MODELING NEKTON HABITAT USE IN GALVESTON BAY, TEXAS:

AN APPROACH TO DEFINE ESSENTIAL FISH HABITAT (EFH)

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EXECUTIVE SUMMARY

The Magnuson-Stevens Fishery Conservation and Management Act requires the identification of Essential Fish Habitat (EFH) for Federally managed fishery species in our Nation's marine and estuarine environments. The intent of this study is describe and discuss a method that can help estuarine resource managers define EFH; this work is currently under joint development between the National Marine Fisheries Service's Southeast Fisheries Science Center (NMFS/SEFSC) Galveston Laboratory and the National Ocean Service's National Centers for Coastal Ocean Science (NOS/NCCOS) Biogeography Program. An analysis of nekton density data in Galveston Bay, Texas was conducted to quantitatively isolate patterns of habitat utilization, based on species abundance, that could potentially be used to define EFH by the Gulf of Mexico Fishery Management Council. Results of this analysis were coupled with a geographical information system (GIS) to provide a spatial mosaic of potential EFH. Nekton densities, from 3,864 drop samples taken over a 16 year period in Galveston Bay, were analyzed to evaluate habitat utilization between vegetated marsh edge (ME), submerged aquatic vegetation (SAV), and shallow non-vegetated bottom (SNB) by brown shrimp (*Farfantepenaeus aztecus*), white shrimp (*Litopenaeus setiferus*), and pinfish (*Lagodon rhomboides*). Although pinfish is not Federally managed, it was selected as a test finfish candidate for the development of the described analytical technique based on data availability. The analysis was further partitioned along seasonal temperature and salinity gradients to explore the extent to which deterministic and/or stochastic factors influence habitat selection. Multiple regression (GLM) was used to develop predictive models based on classified data. Prediction formulae were then applied to habitat geographies in the GIS. The resultant density estimates provided a measure of habitat selection, and subsequently, enable spatial representation and assessment of potential EFH.

The brown shrimp model provides a good example of this approach. Three significant discrete regressors were used to model brown shrimp density: season ($p = <0.0001$); habitat type ($p = 0.0009$); and salinity ($p = <0.0001$). Overall, the model predicted significantly greater densities in high salinity (> 25 ppt) ME and SAV habitats ($p = <0.0001$) explaining 83% of the variance. The model was applied in adjacent estuaries (Aransas, Matagorda, and San Antonio Bays) and regression analysis revealed similar habitat utilization patterns in these systems ($p = <0.0001$). Mapped model results in Galveston Bay revealed a more spatially resolved delineation of potential EFH than existing EFH maps based on ELMR relative abundance data.

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INTRODUCTION

Historically, fishery management practices in the U.S. have focused on assessing stock size and controlling fishing mortality. The Magnuson-Stevens Fisheries Conservation and Management Act of 1996 (MSFCMA) mandates the conservation and management of fishery habitats as an integral component of federal fishery management programs. The National Marine Fisheries Service (NMFS) has developed guidelines to identify EFH based on certain levels of available information that explore the ecological linkages between habitat and fishery production. The most basic level of available information (Level 1, presence/absence data) mainly provides the geographic range of an organism and does little to determine ecological linkages. An examination of habitat use patterns using Level 2 data (habitat-related densities) is needed to determine what habitats are likely to be essential. These patterns are measurable and can be reasonable indicators of habitat value. Considerable variation in structural habitat exists in northern Gulf of Mexico estuaries including, intertidal marsh, submerged aquatic vegetation, oyster reef, mangroves, tidal mudflats, and subtidal bay bottom. Within each of these habitat types there exists numerous physical and structural gradients, which may affect the functional role or importance to a particular species. For example, many estuarine species have been observed to show a physiological and subsequent secondary behavioral response (avoidance/taxis) to salinity within an estuary (Christensen et al. 1997). Elevation and proximity to open water have been observed to affect habitat use in intertidal marsh habitats (Rozas and Reed 1993; Minello et al. 1994; Peterson and Turner 1994; Minello and Webb 1997). Differences in sediment texture in nonvegetated habitats have been related to differences in shrimp (Williams 1958; Rulifson 1981) and fish

(Keefe and Able 1994; Moles and Norcross 1995) distributions. Therefore, not all habitats are of equal importance to the maintenance of a population (Zimmerman et al. 1990b), and the degree to which a specific area of habitat is considered to be essential may change with dynamic gradients.

