113	268	99618	0.27	99.65
118	149	99767	0.15	99.80
123	81	99848	0.08	99.88
128	57	99905	0.06	99.94
133	20	99925	0.02	99.96
138	16	99941	0.02	99.97
143	12	99953	0.01	99.98
148	4	99957	0.00	99.99
153	3	99960	0.00	99.99
158	9	99969	0.01	100.00

Figure 3: Length-Frequency Distribution of Brown Shrimp Caught in the 50 Foot Seine Samples for Louisiana.

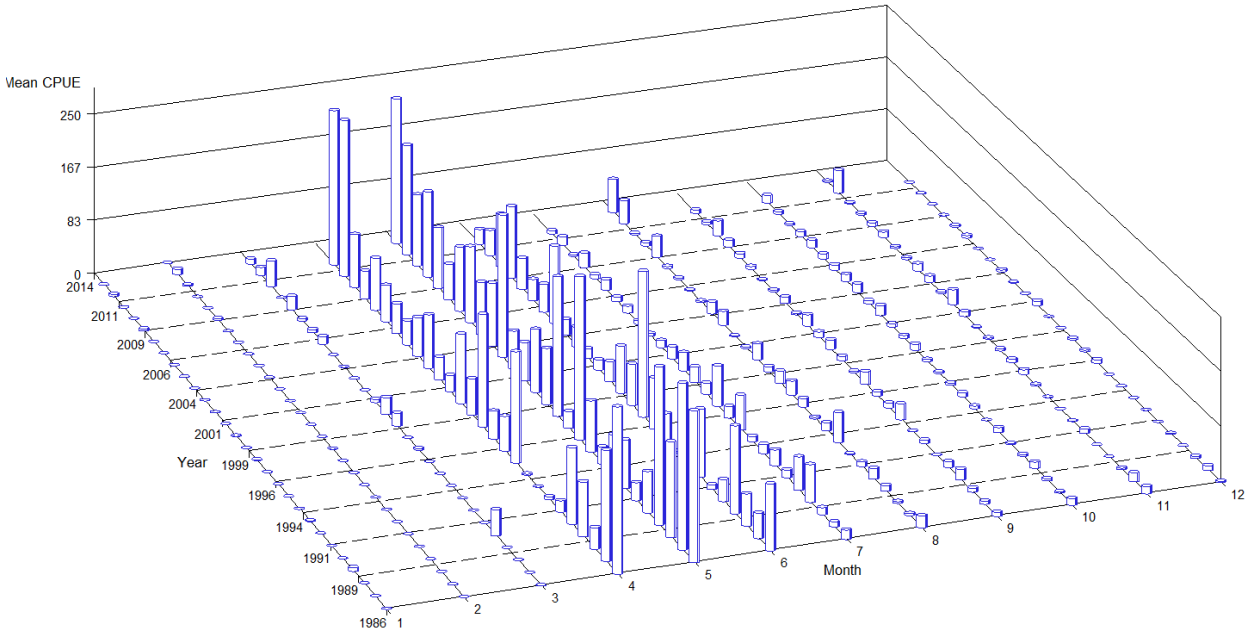


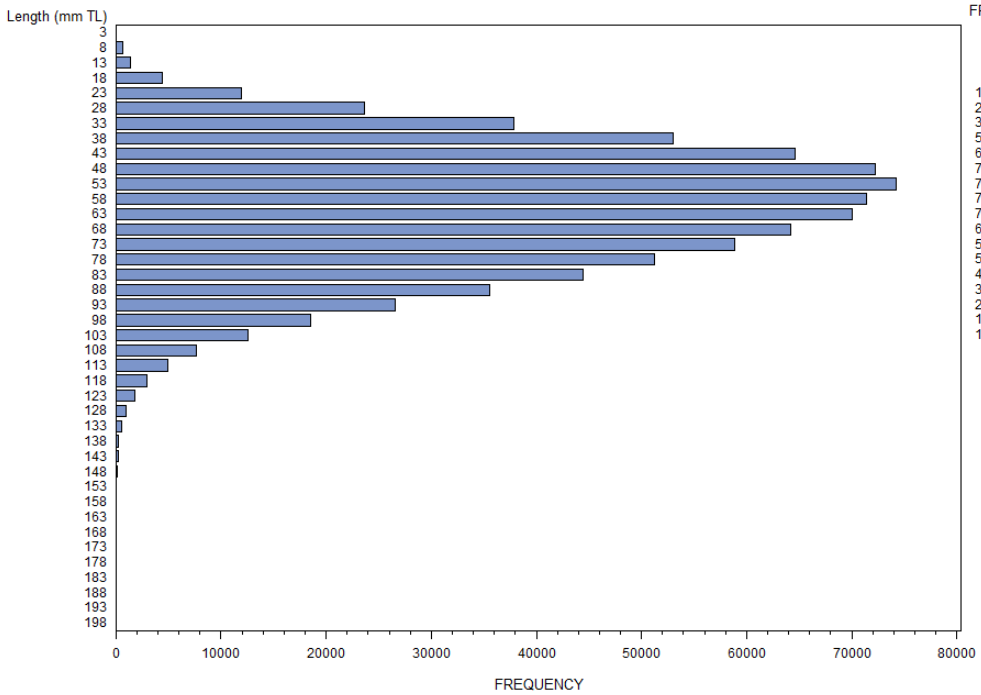
Figure 4: Mean CPUE of Brown Shrimp by Month for Each Year in the 50 Foot Seine Samples.

2.2 6 Toot Trawls

The length distribution of brown shrimp caught in the 6 ft trawl samples indicated that nearly all were larger juveniles (median TL=62.5 mm; Figure 5) than those caught by the seine. Sizes above

140 mm TL constituted less than 1% of the total brown shrimp catch. Therefore, it was assumed that the estimated CPUE from the 6 ft trawl samples were representative of somewhat larger juvenile brown shrimp.

The plot of mean CPUE by month for each year indicated the catch of juvenile brown shrimp in the 6 ft trawls was consistently highest during April through July (Figure 6). Therefore, the 6 ft trawl data from April through July were used for the statistical evaluation of the juvenile brown shrimp CPUE-environment relationships, and the remaining months were dropped from the analysis as those months showed low and inconsistent catch of brown shrimp in the 6 ft trawls (Figure 6).



