Coastal Protection and Restoration Authority
150 Terrace Avenue, Baton Rouge, LA 70802 | coastal@la.gov | www.coastal.la.gov

2017 Coastal Master Plan

Attachment C3-17: Bay Anchovy, *Anchoa mitchilli,* Habitat Suitability Index Model

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Prepared By: Shaye E. Sable (Dynamic Solutions), Ann C. Hijuelos (The Water Institute of the Gulf), Ann M. O'Connell (University of New Orleans), and James P. Geaghan (Louisiana State University)

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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- The Water Institute of the Gulf - Ehab Meselhe, Alaina Grace, and Denise Reed
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Executive Summary

The 2012 Coastal Master Plan utilized Habitat Suitability Indices (HSIs) to evaluate potential project effects on 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 five 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 and adult bay anchovy, *Anchoa mitchilli,* for use in the 2017 Coastal Master Plan modeling effort.

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List of Abbreviations

Chl *a*	Chlorophyll *a*
CPRA	Coastal Protection and Restoration Authority
CPUE	Catch per unit effort
DO	Dissolved oxygen
HSI	Habitat Suitability Index
ICM	Integrated Compartment Model
LDWF	Louisiana Department of Wildlife and Fisheries
SAS	Statistical Analysis Software
SI	Suitability Index
SL	Standard length
TL	Total length
YOY	Young-of-year

1.0 Species Profile

Bay anchovy range from Maine to Tampico, Mexico and likely constitute the greatest biomass of any fish in the estuarine waters of both the southeastern United States and the Gulf of Mexico (Morton, 1989; Pattillo et al., 1997). All life stages of bay anchovy are abundant across the Louisiana coastline (Pattillo et al., 1997). Their numbers dominate the coastal trawl and seine samples collected by the Louisiana Department of Wildlife and Fisheries (LDWF) fisheries-independent monitoring program (LDWF, unpublished data), and larval bay anchovy are one of the dominant ichthyoplankton of the inshore waters during the summer months (Raynie & Shaw, 1994).

Because of their high biomass and importance within estuarine food webs, bay anchovy are often used as an indicator species of estuarine health. Bay anchovy are a schooling species that prey exclusively upon zooplankton and are a dominant prey item for many predatory fish species such as red drum, spotted seatrout, Atlantic croaker, gar, southern flounder and blue catfish (Hildebrand, 1943; Shipp, 1986). Their abundance in coastal estuaries appears to be primarily influenced by their zooplankton food supply (Houde & Zastrow, 1991; Peebles et al., 1996, 2007; Reid, 1955; Rose et al., 1999), and likely accounts for why they prefer bay habitats (Hoese, 1965; Houde & Zastrow, 1991; Rubec et al., 2001). Large schools form during the day in protected areas close to shore to minimize predation risk, and smaller schools form to feed at night (Daly, 1970; Hoese & Moore, 1977).

Figure 1 is the life cycle for the bay anchovy with the life stage size, duration, and associated movements or habitats. Yolk-sac larvae and feeding larvae are separated in the life cycle diagram, but are combined as a single larval stage for further description in this report. Juvenile bay anchovy grow very quickly and are reproductively mature within about 2.5 months (Houde & Zastrow, 1991; Ward & Armstrong, 1980).

Spawning takes place in the estuaries and in waters with depths less than 20 m (Jones et al., 1978; Ward & Armstrong, 1980). Larvae will migrate to shallower and less saline reaches of the estuaries and into river mouths (Peebles, 2002; Raynie & Shaw, 1994), while juveniles and adults form large schools that move into rivers, throughout the estuaries, and into shallow coastal waters (Figure 1).

Bay anchovy exploit a wide variety of habitats including bays and bayous, muddy coves, grassy areas, along beaches, rivers and their mouths, and both shallow and deeper waters offshore, but prefer bays and estuaries in the northern Gulf of Mexico (Pattillo et al., 1997 and references therein). They are particularly abundant in large bays, around shallow bay margins, islands, tidal passes, canals, and sheltered coves (Pattillo et al., 1997). Life history reports and species accounts regard bay anchovy as a true euryhaline and eurythermal species tolerant of a wide range of salinities and temperatures (Houde & Zastrow, 1991; Pattillo et al., 1997). Although bay anchovy can tolerate a wide range of salinities and temperature, their optimum range is considerably narrower, as indicated in Table 1.

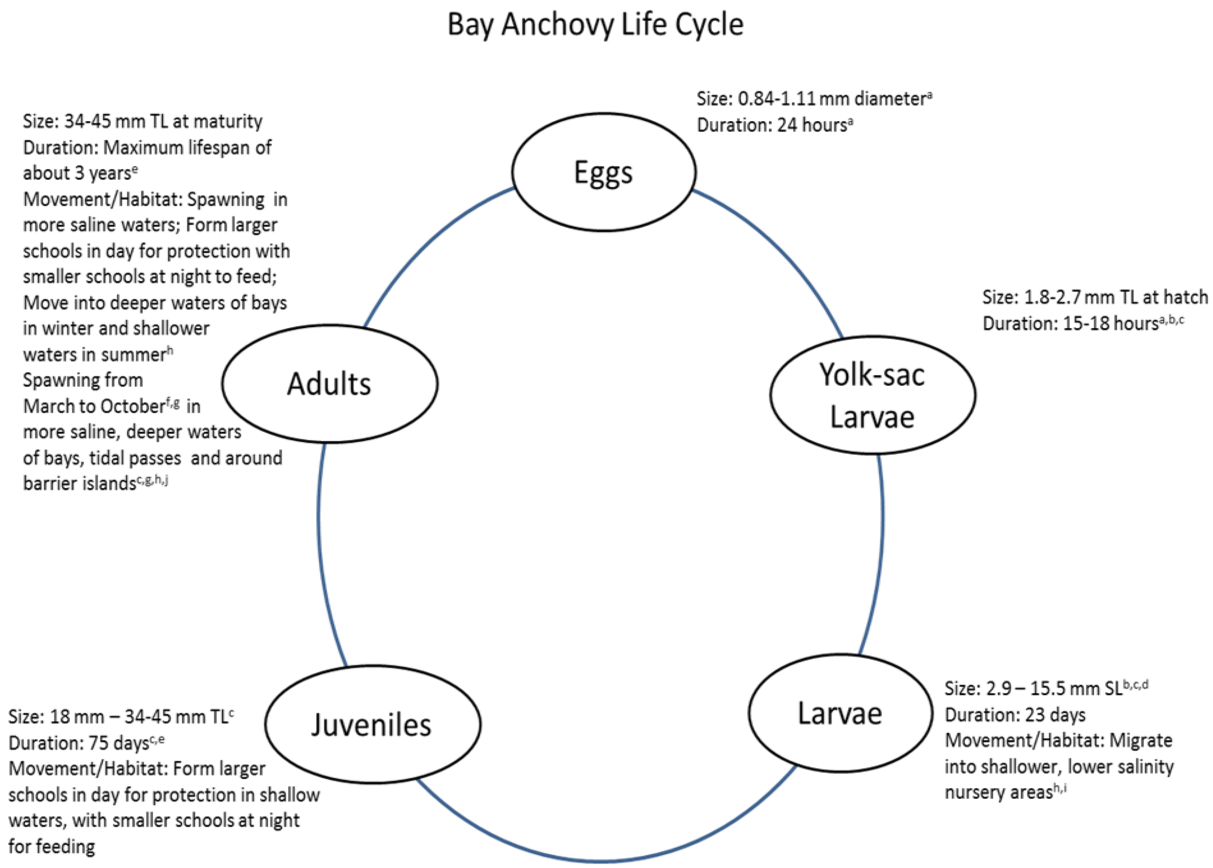


Figure 1: Bay Anchovy Life Cycle Diagram ([a] Morton, 1989; [b] Houde, 1978; [c] Ward & Armstrong, 1980; [d] Pattillo et al., 1997; [e] Houde & Zastrow, 1991; [f] Wagner, 1973; [g] Sabins & Truesdale, 1974; [h] Perry & Boyles, 1977; [i] Raynie & Shaw, 1994; [j] Jones et al., 1978).

The spatial and temporal distribution of bay anchovy life stages within the estuary is summarized by a space-time plot (Figure 2). The space-time plot indicates the relative abundance of each life stage throughout the year in each region: upper, mid, and lower estuary, and inner and outer shelf. The regions of the estuary 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.