Both theoretical and empirical studies indicate that dynamic behavior of natural populations is a result of some mixture of density-dependent factors which tend towards stasis and stochastic factors which impose entropy on natural communities and yield unpredictable population fluctuations (Strange et al. 1986). Understanding estuarine community structure and habitat utilization will depend on our knowledge of how these density-dependent and density-independent processes synergistically regulate fish populations (Christensen 1996). Capone and Kushlan (1991) identified interspecific resource competition and predator-prey interactions as the most important density-dependent (deterministic) processes influencing fish community structure and these relationships are controlled by habitat availability. In contrast, variations in physico-chemical gradients, such as salinity, are the overriding density-independent or stochastic processes.

In this analysis, nekton density data were combined with statistical models to assess EFH in Galveston Bay, Texas. Vegetated estuarine habitats are known to be valuable nursery areas for fishery species (Gunter 1941, 1961; Hildebrand and Gunter 1953; St. Amant et al. 1962; Zein-Eldin 1963). However, most interhabitat comparisons of animal densities have been between seagrass and non-vegetated bottom (Williams et al. 1990; Sheridan 1992; Valentine et al. 1994). Limited comparisons of nekton density are available between tidal marsh and nonvegetated bottom (Zimmerman and Minello

1984; Minello et al. 1991, 1994), while comparisons between tidal marsh and seagrass are rare (Thomas et al. 1990; Heck et al. 1994). Minello (1999) summarized the available data on nekton density patterns in estuaries of Louisiana and Texas. An innovative approach has been developed in this joint effort between NMFS/SEFSC/Galveston Laboratory and the National Ocean Service/National Centers for Coastal Ocean Science/Center for Coastal Monitoring and Assessments (NOS/NCCOS/CCMA) to construct predictive models that compare habitat use patterns and interactions with density-independent (stochastic) processes (salinity, temperature, etc.) in Galveston Bay. Sixteen years of nekton density data collected from three distinct structural habitat types, marsh edge, submerged aquatic vegetation, and submerged nonvegetated bottom, were analyzed to identify potential EFH for federally managed species. Multivariate models were developed for individual species, examining density patterns among estuarine habitats and responses to stochastic processes. Model results were then combined with a Geographic Information System (GIS) to provide a spatial mosaic of potential EFH. This approach provides a tool for fishery managers to make habitat comparisons for different managed species and examines relationships between temporal, spatial and ecological factors and habitat utilization.

METHODS

Geographic Setting

The Galveston Bay complex encompasses approximately 2,020 km^2, and is one of the largest estuaries in the northern Gulf of Mexico (NOAA 1990). Comprised of several

major embayments, including Trinity, Galveston, East, and West Bays, the complex contains many smaller interconnecting subbays, rivers, streams, tidal creeks, wetlands, reefs, and tidal flats around its periphery (Figure 1). The estuarine system is isolated from the Gulf of Mexico by Bolivar Peninsula, Galveston Island, and Follet's Island and is connected only by Bolivar Roads, Rollover Pass, and San Luis Pass.

The bay bottom is mostly flat and shallow with slightly elevated oyster reefs, more elevated dredge material areas, river channels and deeper dredged navigation channels. The shoreline consists of salt marsh, upland bluffs, tidal flats, sand or shell beaches and developed areas. *Spartina alterniflora* is the dominant shoreline vegetation. Sediments are generally abundant, muddy and nutrient rich. The bay receives most of its freshwater from the Trinity River, but contributions from the San Jacinto River, Buffalo Bayou, and other peripheral inflows may be locally significant (Orlando et al. 1993). On average, the Trinity River contributes 83% of gauged inflow, while the San Jacinto contributes an estimated 8%. Remaining estimated freshwater inflow comes from the Houston Ship Channel (HSC), Buffalo Bayou, and Chocolate Bayou. Approximately 3% of the total freshwater flow into the system comes from ungauged sources. Mean water depth of the Galveston Bay complex is 2 m at mid-tide level.

Data Collection and Composition

Data were collected from published studies by Czapla (1991), Minello et al. (1991), Minello and Zimmerman (1992), Minello and Webb (1997), Rozas and Minello (1998), Zimmerman et al. (1984, 1989, 1990a, 1990b), Zimmerman and Minello (1984), and various unpublished data from the Galveston Laboratory of the National Marine Fisheries Service. All samples were collected using a drop trap sampler which employs a