Length (mm TL)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
3	6	6	0.00	0.00
8	668	674	0.08	0.08
13	1389	2063	0.17	0.25
18	4465	6528	0.55	0.80
23	11946	18474	1.46	2.26
28	23653	42127	2.89	5.15
33	37904	80031	4.64	9.79
38	53002	133033	6.49	16.28
43	64626	197659	7.91	24.19
48	72271	269930	8.84	33.03
53	74208	344138	9.08	42.11
58	71399	415537	8.74	50.84
63	70008	485545	8.57	59.41
68	64226	549771	7.86	67.27
73	58852	608623	7.20	74.47
78	51253	659876	6.27	80.74
83	44475	704351	5.44	86.18
88	35600	739951	4.36	90.54
93	26614	766565	3.26	93.80
98	18485	785050	2.26	96.06
103	12583	797633	1.54	97.60
108	7700	805333	0.94	98.54
113	4951	810284	0.61	99.15
118	2969	813253	0.36	99.51
123	1779	815032	0.22	99.73
128	1004	816036	0.12	99.85
133	581	816617	0.07	99.92
138	265	816882	0.03	99.95
143	210	817092	0.03	99.98
148	83	817175	0.01	99.99
153	54	817229	0.01	99.99
158	13	817242	0.00	100.00
163	18	817260	0.00	100.00
168	1	817261	0.00	100.00
173	1	817262	0.00	100.00
178	0	817262	0.00	100.00
183	1	817263	0.00	100.00
188	0	817263	0.00	100.00
193	1	817264	0.00	100.00
198	7	817271	0.00	100.00

Figure 5: Length-Frequency Distribution of Brown Shrimp Caught in the 6 Foot Trawl Samples for Louisiana.

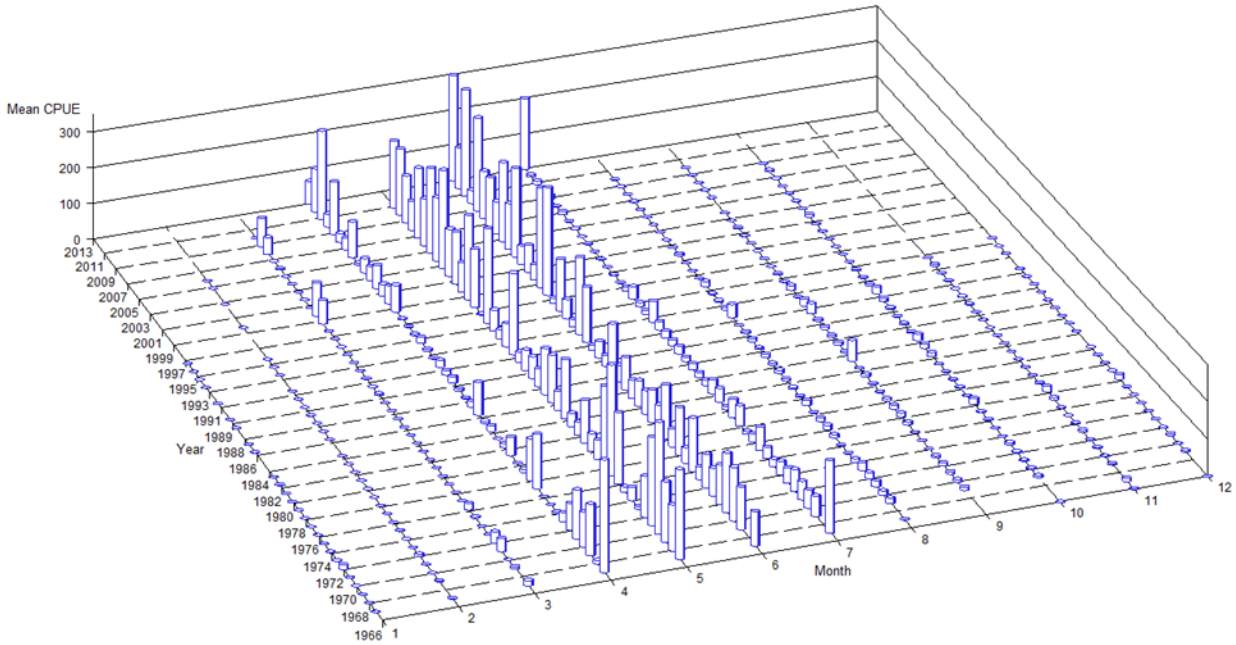


Figure 6: Mean CPUE of Brown Shrimp by Month for Each Year in the 6 Foot Trawl Samples.

2.3 16 Foot Trawls

The length distribution of brown shrimp caught in the 16 ft trawl samples indicated that nearly all were large juveniles (median TL =72.5 mm; Figure 7). Sizes above 140 mm TL constituted less than 1% of the total brown shrimp catch. Therefore, it was assumed that the estimated CPUE from the 16 ft trawl samples were representative of large juvenile brown shrimp

The plot of mean CPUE by month for each year indicated the catch of juvenile brown shrimp in the 16 ft trawls was also consistently highest during April through July (Figure 8). Therefore, the 16 ft trawl data from April through July were used for the statistical evaluation of the juvenile brown shrimp CPUE-environment relationships, and the remaining months were dropped from the analysis as those months showed low and inconsistent catch of brown shrimp in the 16 ft trawls (Figure 8).

The 6 ft and 16 ft trawl data collected in April through July over all available years of record (1966-2013) across the Louisiana coastline were evaluated separately to determine if the averaged salinity and averaged water temperature were related to the juvenile brown shrimp CPUE. Each 16 ft trawl sample was kept as an independent observation even though collections were taken biweekly during certain months. Both environmental variables were examined along with their squared terms and their interactions. Day of year and its squared term were also included in the models to explain any seasonal variation in brown shrimp within the estuaries.