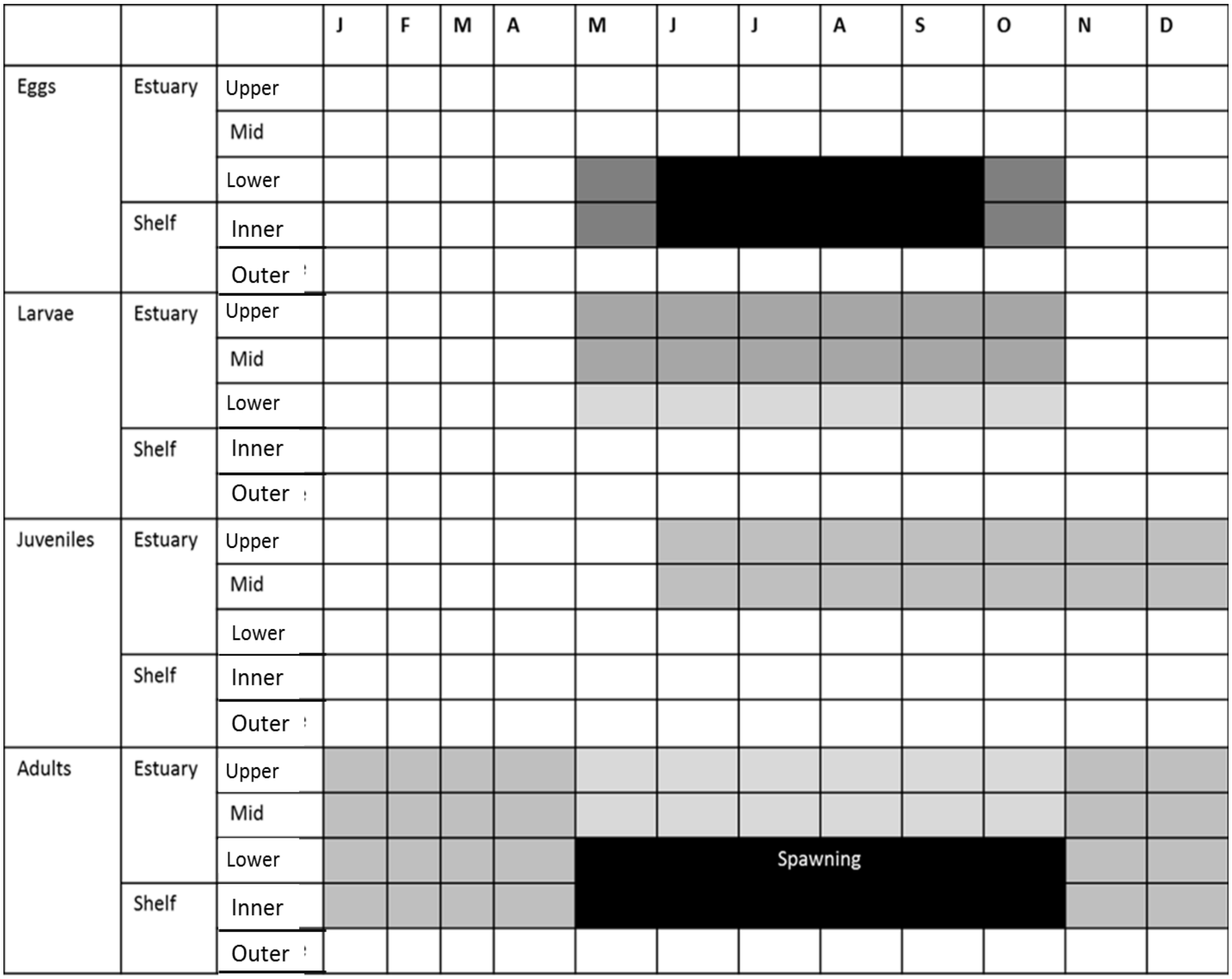


Figure 2: Space-Time Plot by Life Stage for Bay Anchovy Showing Relative Abundance in the Upper, Mid, and Lower Region of the Estuary and the Inner and Outer Shelf Regions by Month. White cells indicate the life stage is not present, light grey cells indicate the life stage is at moderate abundance,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

Table 1: Habitat Requirements for Bay Anchovy Life Stages. Pattillo et al. (1997) was 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 (m)	DO (mg/L)
Egg	30-37	22-32	-	-	-	≤ 3.5 reduces survival
Larvae	3-7 (0-80)	22-32 (5-40)	-	-	-	≤ 3.5 reduces survival
Juvenile	3-10 (0-80)	(5-40)	Can use shallow marsh edge and tidal creeks 1-2.5	Shallow non-vegetated	Attracted to higher turbidity; Found in 0.5-0.7	1.5-12 ≤ 3 limits productivity
Adults: Foraging Spawning	6-15 (0-80) 30-37	8-32 ≥20	1-2.5 (0.5-20) < 20	Shallow non-vegetated Barrier islands, tidal passes	Attracted to higher turbidity; Found in 0.5-0.7	1.5-12 ≤ 3 limits productivity

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. The 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 50 ft seine and the 16 ft trawl were evaluated for statistical relationships among the associated environmental data and bay anchovy CPUE. 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 (LDWF, 2002). 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. The seines consistently sample high numbers of juvenile (i.e., young-of-year; YOY) bay anchovy. The 16 ft trawls have historically been 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 in the larger inshore 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 (LDWF, 2002). The 16 ft trawls also consistently collect high numbers of bay anchovy.

LDWF also measures temperature, conductivity, salinity, turbidity, 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 the trawling method disturbs the sediment and thus greatly affects turbidity and species catchability. For the analyses, the associated turbidity, salinity, and temperature measurements were evaluated with the juvenile CPUE from the seine station samples, whereas salinity and temperature measurements were evaluated with the adult CPUE from the 16 ft trawl station samples. Salinity and temperature are measured at the top and bottom of the water column and an average of their measurements was 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 prey concentration (using chlorophyll concentration as a proxy) and vegetated/non-vegetated habitat are not available from the LDWF datasets. However, a cursory examination of the catch and length data from the seines and trawls was made to support the premise that smaller juveniles would be caught near the shallow vegetated habitats (Baltz & Jones, 2003). Thus, the statistical analysis presented here focused on the water quality data collected by LDWF, and then theoretical, literature-based relationships for prey concentration and wetland vegetation were incorporated.

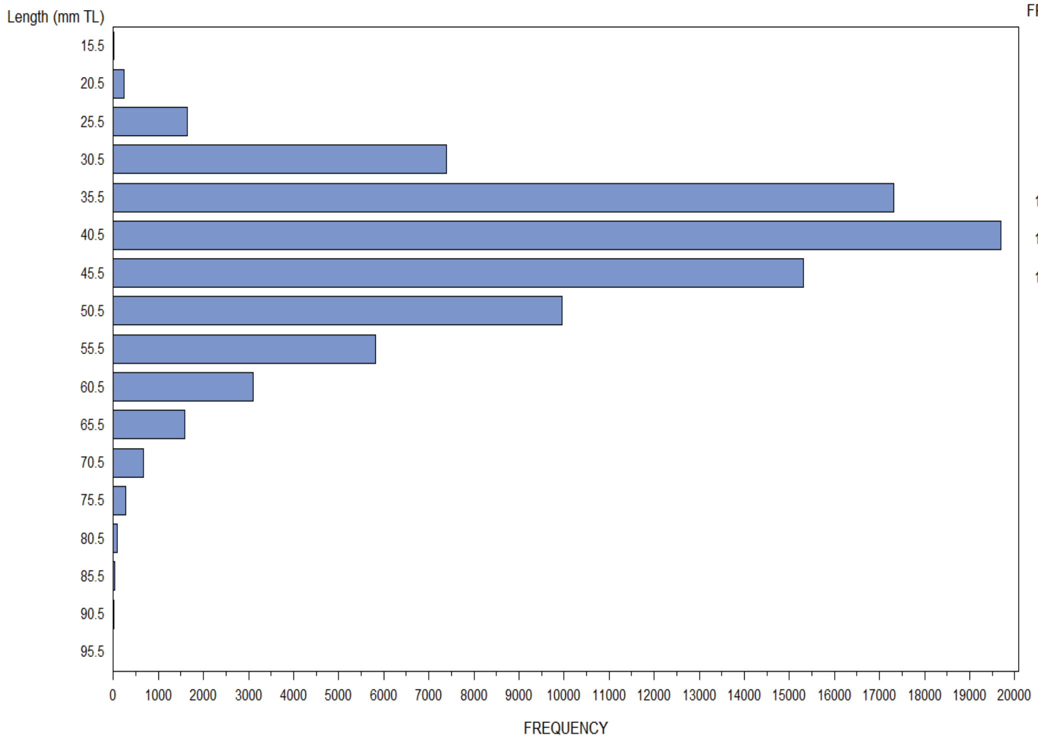
Length distributions of the species were plotted by each gear type to determine if the catch was comprised of primarily juveniles, adults, or a combination of the life stages. Mean monthly CPUE by year was also estimated and then plotted for the species in each gear to determine which months had the highest consistent catch over time and which months had variable and low or no catch over time. These plots allowed us to subset 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 bay anchovy caught in the 50 ft seine samples (Figure 3) showed approximately 74% of the catch were juveniles between 15-45.5 mm total length (TL) with the remaining catch being adults larger than 45.5 mm TL (Houde & Zastrow, 1991). The estimated CPUE from the 50 ft seine samples along the shallow shorelines and marsh edge habitat is therefore primarily representative of juvenile bay anchovy.