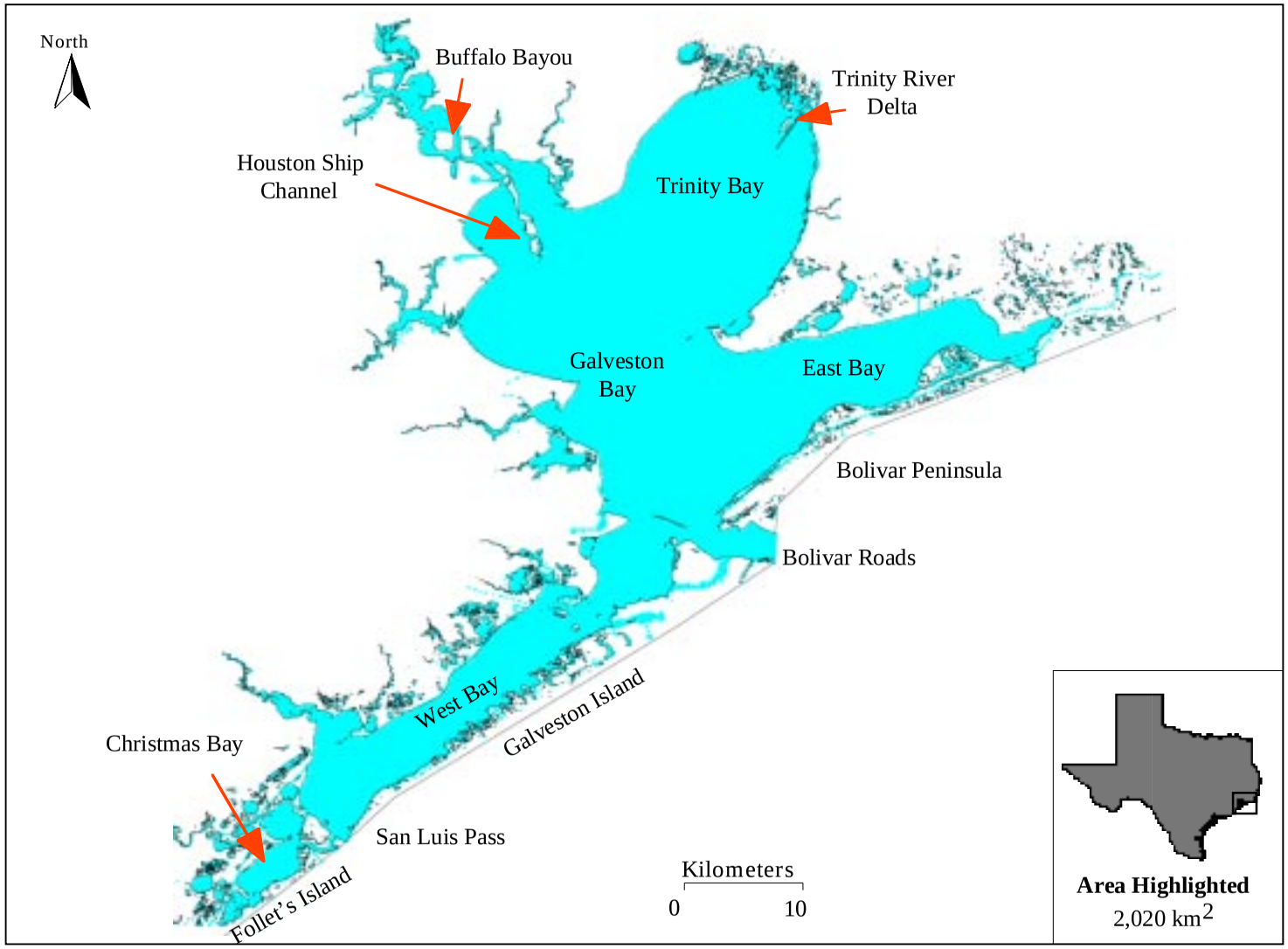


Figure 1. *Galveston Bay, Texas.*

large cylinder (1.0 or 2.6 m^2 area) released from a boom affixed to a boat to entrap organisms (Figure 2). Entrapped fauna are captured using dip nets while the water is pumped out of the sampler. When the cylinder is completely drained, all remaining animals are picked up by hand. This technique was designed to sample fishes and macroinvertebrates in highly-structured shallow-water habitats such as saltmarshes, seagrass beds, and oyster reefs where the more conventional trawl and bag seine catch efficiencies are diminished. Zimmerman et al. (1984) provides a more complete description of the sampling protocol.

Nekton densities, from a total of 3,864 drop samples (Figure 3) taken over a 16 year period, were analyzed from Galveston Bay to evaluate habitat selection between vegetated marsh edge (ME), submerged aquatic vegetation (SAV), and shallow non-vegetated bottom (SNB) by brown shrimp *Farfantepenaeus aztecus* (formerly *Penaeus aztecus*, Perez-Farfante and Kensley 1997), white shrimp *Litopenaeus setiferus* (formerly *P. setiferus*, Perez-Farfante and Kensley 1997), and pinfish *Lagodon rhomboides*. Although pinfish is not federally managed, it was selected as a finfish candidate for the development of the described analytical technique based on relative high densities in habitat types examined.