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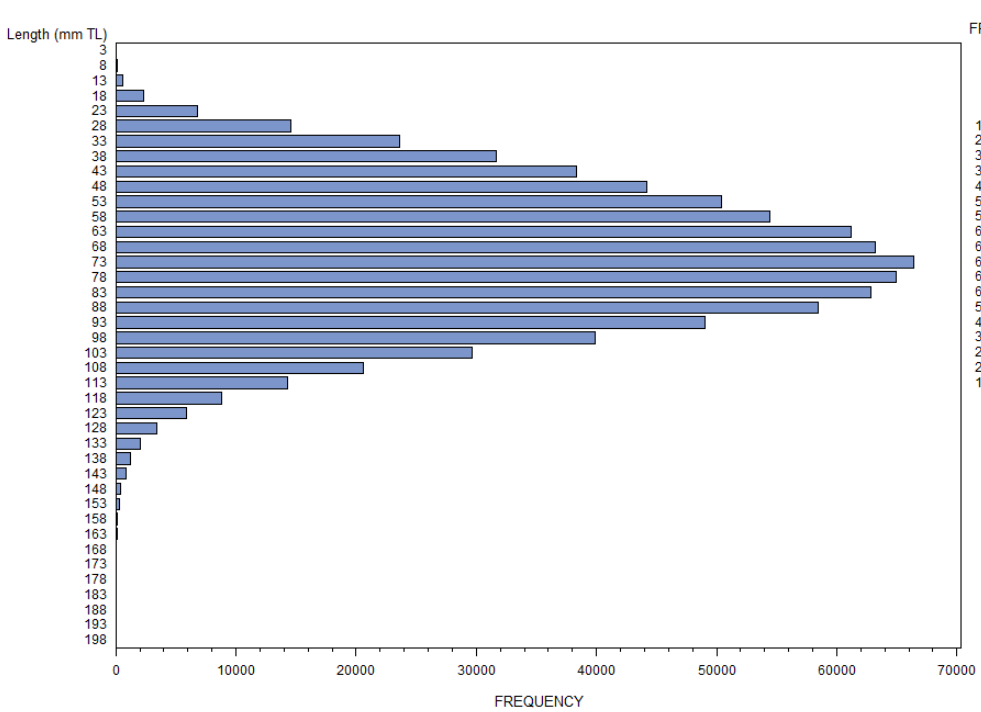

Length (mm TL)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
3	15	15	0.00	0.00
8	88	103	0.01	0.01
13	548	651	0.07	0.08
18	2297	2948	0.28	0.36
23	6831	9779	0.83	1.19
28	14575	24354	1.78	2.97
33	23615	47969	2.88	5.84
38	31640	79609	3.86	9.70
43	38365	117974	4.67	14.38
48	44198	162172	5.39	19.76
53	50432	212604	6.15	25.91
58	54407	267011	6.63	32.54
63	61195	328206	7.46	39.99
68	63212	391418	7.70	47.69
73	66406	457824	8.09	55.79
78	64970	522794	7.92	63.70
83	62796	585590	7.65	71.35
88	58439	644029	7.12	78.47
93	49023	693052	5.97	84.45
98	39923	732975	4.86	89.31
103	29649	762624	3.61	92.92
108	20610	783234	2.51	95.44
113	14334	797568	1.75	97.18
118	8770	806338	1.07	98.25
123	5859	812197	0.71	98.97
128	3364	815561	0.41	99.38
133	2057	817618	0.25	99.63
138	1217	818835	0.15	99.77
143	832	819667	0.10	99.88
148	386	820053	0.05	99.92
153	287	820340	0.03	99.96
158	94	820434	0.01	99.97
163	117	820551	0.01	99.98
168	28	820579	0.00	99.99
173	38	820617	0.00	99.99
178	15	820632	0.00	99.99
183	17	820649	0.00	100.00
188	6	820655	0.00	100.00
193	4	820659	0.00	100.00
198	29	820688	0.00	100.00

Figure 7: Length-Frequency Distribution of Brown Shrimp Caught in the 16 Foot Trawl Samples for Louisiana.

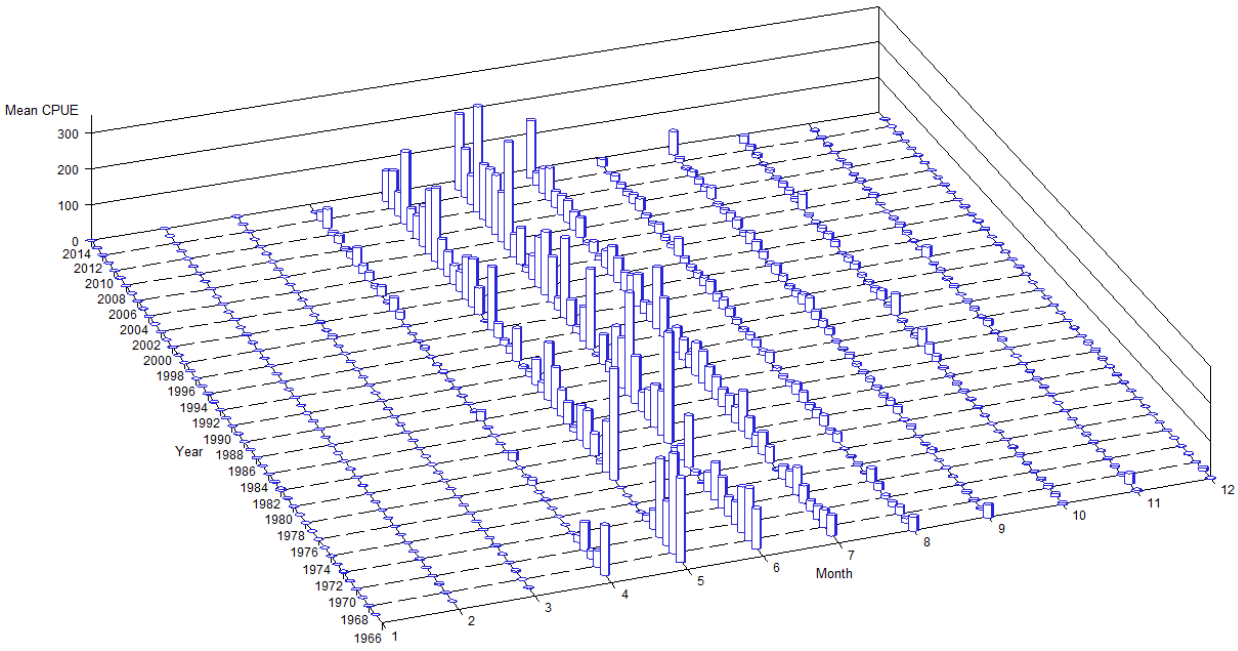

Figure 8: Mean CPUE of Brown Shrimp by Month for Each Year in the 16 Foot Trawl Samples.

2.4 Statistical Analysis

The statistical approach was developed to predict mean CPUE in response to environmental variables for multiple species of interest and was designed for systematic application across the coast. The methods described in detail below rely on the use of polynomial regressions and commonly used Statistical Analysis Software (SAS) procedures that can be consistently and efficiently applied to fishery-independent count data for species with different life histories and environmental tolerances. As a result, the same statistical approach was used for each of the fish and shellfish species that are being modeled with HSIs in the 2017 Coastal Master Plan.