The plot of mean CPUE by month for each year indicated bay anchovy were caught in the 50 ft seines year-round (Figure 4). Therefore, the seine data for all months within a year and over all available years were used for the statistical evaluation of the bay anchovy CPUE-environment relationships.

The seine data collected 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 bay anchovy CPUE. Day of year and its squared term were also included in the model to help account for any seasonal variation in bay anchovy CPUE within the estuaries.



Length (mm TL)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
15.5	15	15	0.02	0.02
20.5	238	253	0.29	0.30
25.5	1646	1899	1.98	2.28
30.5	7399	9298	8.90	11.18
35.5	17318	26616	20.83	32.01
40.5	19691	46307	23.68	55.69
45.5	15304	61611	18.41	74.10
50.5	9950	71561	11.97	86.07
55.5	5819	77380	7.00	93.07
60.5	3108	80488	3.74	96.80
65.5	1582	82070	1.90	98.71
70.5	674	82744	0.81	99.52
75.5	272	83016	0.33	99.84
80.5	96	83112	0.12	99.96
85.5	28	83140	0.03	99.99
90.5	4	83144	0.00	100.00
95.5	2	83146	0.00	100.00

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

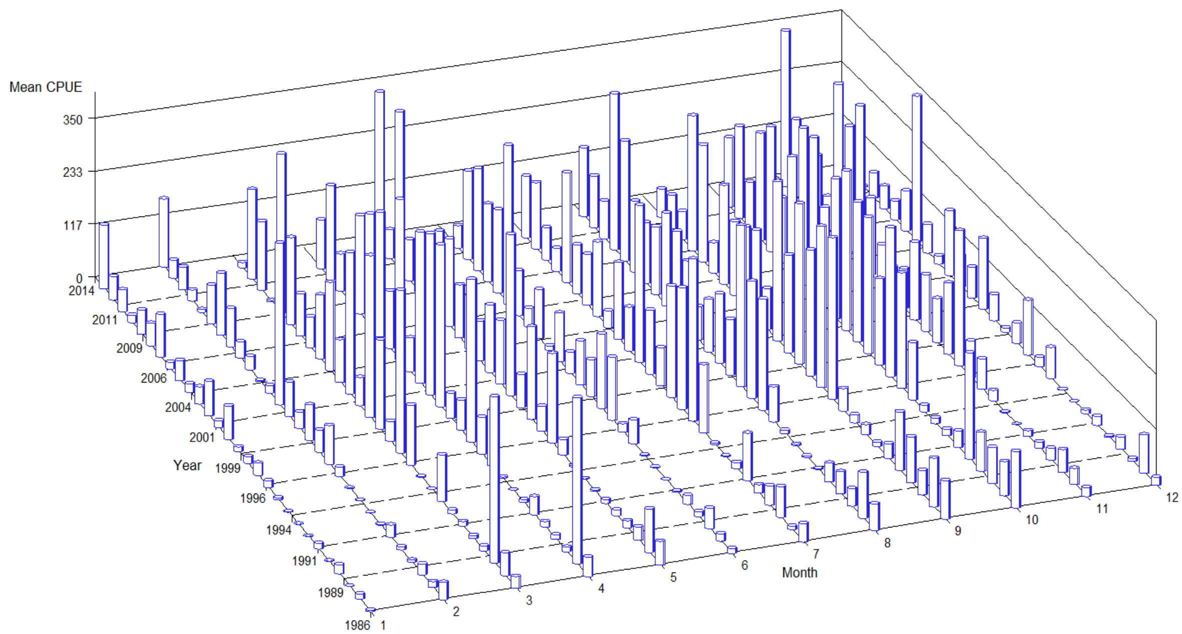


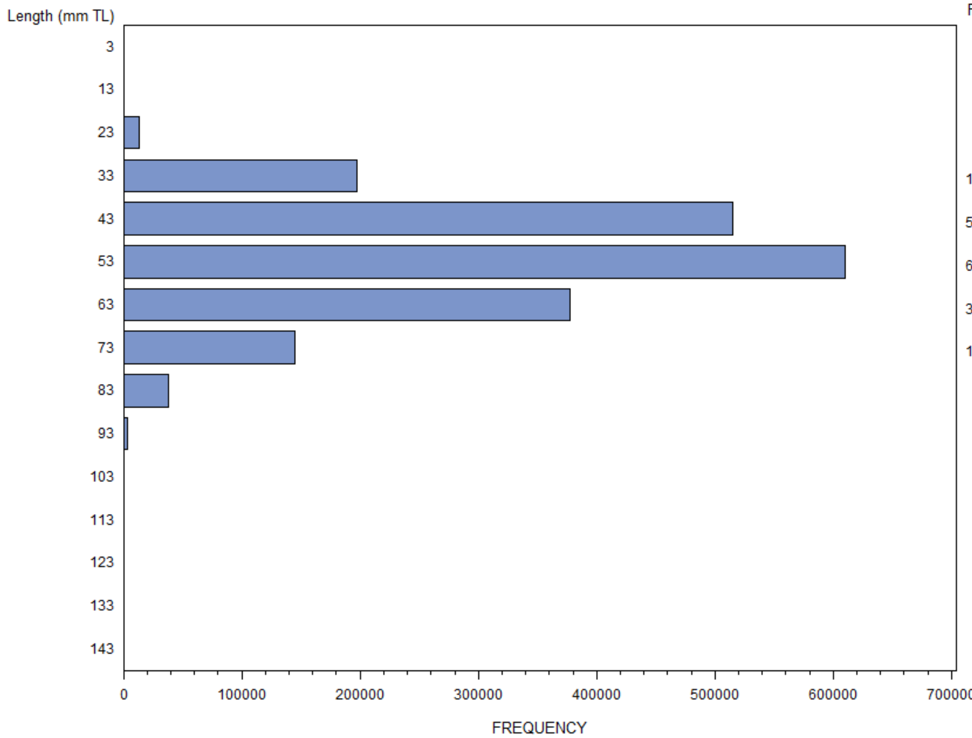
Figure 4: Mean CPUE of Bay Anchovy by Month for Each Year in the 50 Foot Seine Samples.

2.2 16 Foot Trawls

The length distribution of bay anchovy caught in the 16 ft trawl samples showed that the catch was comprised of approximately 40% juveniles (≤ 43 mm TL) and 60% adults (Figure 5). The estimated CPUE from the 16 ft trawl samples taken in the deeper open waters of the bays and estuaries is therefore assumed to be primarily representative of adult bay anchovy.

The plot of mean CPUE by month for each year showed bay anchovy were caught in the 16 ft trawls year-round (Figure 6). Therefore, the trawl data for all months within a year and over all available years were used for the statistical evaluation of the bay anchovy CPUE-environment relationships.