Habitats

Structural habitat types were classified into the following summary habitats for analysis (Figure 4):

Marsh Edge (ME) - intertidal marsh within 5 meters of open water habitat. This class consists primarily of saltmarsh cord grass *(Spartina alterniflora)*, and smaller proportions of salt meadow-grass *(Spartina patens)*, Black needlerush *(Juncus roemerianus)*, salt grass *(Distichlis spicata)*, bullrushes *(Scirpus spp.)*, and cattails *(Typha spp.)*.

Figure 2. *NMFS personnel deploying 2.6 m drop sampler.*

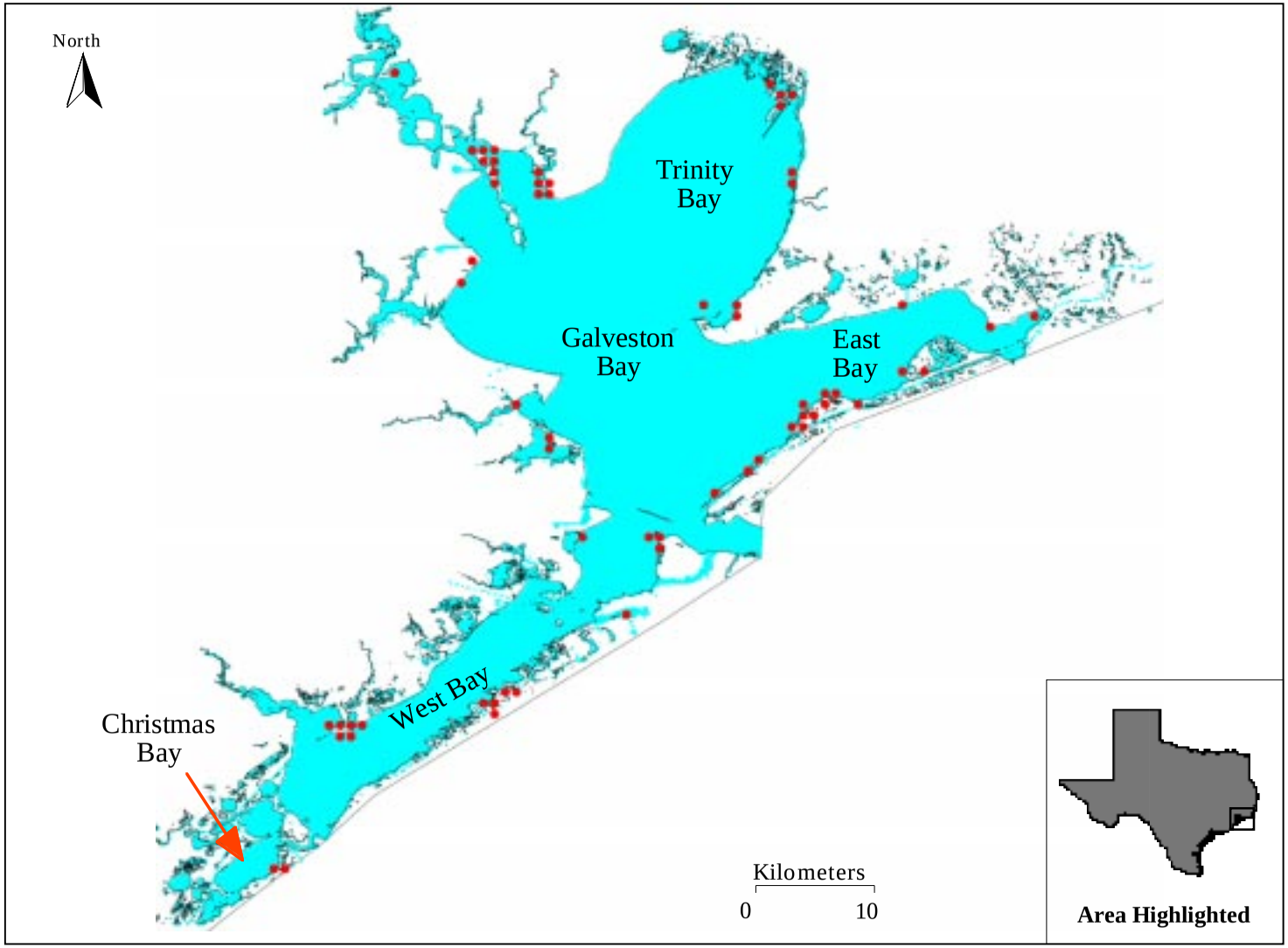


Figure 3. *Sampling locations – Galveston Bay.*

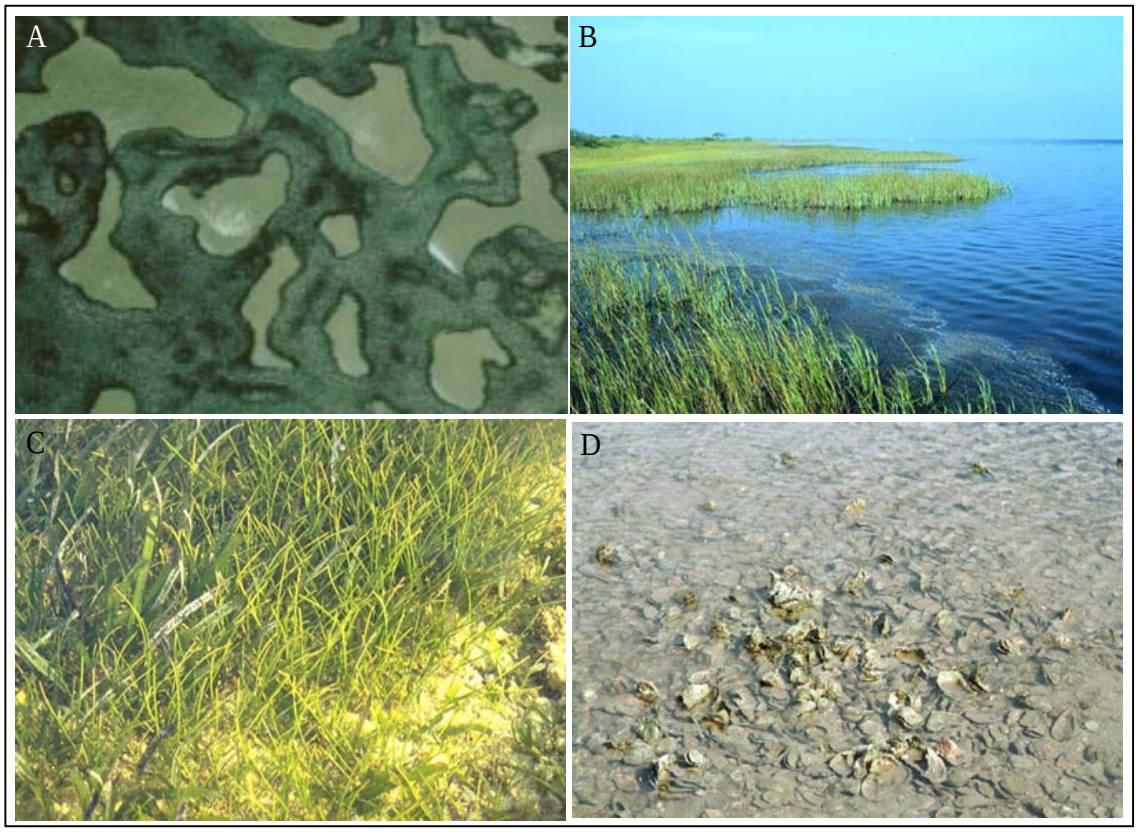


Figure 4. *Structural habitat types within Galveston Bay. Panel A shows a highly reticulated salt marsh containing a large amount of marsh edge (ME). Panel B shows typical marsh edge (ME) with adjacent shallow open water habitat (SNB) in the Galveston Bay complex during high tide. Panel C shows a mixed seagrass bed, prmarily Syringodium, and panel D shows a typical exposed oyster reef during low tide.*

Submerged Aquatic Vegetation (SAV) – consists primarily of shoalgrass (*Halodule wrightii*), wigeongrass (*Ruppia maritima*), and a sporadic distribution of wild celery (*Vallisneria americana*).

Shallow Nonvegetated Bottom (SNB) - generally restricted to waters less than 1 meter deep, including creeks, ponds, shoreline, and open bay habitat.

Density data were also available for inner marsh, defined as marsh more than 5 m from open water, and consisted primarily of *Spartina alterniflora*, *S. patens*, and *Distichlis spicata*. Inner marsh data were limited, therefore, mean values were calculated by salinity zone, where present, and mapped to provide a measure of utilization.

Statistical Analyses

Density values (number/m^2) were calculated for all fish and decapod crustaceans at all sample locations. Mean nekton densities were positively related to the standard deviation indicating that the analysis of variance (ANOVA) assumption of homogeneity of variance was not met, and a natural log transformation was used to correct the heteroscedacity in the density data. Once transformed, a forward-stepwise multiple regression (GLM) procedure was used to identify nekton density predictors. Season, habitat type, and salinity zone were identified as significant density predictors and the data were averaged by these variables to develop a mean log-density matrix for all possible season/habitat/salinity combinations. The resultant mean log-density matrices were then used to develop spatially-explicit multivariate models to predict the likelihood of locations of maximum habitat use.