The species CPUE data were transformed using ln(CPUE+1). Given that the sampling is standardized and CPUE represent discrete values (total catch per sample event), ln(CPUE+1) transformation was appropriate for the analysis. Distributions that are reasonably symmetric often give satisfactory results in parametric analyses, due in part to the effectiveness of the Central Limit Theorem and in part to the robustness of regression analysis. Nevertheless, it is expedient to approximate normality as closely as possible prior to conducting statistical analyses. The negative binomial distribution is common for discrete distributions for samples consisting of counts of organisms when the variance is greater than the mean. In these cases, the natural logarithmic transformation is advantageous in de-emphasizing large values in the upper tail of the distribution in the polynomial regression equation. The transformation worked generally well in meeting the assumptions of the regression analysis.

Predictive models can often be improved by fitting some curvature to the variables by including polynomial terms. This allows the rate of a linear trend to diminish as the variable increases or decreases. Scientists have previously described relationships of estuarine species to factors like salinity and temperature as nonlinear, and it can be expected that brown shrimp may respond nonlinearly to environmental variables as well (i.e., they have optimal values for biological processes; Pérez-Castañeda & Defeo, 2005; Villarreal et al., 2003). Thus, polynomial regression was chosen for the analyses. Another consideration in modeling the abundance of biota is the consistency of the effect of individual variables across the level of other variables. The effect of temperature, for example, may not be consistent across all levels of salinity. These changes can be modeled by considering interaction terms among the independent variables.

Given the large number of potential variables and their interactions, it is prudent to use an objective approach, such as stepwise procedures (Murtaugh, 2009), to select the variables for inclusion in the development of the model. The SAS programming language has a relatively new procedure called PROC GLMSelect, which is capable of performing stepwise selection where at each step all variables are rechecked for significance and may be removed if no longer significant. However, there are a number of limitations to PROC GLMSelect. GLMSelect is intended primarily for parametric analysis where the assumption of a normal distribution is made. It does not differentially handle random variables, so modern statistical techniques involving random components, non-homogeneous variance and covariance structure cannot be used with this technique. As a result, PROC GLMSelect was used as a 'screening tool' to identify the key variables (linear, polynomial, and interactions), while the SAS procedure PROC MIXED was used to calculate parameter estimates and ultimately develop the model. PROC MIXED is intended primarily for parametric analyses, and can be used for regression analysis. Although it is capable of fitting analyses with non-homogenous variances and other covariance structures, the ultimate goal of the analysis was to predict mean CPUE, not hypothesis testing or for placing confidence intervals. The statistical significance levels for the resulting parameters were used to evaluate whether the parameters of the polynomial regression model adequately described the predicted mean ($p<0.05$).

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3.0 Results

3.1 Seines

The regression analyses for the seines were initially run with salinity, temperature and turbidity (i.e., secchi depth) as independent variables, but the range in turbidity values turned out to be very small with nearly all secchi depth measurements at the sampling stations being less than 2 ft. Including turbidity (secchi depth in feet) within the polynomial regression equation caused much more flipping within the function (i.e., quickly changing direction) and unrealistic predicted CPUE values. Therefore, turbidity was dropped as an independent variable and the statistical analysis of the seines was re-run with temperature, salinity, and day.

The resulting polynomial regression model from the seine analysis describes brown shrimp CPUE (natural log transformed) in terms of all significant effects from salinity and temperature, their squared terms and their interactions, and day of year (Equation 1; Table 2). Surface response plots are used to visually depict the relationships for any two interacting independent variables (x,y) and CPUE (z) with the remaining independent variables held constant. The surface response for the resulting polynomial regression (Equation 1) is plotted for the range of salinities and temperatures (Figure 9) with day held at its mean. The scatter plot overlaid on the surface response shows the observed data used to develop the polynomial regression (Figure 9).

The parameter estimates in Table 1 and the surface response plot (Figure 9) indicated salinity explained the majority of variation in juvenile brown shrimp CPUE in the seines. CPUE is highest between 4 and 26 ppt salinity but peaks around 10-16 ppt and 14-30 °C (Figure 9).

$$\ln(CPUE + 1) = -15.9328 + 24.9838(Day) - 9.0311(Day^2) + 0.2203(Salinity) + 0.02229(Temperature) - 0.00629(Salinity^2) + 0.000544(Temperature^2) - 0.00007(Salinity * Temperature^2) \quad (1)$$

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Table 2: List of Selected Effects with Parameter Estimates and their Level of Significance for the Resulting Polynomial Regression in Equation 1. Interactions between variables are denoted by *.

Selected Effects	Parameter Estimate[1]	p value
Intercept	-15.9328	<0.0001
Day	24.9838	<0.0001
Day^2	-9.0311	<0.0001
Salinity	0.2203	<0.0001
Temperature	0.02229	0.7070
$Salinity^2$	-0.00629	<0.0001
$Temperature^2$	0.000544	0.6671
Salinity* $Temperature^2$	-0.00007	0.0010