The trawl data collected over all available years of record (1966-2013) across the Louisiana coastline were evaluated to determine if the averaged salinity and averaged water temperature were related to the bay anchovy CPUE. Day of year and its squared term were also included in the model to help account for any seasonal variation in bay anchovy CPUE within the estuaries.



Length (mm TL)	FREQ.	CUM. FREQ.	PCT.	CUM. PCT.
3	7	7	0.00	0.00
13	251	258	0.01	0.01
23	13531	13789	0.71	0.73
33	197593	211382	10.39	11.12
43	515107	726489	27.10	38.21
53	609585	1336074	32.06	70.28
63	377307	1713381	19.85	90.13
73	145162	1858543	7.64	97.76
83	38417	1896960	2.02	99.78
93	3363	1900323	0.18	99.96
103	360	1900683	0.02	99.98
113	127	1900810	0.01	99.99
123	56	1900866	0.00	99.99
133	43	1900909	0.00	99.99
143	183	1901092	0.01	100.00

Figure 5: Length-Frequency Distribution of Bay Anchovy Caught in the 16 Foot Trawl Samples for Louisiana.

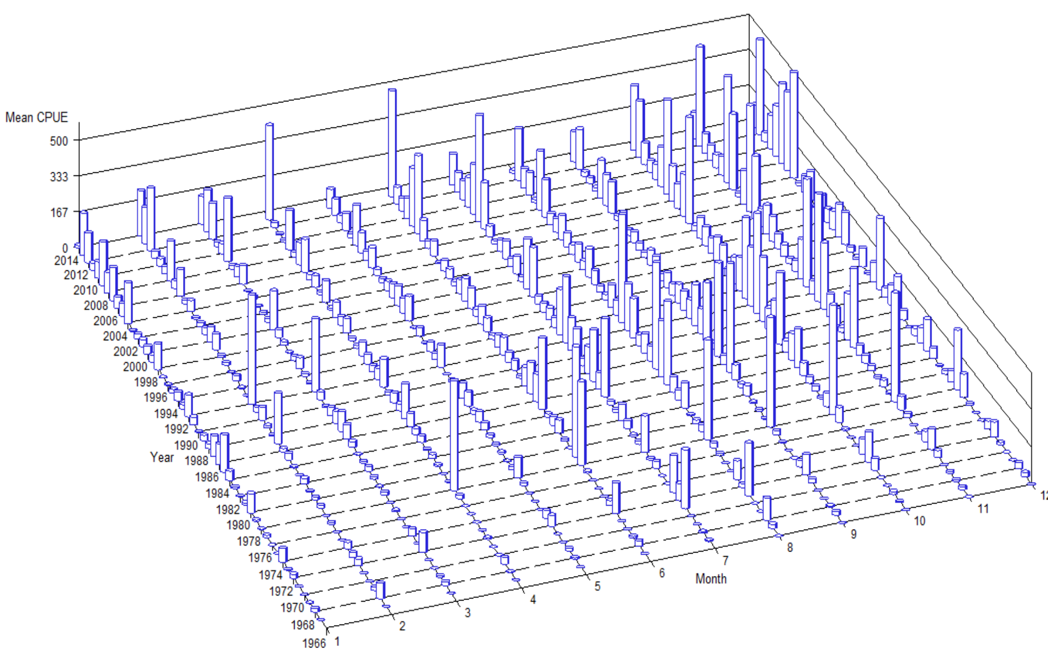


Figure 6: Mean CPUE of Bay Anchovy by Month for Each Year in the 16 Foot Trawl Samples.

2.3 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. As a result, the data were natural log-transformed for the analysis. 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 the bay anchovy respond nonlinearly to environmental variables as well (i.e., they have optimal values for biological processes; Rubec et al., 2001). 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 in the polynomial regression equation.

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 on the model estimates. 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 ($p<0.05$).

3.0 Results

3.1 Seines

The regression analyses for the seines were initially run with salinity, temperature and turbidity 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 (i.e., quickly changing direction) within the function 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 juvenile bay anchovy CPUE (natural log transformed) in terms of all significant effects from salinity and temperature, the squared terms and the interactions, and day of year (Equation 1; Table 2). Surface response plots are used to visually depict the relationships for the two interacting independent variables (x,y) and CPUE (z) with the day variable set to its mean value (Figure 7). The scatter plot overlaid on the surface response shows the LDWF data used to develop the polynomial regression.

The surface response plot (Figure 7) shows that juvenile bay anchovy abundance [ln(CPUE+1)] is a peak function of temperature. Bay anchovy catch in the seines increases from low temperatures between 5 and 10°C to peak from about 20°C through 30°C and then decrease again at higher temperatures. There is no relationship between juvenile bay anchovy CPUE and salinity (Figure 7, Table 2). These results generally agree with the life history information (Figure 1 and Table 1) for the seasonal timing and wide-scale distribution of anchovy throughout the estuary. The surface response equation (Figure 7) is truncated to predict zero catch when temperatures fall below 5-10°C because there were no catch data for juvenile bay anchovy below these temperatures.

$$\begin{aligned}\ln(CPUE+1) = & -2.6496 + 0.8946(Day) - 0.1896(Day^2) - 0.00678(Salinity) \\ & +0.4324(\text{Temperature}) - 0.0003(Salinity^2) + 0.000008(Salinity^2 * Temperature^2) \\ & -0.00023(Temperarature * Salinity^2) - 0.00924(Temperature^2) \qquad (1)\end{aligned}$$

Table 2: List of Selected Effects with Parameter Dstimates 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	-2.6496	<.0001
Day	0.8946	<.0001
Day^2	-0.1896	<.0001
Salinity	-0.00678	0.2793
Temperature	0.4324	<.0001
$Salinity^2$	-0.0003	0.7296

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

Selected Effects	Parameter Estimate[1]	p value
$Salinity^2*Temperature^2$	0.000008	<.0001
$Temperature*Salinity^2$	-0.00023	0.0032
$Temperature^2$	- 0.00331	<.0001

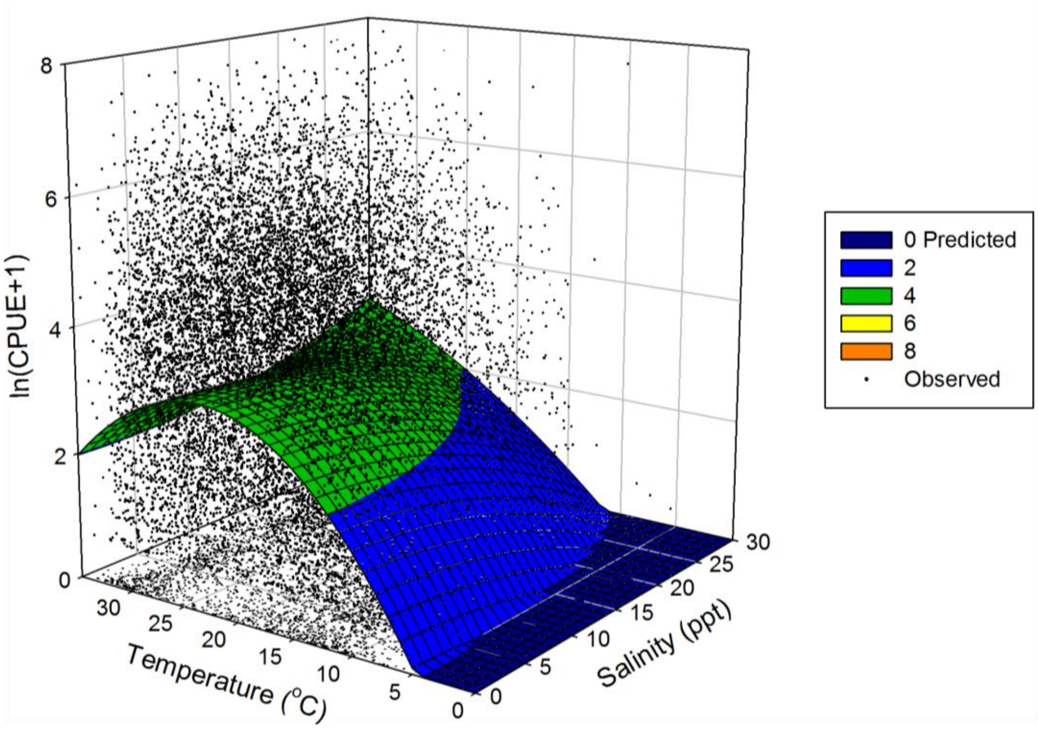


Figure 7: Surface Plot for the Polynomial Regression in Equation 1 over the Range of Salinity and Temperature Values and using a Mean Day of June 29 in the Equation. The scatter plot of salinity, temperature and bay anchovy CPUE data from the 50 ft seine station samples are overlaid on the plot.