The standard multiple regression equation can be expressed as:

$$\hat{Y} = a + b_{y1}.X_1 + b_{y2}.X_2 + \ldots + b_{yk}.X_k \ ,$$

Where the estimate of the dependent variable is a function of k independent variables X_1, X_2, . . . , X_k. The partial coefficient (b_{yj}) denotes the regression coefficient of Y on variable X_j that one would expect if all other variables in the regression equation were held constant. The "P-to-enter" nominal probability level for the whole model test was set to 0.05 for the selection process (Sokal and Rohlf 1995). Because our intent was to elucidate differential habitat use, models were developed for months when the animal was in substantial abundance. As such, temporal subsets were extracted from the data matrix using only those months exceeding the median of mean monthly log transformed density values. This reduced dataset was weighted by sampling effort in each prediction formula for each habitat combination (salinity zone x season x habitat). This technique can be used to maintain reliability in a dataset with disproportionate sample sizes (Sokal and Rohlf 1995). Prediction formulae were then applied to digital habitat geographies in the GIS. The density estimates were then classified into 5 equal quantiles based on the resultant density distribution: 0-20% = red; 20-40% = orange; 40-60% = yellow; 60-80% = green; and, 80-100% = blue, and subsequently mapped in the GIS (Figure 5).

Spatial Framework

Once the models were developed, geographic covers corresponding to the regression predictors were developed using the ARC/VIEW geographical information system (GIS). Several environmental coverages were developed as the underlying framework for populating biological model predictions into the GIS, including: 1) an

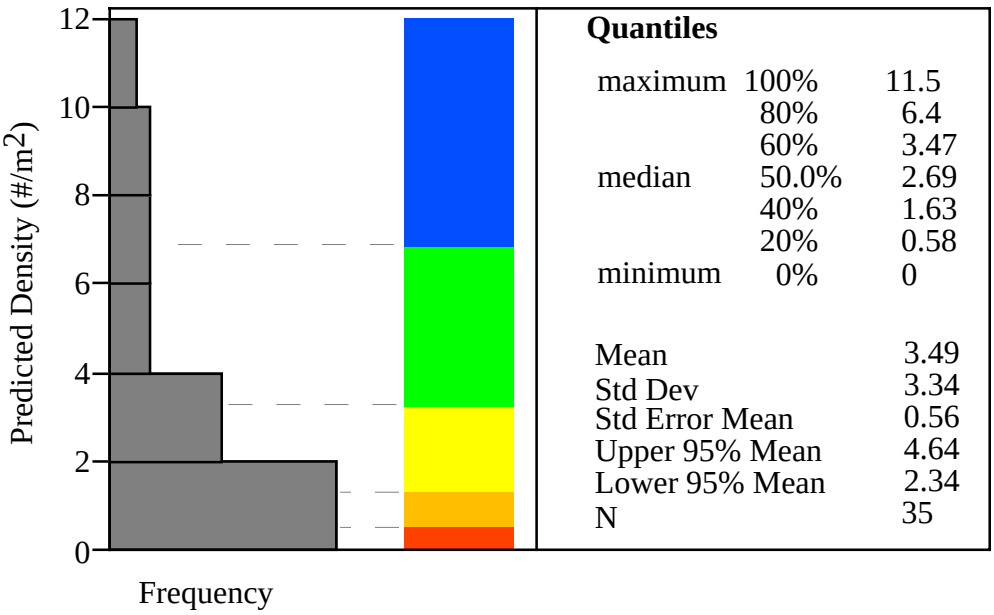


Figure 5. *Classification scheme used in mapping density estimates, example brown shrimp.*

annualized salinity coverage, 2) bathymetry, 3) submerged aquatic vegetation, and 4) emergent vegetation.

NOAA/NOS developed a map of mean annual salinity distribution throughout the Galveston Bay complex (Figure 6). Approximately 200,000 data points were interpolated (inverse distance weighted, eight nearest neighbors), and mapped. This analysis revealed a large expanse of water in West and Lower Galveston Bays with salinities consistently exceeding 25 ppt. The central portion of Galveston Bay ranged, on average, between 15-25 ppt, while Upper Galveston and East Bays ranged from 5-15 ppt. Trinity Bay exhibited lowest mean salinities, ranging from 0-5 ppt.