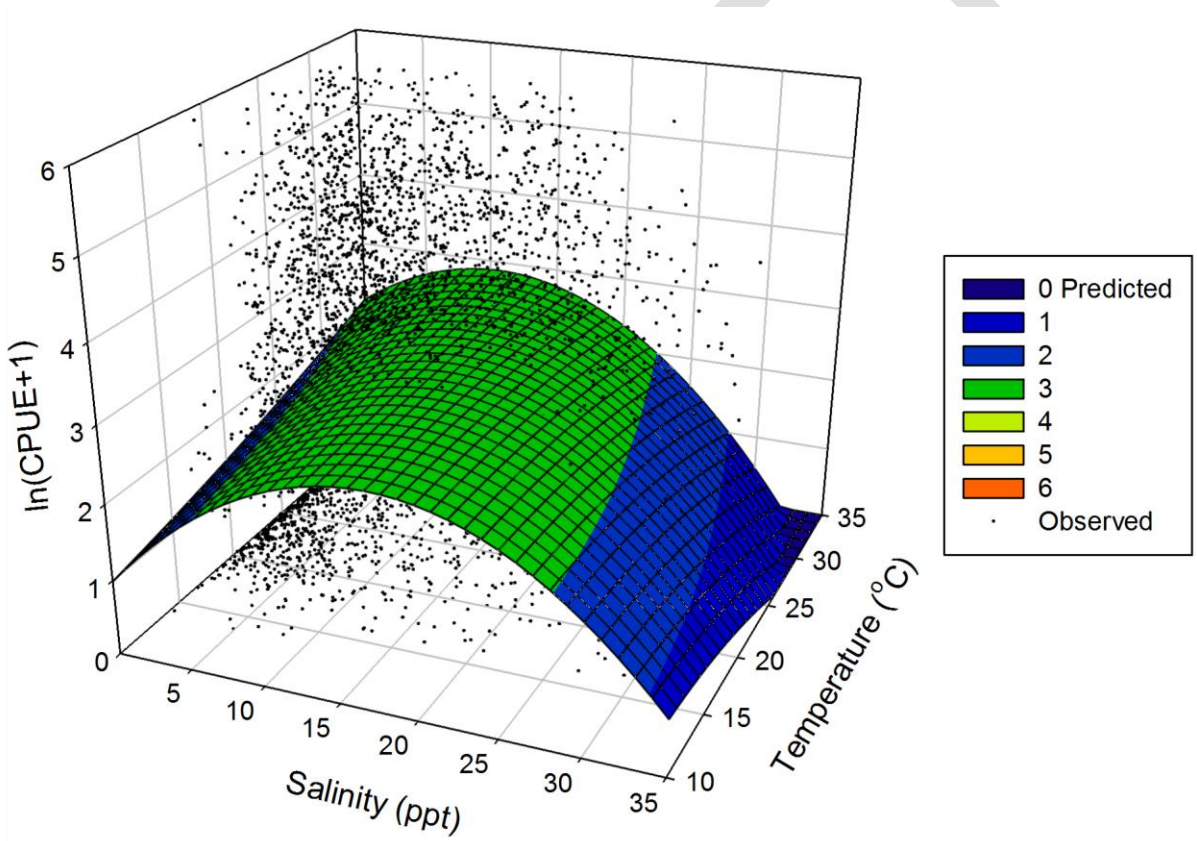

Figure 9: Surface Plot for the Polynomial Regression in Equation 1 over the Range of Salinity and Temperature Values and Substituting a Mean Day of May 15 into the Equation. The scatter plot of salinity, temperature and juvenile brown shrimp CPUE data from the 50 ft seine station samples are overlaid on the plot.

[1] Significant figures may vary among parameters due to rounding or accuracy of higher order terms.

3.2 Trawls

Preliminary analysis indicated the two trawl gear types had similar predictions of brown shrimp CPUE in response to salinity and temperature. As a result, the data for both trawls were combined and the resulting polynomial regression model (Equation 2) from the analysis describes brown shrimp CPUE in terms of all significant effects from salinity, temperature, their squared terms and their interactions, and day of year. A dummy variable, "gear", was used to control for the effect of the different gears on model predictions: when its value is "1" the prediction represents the 6 ft trawl; when its value is "0" the results are adjusted for the 16 ft trawl.

The parameter estimates (Table 3) and the surface response plot (Figure 10) indicate that temperature and an interaction between temperature and salinity explain most of the variation in the brown shrimp catch within the 6 ft and 16 ft trawl samples. Brown shrimp catch [ln(CPUE+1)] in the 6 ft and 16 ft trawls increases with temperatures at 8 to 32°C and peaks at 18-24°C. The curvature of the polynomial function that is capturing the interacting effects of temperature and salinity makes the function highest at the extreme minimum and maximum salinities and maximum temperature values. As a result, the function is truncated at reasonable extreme values based on the available data so that unrealistic predictions are removed. CPUE is highest at salinities of 4-26 ppt (at temperatures of 8 to 32°C) with a peak at 14-20 ppt (Figure 10). The peaks identified here are roughly similar to the optimums used in the brown shrimp HSI for the 2012 Coastal Master Plan (10-20 ppt and 20-30°C; CPRA, 2012). The coefficient for the 'gear' variable is relatively small, albeit significant, indicating there is a slight increase in brown shrimp catch when gear is set to 1 (6 ft trawl) rather than 0 (16 ft trawl). However, these differences have no effect on the overall shape of the responses to salinity and temperature. As a result, gear was held constant at 0 for the development of the suitability index, as described below.

$$\ln(CPUE+1) = -8.931 - 0.1434(Salinity) - 0.1801(Temperature) + 0.003639(Salinity^2) + 0.006205(Temperature^2) + 0.04524(Salinity * Temperature) + 0.000034(Salinity^2 * Temperature^2) - 0.00126(Salinity * Temperature^2) - 0.00125(Temperature * Salinity^2) + 15.973(Day) - 5.3793(Day^2) + 0.0676(Gear) \quad (2)$$

Table 3: List of Selected Effects with Parameter Estimates and their Level of Significance for the Resulting Polynomial Regression in Equation 2. Interactions between variables are denoted by *.

Selected Effects	Parameter Estimate	p value
Intercept	-8.9310	<0.0001
Salinity	-0.1434	0.1147
Temperature	-0.1801	<0.0001
Salinity^2	0.003639	0.2717
Temperature^2	0.006205	<0.0001
Salinity*Temperature	0.04524	<0.0001
Salinity^2*Temperature^2	0.000034	<0.0001
Salinity*Temperature^2	-0.00126	<0.0001
Temperature*Salinity^2	-0.00125	<0.0001
Day	15.973	<0.0001
Day^2	-5.3793	<0.0001
Gear	0.0676	<0.0001

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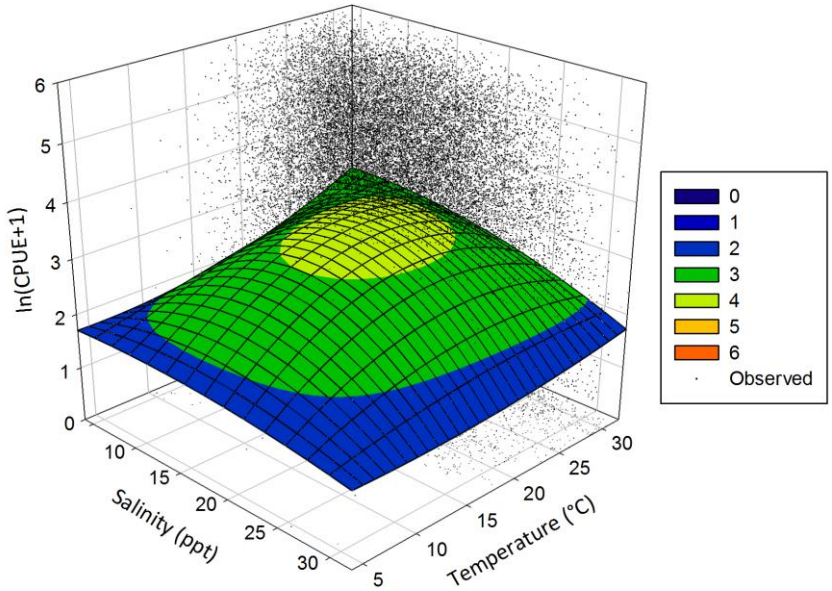