3.2 16 Foot Trawls

The resulting polynomial regression model (Equation 2) from the trawl analysis describes adult bay anchovy (natural log transformed) in terms of all significant effects from salinity and temperature, the squared terms and the interactions, and day of year. Table 3 lists the selected effects with the parameter estimates and their resulting level of significance for the polynomial regression. The surface response plot demonstrates the relationships for the two interacting independent variables (x,y) and CPUE (z) with the day variable set to its mean value (Figure 8). The scatter plot overlaid on the surface response shows the LDWF 16 ft trawl data used to develop the polynomial regression.

The surface response plot (Figure 8) shows that bay anchovy CPUE [ln(CPUE+1)]is a gradually peaking function of both temperature and salinity. Bay anchovy catch in the trawls increases from low and high temperatures to gradually peak around 20°C for most salinities. Likewise, bay anchovy catch in the trawls increases from low and high salinities to peak around 18-22 ppt over most temperatures. An increase in CPUE occurs at the extreme salinity and temperature combinations and is an artifact of the polynomial regression. There are few observed salinities and temperatures at the extremes and the model does not accurately predict beyond the available data.

$$\ln(CPUE+1) = 4.3195 - 0.363(Salinity) - 0.3057(Temperature) + 0.0108(Salinity^2) + 0.00872(Temperature^2) + 0.0633(Salinity * Temperature) + 0.000045(Salinity^2 * Temperature^2) - 0.00162(Salinity * Temperature^2) - 0.00183(Salinity^2 * Temperature) \quad (2)$$

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	4.3195	<.0001
Salinity	-0.363	<.0001
Temperature	-0.3057	<.0001
$Salinity^2$	0.01084	<.0001
$Temperature^2$	8.72E-03	<.0001
Salinity*Temperature	0.0633	<.0001
$Salinity^2$*$Temperature^2$	4.5-05	<.0001
Salinity*$Temperature^2$	-1.62E-03	<.0001
$Salinity^2$*Temperature	-1.83E-03	<.0001

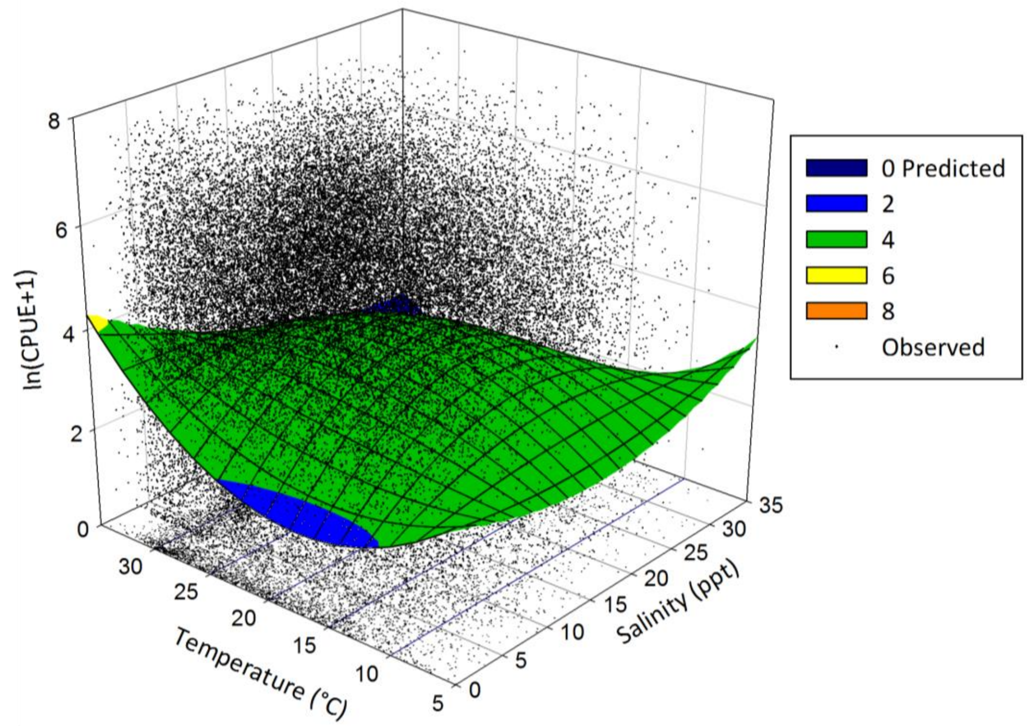


Figure 8: Plot for the Polynomial Regression in Equation 2 over the Range of Salinity and Temperature Values and using a Mean Day of June 29 (Day 180) in the Equation. The scatter plot of salinity, temperature and bay anchovy CPUE data from the 16-foot trawl station samples are overlaid on the plot.

4.0 Habitat Suitability Index Model for Juvenile Bay Anchovy

Although the polynomial regression function in Equation 1 appears complex, the regression model is simply describing the relationship among juvenile anchovy catch in the seines and the salinity and temperature taken with the samples. In order to use the polynomial regression (Equation 1) within the juvenile anchovy HSI model, the equation was standardized to a 0-1 scale. Standardization of the equation was performed by first back-transforming the predicted CPUE [ln(CPUE+1)] to untransformed CPUE values. The predicted untransformed CPUE values were then standardized by the maximum predicted (untransformed) CPUE value from the response function. Maximum CPUE was calculated by running the polynomial model through salinity and temperature combinations that fall within plausible ranges.

A predicted maximum juvenile anchovy ln(CPUE+1) value of 3.43 was generated from the seine polynomial regression at a temperature of 23°C and salinity of 0 ppt. Recall the anchovy CPUE did not show a significant relationship with salinity in the seines, so the maximum at 0 ppt is not surprising. The back-transformed CPUE value (30.14) was used to standardize the other predicted untransformed CPUE values from the regression. The resulting standardized water quality suitability index was combined with standardized (0-1) indices for emergent vegetation and plankton prey concentration (as indicated by Chlorophyll *a* concentration) to produce the juvenile bay anchovy HSI model. All three components of the model are equally weighted and the geometric mean is used as all variables are considered essential to juvenile bay anchovy:

$$HSI = (SI_1 * SI_2 * SI_3)^{1/3}$$

Where:

SI_1 – Suitability index for juvenile anchovy in relation to salinity and temperature (V_1)

SI_2 – Suitability index for juvenile anchovy in relation to the percent of cell that is emergent vegetation (V_2)

SI_3 – Suitability index for juvenile anchovy in relation to Chlorophyll *a* concentration in the cell (V_3)

4.1 Applicability of the Model

This model is applicable for calculating the habitat suitability index for YOY juvenile bay anchovy (median size about 40 mm TL from Figure 3) year-round in coastal Louisiana marsh edge and shallow shoreline habitats of the estuaries.

4.2 Response and Input Variables

V_1: Salinity and temperature throughout the year

Calculate monthly averages of salinity (ppt) and temperature (°C) throughout the year:

$$V_1 = -2.6496 + 0.8946(2) - 0.1896(2^2) - 0.00678(Salinity) + 0.4324(\text{Temperature}) - 0.0003(Salinity^2) + 0.000008(Salinity^2 * Temperature^2) - 0.00023(Temperarature * Salinity^2) - 0.00924(Temperature^2)$$

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

$$SI_1 = \frac{e^{\ln(CPUE+1)} - 1}{30.14}$$

which includes the steps for back-transforming the predicted CPUE from Equation 1 and standardizing by the maximum predicted (untransformed) CPUE value equal to 30.14. The surface response for SI_1 is demonstrated in Figure 9.