Galveston Bay bathymetry data were obtained from GEODAS (Geophysical Data System), an interactive database management system provided by NOAA's National

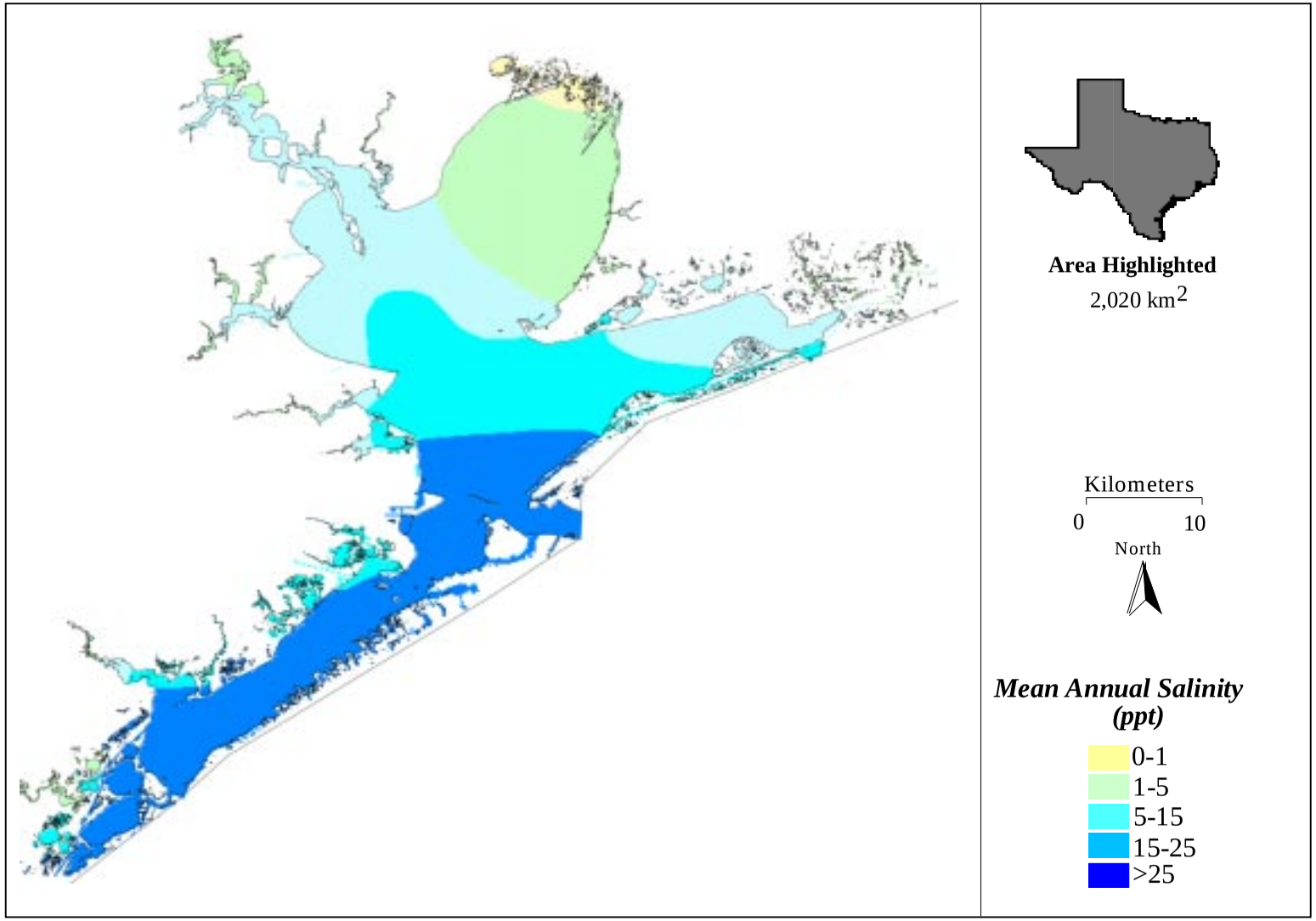


Figure 6. *Mean annual salinity for Galveston Bay, TX.*

Geophysical Data Center (NGDC). Approximately 400,000 depth soundings were inverse-distance weighted examining eight nearest neighbors to interpolate a high resolution bathymetric coverage (Figure 7).

Wetland geographies were obtained through the U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI). The NWI are digitized aerial photographs of coastal wetlands. NWI digital data files contain records of wetland location and classification as defined by the U.S. Fish and Wildlife Service (Cowardin et al. 1979). Digital data were stored in 7.5 minute by 7.5 minute grids containing ground planimetric coordinates of wetland point, line, and area features and wetland attributes. Galveston Bay NWI data were collected during 1989. In the analyses, NWI data for regularly flooded emergent wetlands (E2EM1N) were equated with marsh edge habitat, and E2EM1P represented inner marsh habitat (Figure 8). Areas designated as E2EM1N contain a large amount of marsh edge, however, they are generally a mosaic of ME, SNB, and inner marsh. Consequently, the geographic cover for ME is not exclusive. Similarly, areas designated E2EM1P contain a mixture of ME, SNB, and inner marsh. The SAV coverage was derived using the E1AB3 NWI classification. The total area of SAV was approximately 5.5 km^2, however, White et al. (1993) discovered several errors in E1AB3 classification. These areas identified were omitted, and the total area was reduced to 4.5 km^2.