Figure 10: Surface Response Plot for Brown Shrimp in 6 Foot and 16 Foot Trawls in Relation to Temperature and Salinity and with the Response Surface Truncated at the Combined Salinity and Temperature Extremes (< 4 and > 32 ppt and < 4 and > 32°C) to Remove the "Flips" from the Polynomial Regression.

4.0 Habitat Suitability Index Model for Juvenile Brown Shrimp (Seine)

Although the polynomial regression functions appear long and complex, the regression models are simply describing the relationships between brown shrimp catch in the seine and the salinity and temperature taken with the samples. The surface plots demonstrate the relationships and interactions between the independent variables that predict the mean brown shrimp CPUE.

In order to use the polynomial regression functions in an HSI model, the equations were standardized to a 0-1 scale. Standardization of the CPUE data is relatively straightforward and begins with converting the predicted log-transformed CPUE [ln(CPUE+1)] back to raw, untransformed CPUE values. The predicted untransformed CPUE values were then standardized by the maximum CPUE value. Maximum CPUE was calculated by running the model through salinity and temperature combinations that fall within plausible ranges.

A predicted maximum juvenile brown shrimp ln(CPUE+1)] value of 3.501 was generated from the seine polynomial regression at a temperature of 35°C and salinity of 11 ppt. The back-transformed CPUE value (32.17) was used to standardize the other predicted untransformed CPUE values from the regression. The resulting standardized water quality suitability index was combined with a standardized (0-1) index for emergent vegetation to produce the small juvenile brown shrimp HSI model. Both components of the model are equally weighted and the geometric mean is used as all variables are considered essential to small juvenile brown shrimp:

$$\mathbf{HSI = (SI_1 * SI_2)^{1/2}}$$

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Where:

SI_1 – Salinity and temperature during the months of April through June (V_1)

SI_2 – Percent of cell that is emergent vegetation (V_2)

4.1 Applicability of the Model

This model is applicable for calculating the habitat suitability index of small (median TL=53 mm; Figure 3) juvenile brown shrimp from April through June in coastal Louisiana marsh edge and shallow shoreline habitats.

4.2 Response and Input Variables

V_1: Salinity and temperature during the months of April through June

Calculate monthly averages of salinity (ppt) and temperature (°C) from April through June:

$$V_1 = -15.9328 + 24.9838(1.35) - (9.0311(1.35^2) + 0.2203(Salinity) + 0.02229(Temperature) - 0.00629(Salinity^2) + 0.000544(Temperature^2) - 0.00007(Salinity * Temperature^2)$$

The resulting suitability index (SI_1) should then be calculated as:

$$SI_1 = \frac{e^{V_1} - 1}{32.17}$$

which includes the steps for back-transforming the predicted CPUE from Equation 1 and standardizing by the maximum predicted (untransformed) CPUE value equal to 32.17. The surface response for SI_1 is demonstrated in Figure 11.

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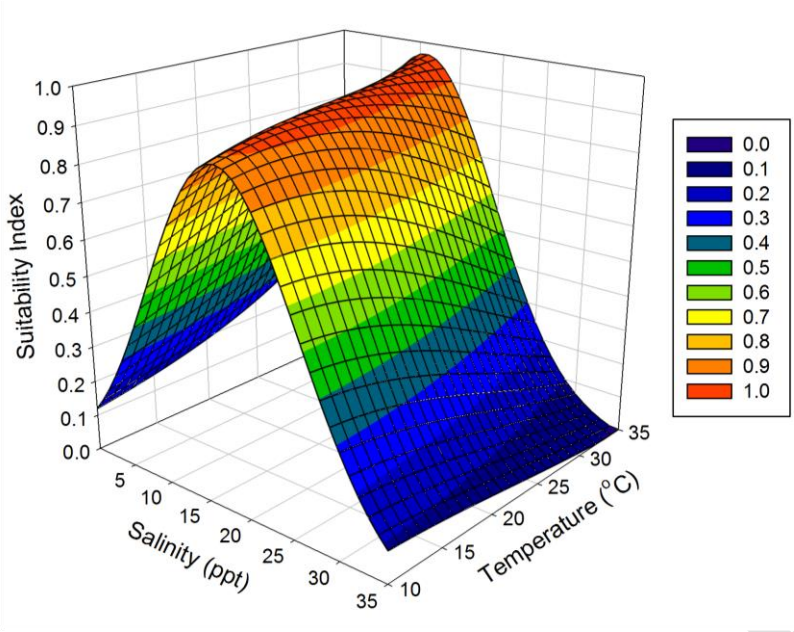

Figure 11: Surface Plot Demonstrating the Predicted Suitability Index (0-1) for Small Juvenile Brown Shrimp in Relation to Salinity and Temperature and Resulting from the Back-Transformation and Standardization of the Polynomial Regression in Equation 1.

Rationale*:* Salinity and temperature are important abiotic factors that can influence the spatial and temporal distribution of juvenile brown shrimp in the estuaries within a year. The suitability index for small juvenile brown shrimp resulted from the polynomial regression model that described the fit to the observed seine catch data in relation to the salinity and temperature measurements taken concurrent with LDWF seine samples. The resulting suitability index predicts salinity and temperature ranges and optimums that agree well with the ranges and optimums previously described in the literature for juvenile brown shrimp (Table 1). The previous master plan HSI combined seine and trawl gears (CPRA, 2012). Because these gears employ different levels of effort (as previously described) and target different parts of the shrimp life cycle, it was felt that relationships specific to each gear were warranted.