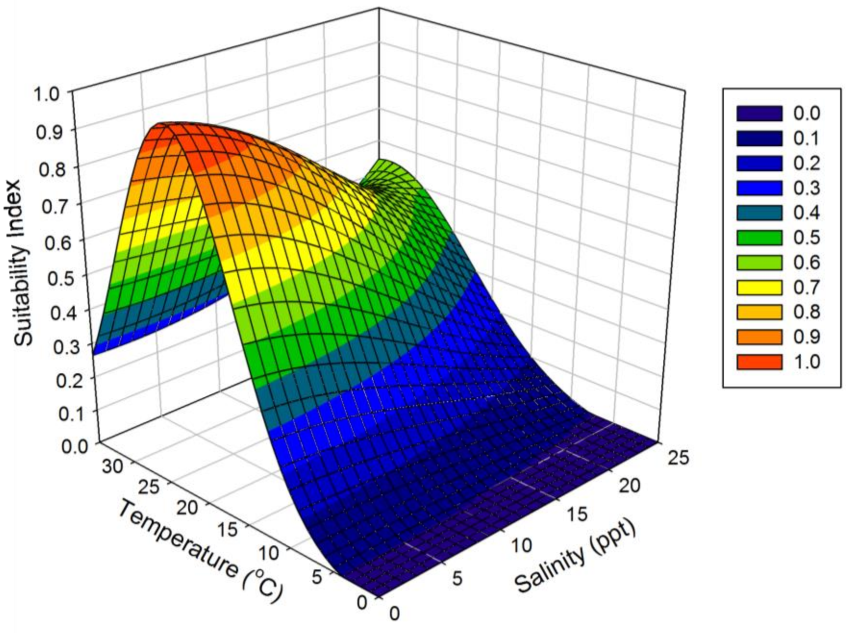


Figure 9: Surface Plot Demonstrating the Predicted Suitability Index (0-1) for Juvenile Bay Anchovy in Relation to Salinity and Temperature and Resulting from the Back-Transformation and Standardization of the Polynomial Regression in Equation 1.

Rationale*:* Salinity and temperature are important abiotic factors that can influence the spatial and temporal distribution of juvenile bay anchovy in the estuaries within a year. The suitability index for juvenile anchovy 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 the 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 bay anchovy (Table 1).

Limitations*:* The variable 'day' in Equation 1 has been replaced by a constant value equal to the mean day from the analysis (June 29).[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 the juvenile bay anchovy most commonly occur, as dictated by physiological tolerances, prey availability, mortality, seasonal movements, and other factors.

V_2: Percent of cell that is covered by land, including all types of emergent vegetation

V_2 is the percent of the (500 x 500 m) cell that is covered by land (i.e., emergent wetland vegetation of all types). The equation for SI_2 is plotted in Figure 10. The index is calculated as:

[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.

$SI_2 = 0.028 * V_2 + 0.3$ for $V_2 < 25$

1.0 for $25 \le V_2 \le 80$

$5.0 - 0.05 * V_2$ for $V_2 > 80$

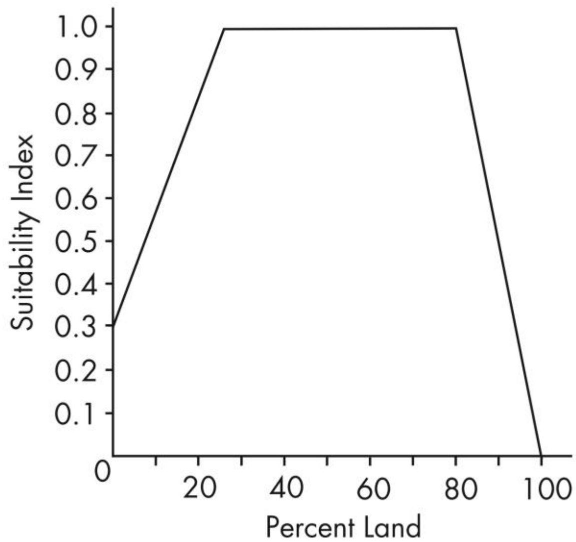


Figure 10: The Suitability Index for Juvenile Bay Anchovy in Relation to the Percent Emergent Vegetation (Percent Land = V_2).

Rationale: The percent of wetland or total vegetated area within the cell is directly proportional to the marsh habitat's long-term carrying capacity for the juvenile anchovy. This relationship was initially defined 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 juvenile spotted seatrout in the 2012 Coastal Master Plan (CPRA, 2012) to represent these species dependence upon shallow marsh habitats for feeding and growth (Baltz & Jones, 2003). Shallow marsh edge habitat and shallow tidal marsh creeks and channels are also important habitat to juvenile bay anchovy in their first year of life, providing prey and increased cover from predators. Thus, the optimum percent wetland SI for juvenile anchovy was set similar to that of the 2012 Coastal Master Plan HSIs (CPRA, 2012) at 25-80%. The SI for 0% land (or 100% open water) was set at 0.3 to reflect the lower protection from predation afforded by open water.

Limitations: The model does not quantify specific habitats such as submerged aquatic vegetation or marsh edge, and instead identifies the general landscape configuration (land:water) where optimum levels of these habitats are expected to occur.

V_3: Chlorophyll *a* concentration in cell

V_3 is the concentration of Chl *a* (µg/l) for the 500 X 500 m cell. The suitability index describes juvenile bay anchovy feeding in response to Chl *a* concentration, as described by Lynch (2007; Figure 11).

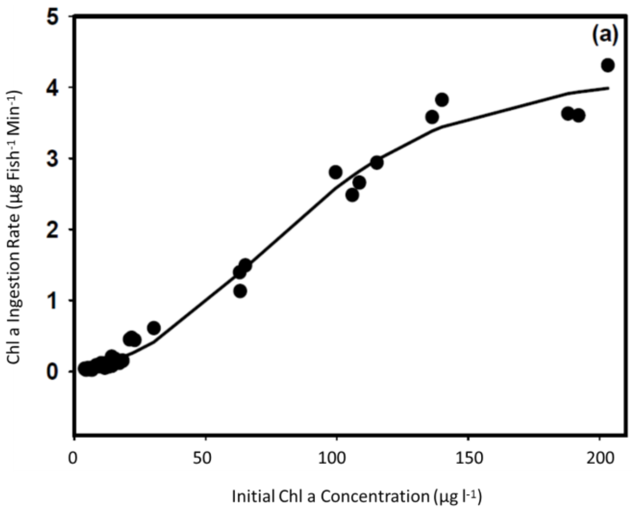


Figure 11: Holling Type III Functional Response (Holling, 1959) Fit to Data Describing Juvenile Gulf Menhaden Ingestion Rate by Chl a Concentration (taken from Lynch, 2007).

The resulting suitability index (SI_3) demonstrated in Figure 12 is standardized by simply dividing the predicted ingestion rates from Lynch (2007) by the maximum predicted ingestion rate of 3.82 µg fish^{-1} min^{-1}(Figure 11).

$$SI_3 = \frac{4.18e^{(-4.59e^{(-0.02*Chl\ a)})}}{3.82}$$

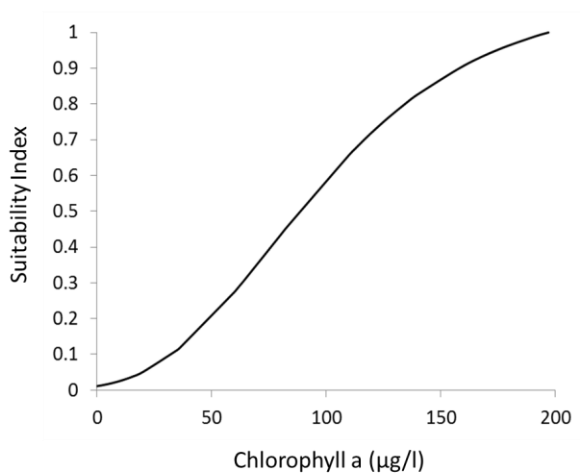


Figure 12: The Resulting Suitability Index (SI_3) for Juvenile Bay Anchovy in Relation to Chlorophyll a Concentration in a 500 X 500 m Cell.

Rationale: The Type III (sigmoidal) feeding response function was found to be the best fit for menhaden ingestion rate data when compared to Holling Type I (linear) and Type II (asymptotic) feeding functions (Lynch, 2007). The sigmoidal response is often used to describe fish feeding in response to plankton prey concentration because ingestion rates are low at low plankton concentrations and rates increase with increases in prey but also as fish swimming speed increases (Durbin et al., 1981; Luo et al., 2001; Lynch, 2007). Although the feeding response described herein was found for menhaden feeding primarily on phytoplankton, it should also apply to bay anchovy because concentrations of their zooplankton prey, which determine bay anchovy movement on the shelf and within the estuaries (Pattillo et al., 1997; Houde & Zastrow, 1991), are often found in close association with phytoplankton (Chl a) concentrations. Therefore, the suitability index is appropriate to describe the dependence of bay anchovy juveniles on Chl *a* concentration and distribution within the estuaries.

Limitations: The assumption is that the relationship found for juvenile Gulf menhaden may also be applied to bay anchovy. The relationship assumes that habitat suitability for juvenile anchovy is directly related to Chl *a* concentration, and that phytoplankton and zooplankton sizes and composition, suspended detritus and particulate organic carbon do not affect anchovy ingestion rates.

5.0 Habitat Suitability Index Model for Adult Bay Anchovy

A predicted maximum adult anchovy ln(CPUE+1) value of 3.782 was generated from the 16 ft trawl polynomial regression at a temperature of 21°C and salinity of 18 ppt (see Section 4.0 for description of how the maximum value was generated). The back-transformed CPUE value (42.92) was used to standardize the other predicted untransformed CPUE values from the regression. The surface response that describes the standardized adult anchovy response (0-1) to salinity and temperature is shown in Figure 13. This predicted response surface is the resulting water quality suitability index to be used for the adult anchovy.

The standardized water quality index was combined with standardized (0-1) indices for percent wetland (open water) habitat and plankton prey concentration (as indicated by Chlorophyll *a* concentration) to produce the adult bay anchovy HSI model. All three components of the model are equally weighted and the geometric mean is used as all variables are considered essential to adult bay anchovy:

$$HSI = (SI_1 * SI_2 * SI_3)^{1/3}$$

Where:

SI_1 – Suitability index for adult anchovy in relation to salinity and temperature (V_1)

SI_2 – Suitability index for adult anchovy in relation to the percent of cell that is emergent vegetation (V_2)

SI_3 – Suitability index for adult anchovy in relation to Chlorophyll *a* concentration in the cell (V_3)

5.1 Applicability of the model

This model is applicable for calculating the habitat suitability index for adult bay anchovy (median size about 50 mm TL from Figure 5) in the open waters of Louisiana estuaries.

5.2 Response and Input Variables

V_1: Salinity and temperature throughout the year

Calculate monthly averages of salinity (ppt) and temperature (°C) throughout the year:

$V_1 = 4.3195 - 0.363(Salinity) - 0.3057(Temperature) + 0.0108(Salinity^2) + 0.00872(Temperature^2) + 0.0632(Salinity * Temperature) + 0.000045(Salinity^2 * Temperature^2) - 0.00162(Salinity * Temperature^2) - 0.00183(Salinity^2 * Temperature)$

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

$$SI_1 = \frac{e^{V_1} - 1}{42.92}$$

which includes the steps for back-transforming the predicted CPUE from Equation 2 and standardizing by the maximum predicted (untransformed) CPUE value equal to 42.92. The surface response for SI_1 is demonstrated in Figure 13.

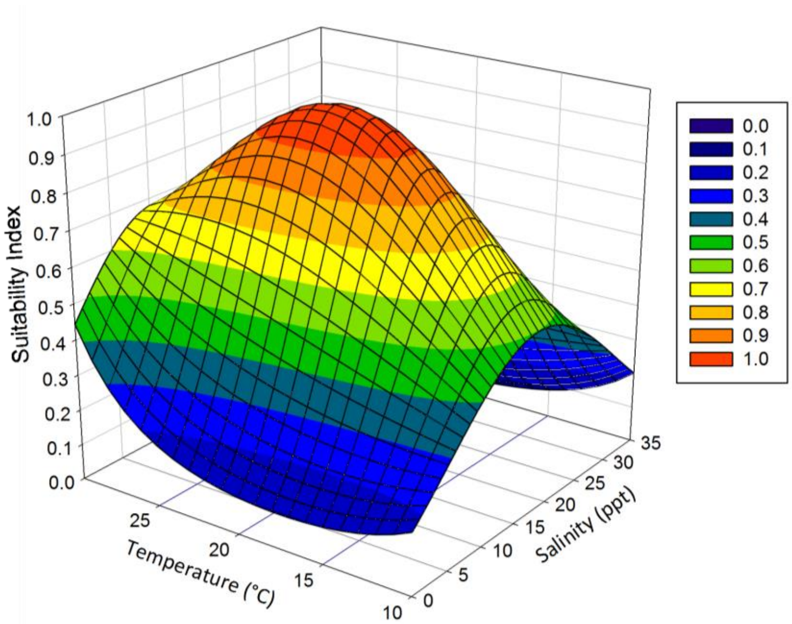


Figure 13: Surface Plot Demonstrating the Predicted Suitability Index (0-1) for Adult Bay Anchovy in Relation to Salinity and Temperature and Resulting from the Back-Transformation and Standardization of the Polynomial Regression in Equation 2.

Rationale*:* Salinity and temperature are important abiotic factors that can influence the spatial and temporal distribution of adult bay anchovy in the estuaries within a year. The suitability index for adult anchovy 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 the LDWF 16 ft trawl samples. The resulting suitability index predicts salinity and temperature ranges and optimums that generally correspond with the ranges and optimums previously described in the literature for bay anchovy (Table 1).

Limitations*:* The variable 'day' in Equation 2 has been replaced by a constant value equal to the mean day from the analysis (June 29). 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 results may be skewed by the presence of juveniles in the trawl catch data. Finally, 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 adult bay anchovy most commonly occur, as dictated by physiological tolerances, prey availability, mortality, seasonal movements, and other factors.

V_2: Percent of cell that is covered by land

V_2 is the percent of the (500 x 500 m) cell that is covered by land (i.e., emergent wetland vegetation of all types). The equation for SI_2 is plotted in Figure 14. The index is calculated as:

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

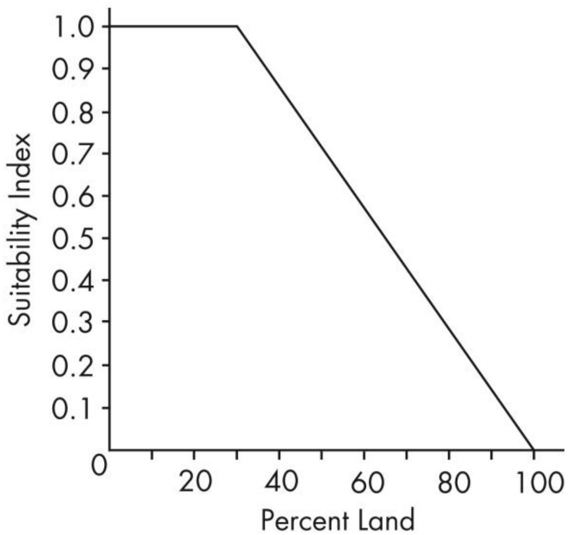


Figure 14: The Suitability Index for Adult Bay Anchovy in Relation to the Percent Land = V_2.

Rationale: Adult anchovy more commonly use the larger open water habitats presumably because their plankton prey are more abundant and concentrated in the open waters. The SI for adult anchovy was set to 1.0 when percent land within a cell is zero to 30% (or open water at 100 to 70%) in order to place adults within the open water habitats of the estuaries. It is assumed the suitability of a cell for supporting adult anchovy will decrease as percent land increases beyond 30%, and the cell is not suitable for adult anchovy when percent land reaches 100%.

Limitations: None.

V_3: Chlorophyll *a* concentration in cell

V_3 is the concentration of Chl *a* (µg/l) for the 500 X 500 m cell. The suitability index describes adult bay anchovy feeding in response to Chl *a* concentration, as described by Lynch (2007; Figure 11). Use the same relationship for adult bay anchovy with the same resulting suitability index (SI_3) demonstrated in Figure 12.