Limitations*: T*he variable 'day' in Equation 1 has been replaced by a constant value equal to the mean day from the analysis (May 15).[2] Holding 'day' constant prevents the variable from contributing to the within- or among-year variation, so that only salinity and temperature can vary within and among years. Further, the optimal salinities and temperatures should not be interpreted as optimums for specific biological processes, such as growth or reproduction. Instead, the optimums represent the conditions in which small juvenile brown shrimp most commonly occur, as dictated by physiological tolerances, prey availability, mortality, seasonal movements, and other factors.

[2] Day of the year is scaled between 1 and 3.65 (i.e., 365/100) because the coefficients for higher power terms get exceedingly small and often do not have many significant digits. For example, a coefficient of 0.00004 may actually be 0.0000351 and that can make a big difference when multiplied by 365 raised to the power of 2. By using a smaller value, decimal precision is improved.

V_2: Percent of cell that is land

V_2 is the percent of the cell that is covered by land (emergent wetland vegetation of all types). The equation for SI_2 is plotted in Figure 12.

$SI_2 = 0.028 * V_2 + 0.3$	for $V_2 < 25$
1.0	for $25 \leq V_2 \leq 80$
$5.0 – 0.05 * V_2$	for $V_2 > 80$

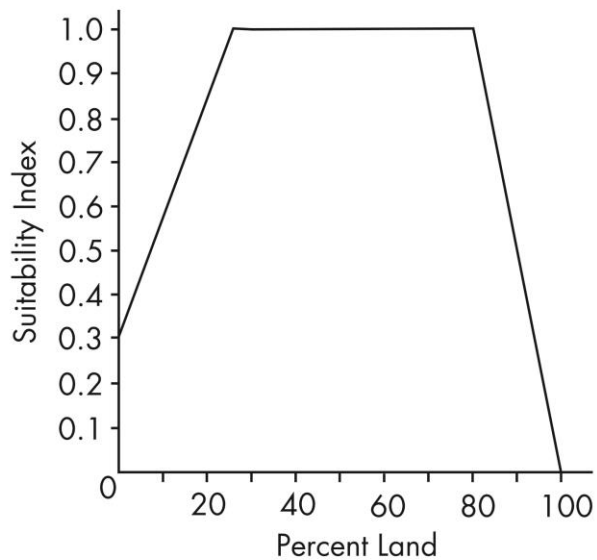

Figure 12: The Suitability Index for Juvenile Brown Shrimp in Relation to the Percent Emergent Vegetation (Percent Land= V_2).

Rationale: The percent of land or total vegetated area within the cell is directly proportional to the marsh habitat's long-term carrying capacity for juvenile brown shrimp. This relationship was developed by Minello and Rozas (2002) for juvenile brown shrimp, white shrimp and blue crab and subsequently incorporated into HSIs for the brown shrimp, white shrimp, and seatrout in the 2012 Coastal Master Plan. The 2012 brown shrimp HSI wetland suitability index was utilized in the 2017 HSI model; however, the SI was increased to 0.3 at 0% wetland as brown shrimp juveniles can occur in shallow non-vegetated bottom, and SI was decreased to 0 at 100% wetland as this configuration is not expected to hold value for this species.

Limitations: Juvenile brown shrimp also use submerged aquatic vegetation (SAV; Clark et al., 1999) and seagrass beds are considered prime habitat for brown shrimp due to increased prey as well as for cover from predators. However, the 2017 Coastal Master Plan HSI model does not quantify specific habitats such as SAV or marsh edge, and instead identifies the general landscape configuration (land:water) where optimum levels of these habitats are expected to occur.

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5.0 Habitat Suitability Index Model for Juvenile Brown Shrimp (Trawl)

A predicted maximum juvenile brown shrimp ln(CPUE+1) value of 3.942 was generated from the trawl polynomial regression at a temperature of 21°C and salinity of 16 ppt (see Section 4.0 for description of how the maximum value was generated). The back-transformed CPUE value (50.55) was used to standardize the other predicted untransformed CPUE values from the regression. The resulting standardized water quality suitability index was combined with a standardized (0-1) index for emergent vegetation to produce the large juvenile brown shrimp HSI model. Both components of the model are equally weighted and the geometric mean is used as all variables are considered essential to large juvenile brown shrimp:

$HSI = (SI_1 * SI_2)^{1/2}$

Where:

SI_1 – Salinity and temperature during the months of April through July (V_1)

SI_2 – Percent of cell that is emergent vegetation (V_2)

5.1 Applicability of the Model

This model is applicable for calculating the habitat suitability index of large (median TL = 72 mm) juvenile brown shrimp from April through July in Louisiana's in-shore and deeper estuarine waters as they are emigrating from the estuary.

5.2 Response and Input Variables

V_1: Salinity and temperature during the months of April through July

Calculate monthly averages of salinity (ppt) and temperature (°C) from April through July. Suitability index should be calculated as followed:

$$V_1 = \ln(CPUE + 1) = -8.931 - 0.1434(Salinity) - 0.1801(Temperature) + 0.003639(Salinity^2) + 0.006205(Temperature^2) + 0.04524(Salinity * Temperature) + 0.000034(Salinity^2 * Temperature^2) - 0.00126(Salinity * Temperature^2) - 0.00125(Temperature * Salinity^2) + 15.973(1.4578) - 5.3793(1.4578^2)$$

The resulting suitability index (SI_1) should then be calculated as:

$$SI_1 = \frac{e^{V_1} - 1}{50.55}$$

which includes the steps for back-transforming the predicted CPUE from Equation 2 and standardizing by the maximum predicted (untransformed) CPUE value equal to 50.55. The surface response for SI_1 is demonstrated in Figure 13.

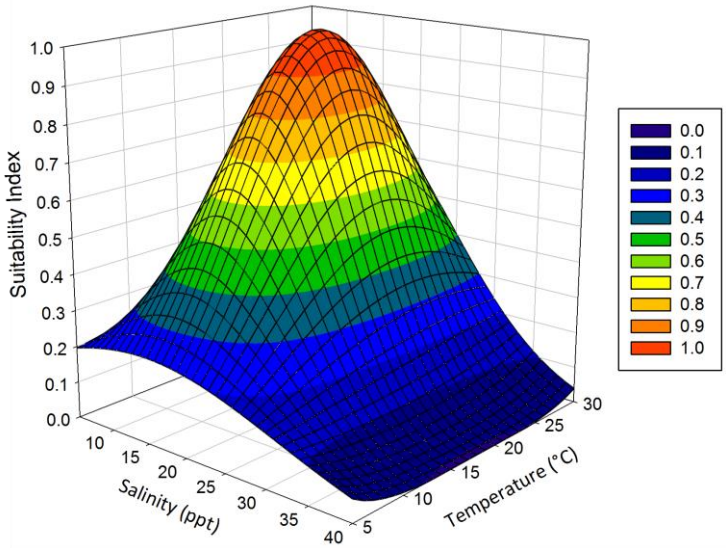

Figure 13: Surface Plot Demonstrating the Predicted Suitability Index (0-1) for Large Juvenile Brown Shrimp in Relation to Salinity and Temperature and Resulting from the Back-Transformation and Standardization of the Polynomial Regression in Equation 2.

Rationale: Salinity and temperature are important abiotic factors that can influence the spatial and temporal distribution of juvenile brown shrimp in the estuaries within a year. The suitability index for large juvenile brown shrimp resulted from the polynomial regression model that described the fit to the observed trawl catch data in relation to the salinity and temperature measurements taken concurrent with LDWF trawl samples. The resulting suitability index predicts salinity and temperature ranges and optimums that agree well with the ranges and optimums previously described in the literature for juvenile brown shrimp (Table 1). The previous master plan HSI combined seine and trawl gears (CPRA, 2012). Because these gears employ different levels of effort (as previously described) and target different parts of the shrimp life cycle, it was felt that relationships specific to each gear were warranted.

Limitations: The variable 'day' in Equation 1 has been replaced by a constant value equal to the mean day from the analysis (May 25). Holding 'day' constant prevents the variable from contributing to the within- or among-year variation, so that only salinity and temperature can vary within and among years. Further, the optimal salinities and temperatures should not be interpreted as optimums for specific biological processes, such as growth or reproduction. Instead, the optimums represent the conditions in which the large juvenile brown shrimp most commonly occur, as dictated by physiological tolerances, prey availability, mortality, seasonal movements, and other factors. Lastly, V_1 is inaccurate at temperature extremes (< 4 and > 32°C). As a result, a conditional statement should be applied and the model should be adjusted as followed:

If temperature <4 or temperature > 32°C then $V_1 = 0$

V_2: Percent of cell that is land

V_2 is the percent of the cell that is covered by land (emergent wetland vegetation of all types). The equation for SI_2 is plotted in Figure 14.

$SI_2 = 1.0$	for $V_2 \leq 30$
$1.43-0.0143*V_2$	for $V_2 > 30$

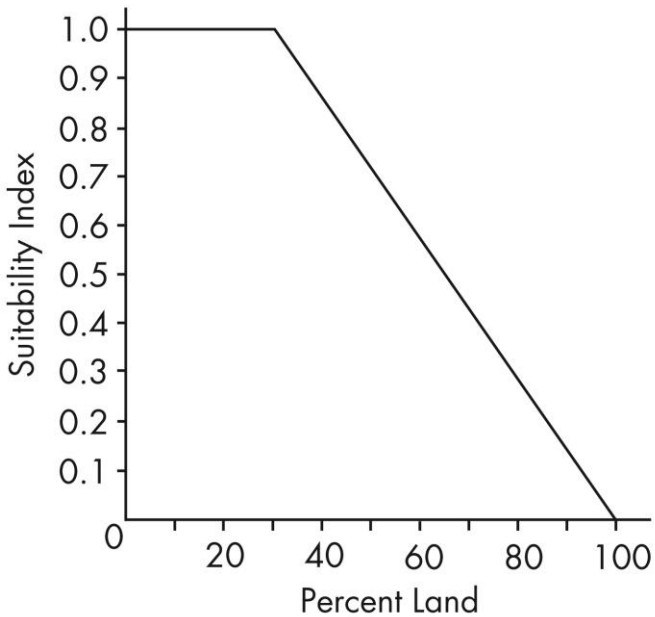

Figure 14: The Suitability Index for Large Juvenile Brown Shrimp in Relation to the Percent Emergent Vegetation (Percent Land = V_2).

Rationale: This relationship represents large juvenile brown shrimp that are moving away from the shoreline into in-shore and deeper estuarine waters. Therefore, it is thought that areas with more water (up to 30% land) would be appropriate for this life stage. The benefits of edge and shoreline habitat lessen during this part of the species' life cycle as it emigrates off-shore.

Limitations: None.

6.0 Model Verification and Future Improvements

A verification exercise was conducted to ensure the distributions and patterns of HSI scores across the coast were realistic relative to current knowledge of the distribution of brown shrimp. In order to generate HSI scores across the coast, the HSI models were run using calibrated and validated Integrated Compartment Model (ICM) spin-up data to produce a single value per ICM grid cell. Given the natural interannual variation in salinity patterns across the coast, several years of model output were examined to evaluate the interannual variability in the HSI scores.

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For the small juvenile brown shrimp model, high scores were observed around fragmented marsh areas, such as those within Barataria, Breton, and Terrebonne basins. Scores were lowest in open water bodies closest to the Gulf of Mexico, such as Chandeleur Sound, southern Barataria Bay, and Atchafalaya Bay. For large juvenile brown shrimp, the reverse was observed. Highest scores were observed in lakes and bays closest to the Gulf, with HSI scores decreasing further inland into fresher areas. A limitation of the HSI models is that there are no geographic constraints that prevent the model from generating HSI scores in areas where the species are not likely to occur. For example, habitat in certain areas may be highly suitable but likely may never be occupied due to accessibility constraints (e.g., impounded wetlands) or perhaps because of the life cycle (e.g., larvae are not carried into the upper basins and therefore these areas may be under-utilized by juveniles). In both the small and large juvenile models, HSI scores greater than 0 were observed in isolated areas in the upper Atchafalaya Basin, where the species are not known to occur. As a result, the areas of the northern Atchafalaya are being excluded from the HSI model domain. Overall, the results of the verification exercise were determined to be accurate representations of both small and large juvenile brown shrimp habitat distributions in coastal Louisiana.

Although the polynomial regression model used to fit LDWF seine and trawl data produced functions relating brown shrimp catch to salinity and temperature that generally agreed with their life history information and distributions (Pattillo et al., 1997), polynomial models can predict unreasonable results outside of the modeled data range. Other statistical methods and modeling techniques exist for fitting nonlinear relationships among species catch and environmental data that could potentially improve the statistical inferences and model behavior outside of the available data. A review of other statistical modeling techniques could be conducted in order to determine their applicability in generating improved HSI models in the future.

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