Rationale: The sigmoidal response is often used to describe fish feeding in response to plankton prey concentration because ingestion rates are low at low plankton concentrations and rates increase with increases in prey but also as fish swimming speed increases (Durbin et al., 1981; Luo et al., 2001; Lynch, 2007). Although the ingestion response described herein relates to menhaden primarily feeding on phytoplankton, it should also apply to bay anchovy because concentrations of their zooplankton prey, which determine bay anchovy movement on the shelf and within the estuaries (Pattillo et al., 1997; Houde & Zastrow, 1991), are often found in close association with phytoplankton (Chl a) concentrations. Therefore, the suitability index is appropriate to describe the dependence of adult bay anchovy on Chl *a* concentration and distribution within the estuaries.

Limitations: The suitability index assumes that the relationship found to exist between juvenile Gulf menhaden and Chl *a* concentration is the same for juvenile and adult bay anchovy.

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 bay anchovy. 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. An accurate representation of phytoplankton in the system was not available as input to generate a chlorophyll *a* suitability index score, and thus SI_3 was held constant at 1 for all model runs.

For the juvenile bay anchovy 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 Terrebonne Bay. For adult bay anchovy, the reverse was observed. Highest scores were observed in all open water bodies across the coast, 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 juvenile and adult models, HSI scores greater than 0 were observed in isolated areas in the upper Atchafalaya Basin. In a survey of finfish fauna between Simmesport and Morgan City, anchovies were limited to the marine and estuarine areas of the Atchafalaya Basin (Lambou, 1990) and thus are not likely to occur in these most northern reaches. 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 juvenile and adult bay anchovy habitat distributions in coastal Louisiana.

Although the polynomial regression model used to fit the LDWF seine and trawl data produced functions relating bay anchovy 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.

7.0 References

Baltz, D.M., and Jones, R.F. (2003). Temporal and spatial patterns of microhabitat use by fishes and decapod crustaceans in a Louisiana estuary. *Transactions of the American Fisheries Society* 132, 662–678.

Coastal Protection and Restoration Authority (CPRA). (2012). *Louisiana's Comprehensive Master Plan for a Sustainable Coast*. Baton Rouge, LA: CPRA. (p. 186).

Daly, R.J. (1970). Systematics of southern Florida anchovies (Pisces: Engraulidae). *Bulletin of Marine Science* 20, 70–104.

Durbin, A.G., Durbin, E.G., Verity, P.G., and Smayda, T.J. (1981). Voluntary swimming speeds and respiration rates of a filter feeding planktivore, the Atlantic menhaden. *Fisheries Bulletin 78*, 877–886.

Hildebrand, S.F. (1943). *A review of the American anchovies*. Bingham Oceanographic Laboratory 8, 29–37.

Holling, C.S. (1959). Some characteristics of simple types of predation and parasitism. *Canadian Entomology*, 91, 385-398.

Hoese, H.D. (1965). *Spawning of marine fishes in the Port Aransas Texas, area as determined by the distribution of young and larvae*. M. S. Thesis, University of Texas, Austin, TX.

Hoese, H.D., and Moore, R.H. (1977). *Fishes of the Gulf of Mexico: Texas, Louisiana, and adjacent waters*. Texas A&M University Press, College Station, TX.

Houde, E. D. (1978). Critical food concentrations for larvae of three species of subtropical marine fishes. *Bulletin of Marine Science, 28,* 395-411.

Houde, E.D., and Zastrow, C.E. (1991). Bay anchovy. In Funderburk, S.L., Jordan, S.J., Mihursky, J.A., and Riley, D. (Eds.) *Bay Anchovy*. Chesapeake Bay Program, Annapolis, MD, pp. 8–14.

Jones, P.W., Martin, F.D., Hardy, J.D., Johnson, G.D., Fritzsche, R.A., and Drewry, G.E. (1978). *Development of fishes of the Mid-Atlantic Bight. An atlas of egg, larval and juvenile stages.* No. U.S. Fish and Wildlife Service FWS/OBS-78/12.

Lambou, V.W. (1990). *Importance of bottomland hardwood forest zones to fishes and fisheries: the Atchafalaya Basin, a case history*. Pages 125–193 in J. G. Gosselink, L. C. Lee, and T. A. Muir, editors. Ecological processes and cumulative impacts: illustrated by bottomland hardwood wetland ecosystems. Lewis Publishers, Inc., Chelsea, Michigan.

Louisiana Department of Wildlife and Fisheries (LDWF). (2002). *Marine Fisheries Division Field Procedure Manual (Ver. 02-1)*. Baton Rouge, LA.

Luo, J., Hartman, K.J., Brandt, S.B., Cerco, C.F., and Rippetoe, T.H. (2001). A spatially-explicit approach for estimating carrying capacity: an application for the Atlantic menhaden (*Brevoortia tyrannus*) in Chesapeake Bay. *Estuaries and Coasts 24,* 545–556.

Lynch, P. D. (2007). *Feeding ecology of Atlantic menhaden (Brevoortia tyrannus) in Chesapeake Bay*. M. S. Thesis, The College of William and Mary, Virginia.

Minello, T. J., and Rozas, L. P. (2002). Nekton in Gulf coast wetlands: Fine-scale distributions, landscape patterns, and restoration implications. *Ecological Applications*, *12*(2), 441–455.

Morton, T. (1989). *Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Mid-Atlantic) --bay anchovy*. U. S. Fish and Wildlife Service Report, 82.

Murtaugh, P. A. (2009). Performance of several variable-selection methods applied to real ecological data. *Ecology Letters, 12(10),*1061-1068.

Pattillo, M. E., Czapla, T. E., Nelson, D. M., and Monaco, M. E. (1997). *Distribution and abundance of fishes and invertebrates in Gulf of Mexico estuaries, Volume II: Species life history summaries.* ELMR Rep. No. 11. NOAA/NOS Strategic Environmental Assessments Division, Silver Spring, MD. 377 p.

Peebles, E.B., Hall, J.R., and Tolley, S.G. (1996). Egg production by the bay anchovy *Anchoa mitchilli* in relation to adult and larval prey fields. *Marine Ecology Progress Series* 131:61–73

Peebles, E.B. (2002). Temporal resolution of biological and physical influences on bay anchovy *Anchoa mitchilli* egg abundance near a river-plume frontal zone. *Marine Ecology Progress Series* 237: 257–269

Peebles, E.B., Burghart, S.E., and Hollander, D.J. (2007). Causes of interestuarine variability in Bay anchovy (*Anchoa mitchilli*) salinity at capture. *Estuaries and Coasts* 30(6):1060-1074

Perry, H.M., and Boyles, D. L. (1977). Menhaden and other coastal pelagic fish. Unpublished manuscript. Gulf Coast Res. Lab., Ocean Springs, MS, 35 p.

Raynie, R.C., and Shaw, R.F. (1994). Ichthyoplankton abundance along a recruitment corridor from offshore spawning to estuarine nursery ground. *Estuarine, Coastal and Shelf Science* 39, 421 – 450.

Reid, G.K. (1955). A Summer Study of the Biology and Ecology of East Bay, Texas. *Texas Journal of Science* 7, 316–343.

Rose, K.A., Cowan Jr, J.H., Clark, M.E., Houde, E.D., and Wang, S.B. (1999). An individual-based model of bay anchovy population dynamics in the mesohaline region of Chesapeake Bay. *Marine Ecology Progress Series* 185, 113–132.

Rubec, P.J., Smith, S.G., Coyne, M.S., White, M., Sullivan, A., MacDonald, T.C., McMichael Jr, R.H., Wilder, D.T., Monaco, M., and Ault, J.S. (2001). Spatial modeling of fish habitat suitability in Florida estuaries, in: Proceedings of Symposium on Spatial Processes and Management of Marine Populations. pp. 1–18.

Sabins, D.S., and Truesdale, F. M. (1974). Diel and seasonal occurrence of immature fishes in a Louisiana tidal pass. Proceedings of the Southeastern Association of Game and Fisheries Commission, 28, 161-171. Louisiana State University, Baton Rouge, LA, 207 p.

Shipp, R.L. (1986). *Guide to fishes of the Gulf of Mexico*. Dauphin Island Sea Lab, Dauphin Island, AL.

Wagner, P.R. (1973). Seasonal biomass, abundance, and distribution of estuarine dependent fishes in the Caminada Bay System of Louisiana. Ph.D. dissertation,

Ward, G.H., and Armstrong, N.E. (1980). *Matagorda Bay, Texas: its hydrography, ecology and fishery resources*. Fish and Wildlife Service Office of Biological Services FWS/OBS-81/52.