All vector data were rasterized to 10 x 10 meter ($100m^2$) resolution to make use of Arc/View's spatial analyst inter-grid processing environment. This allowed us to apply

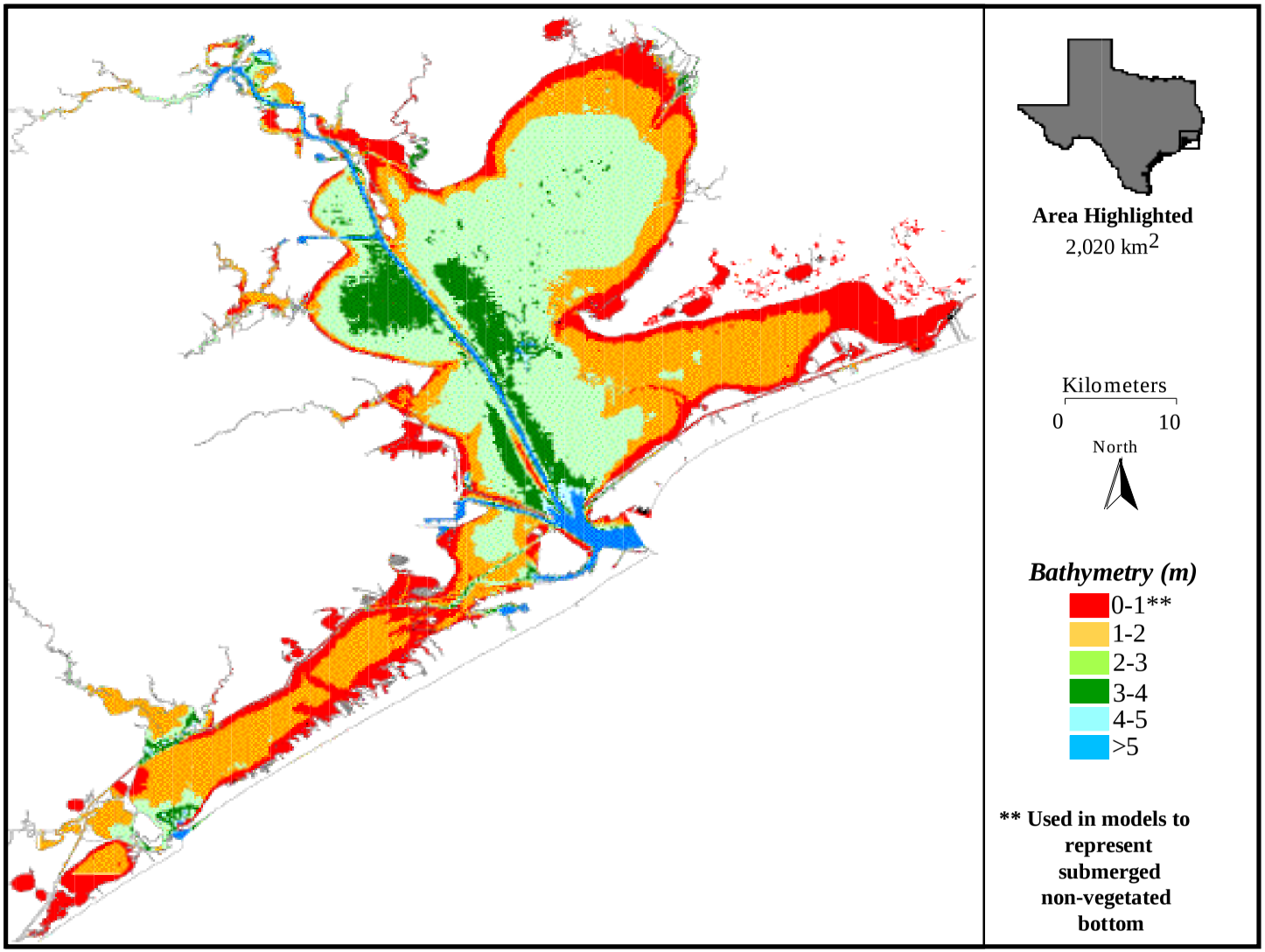


Figure 7. *Galveston Bay bathymetry.*

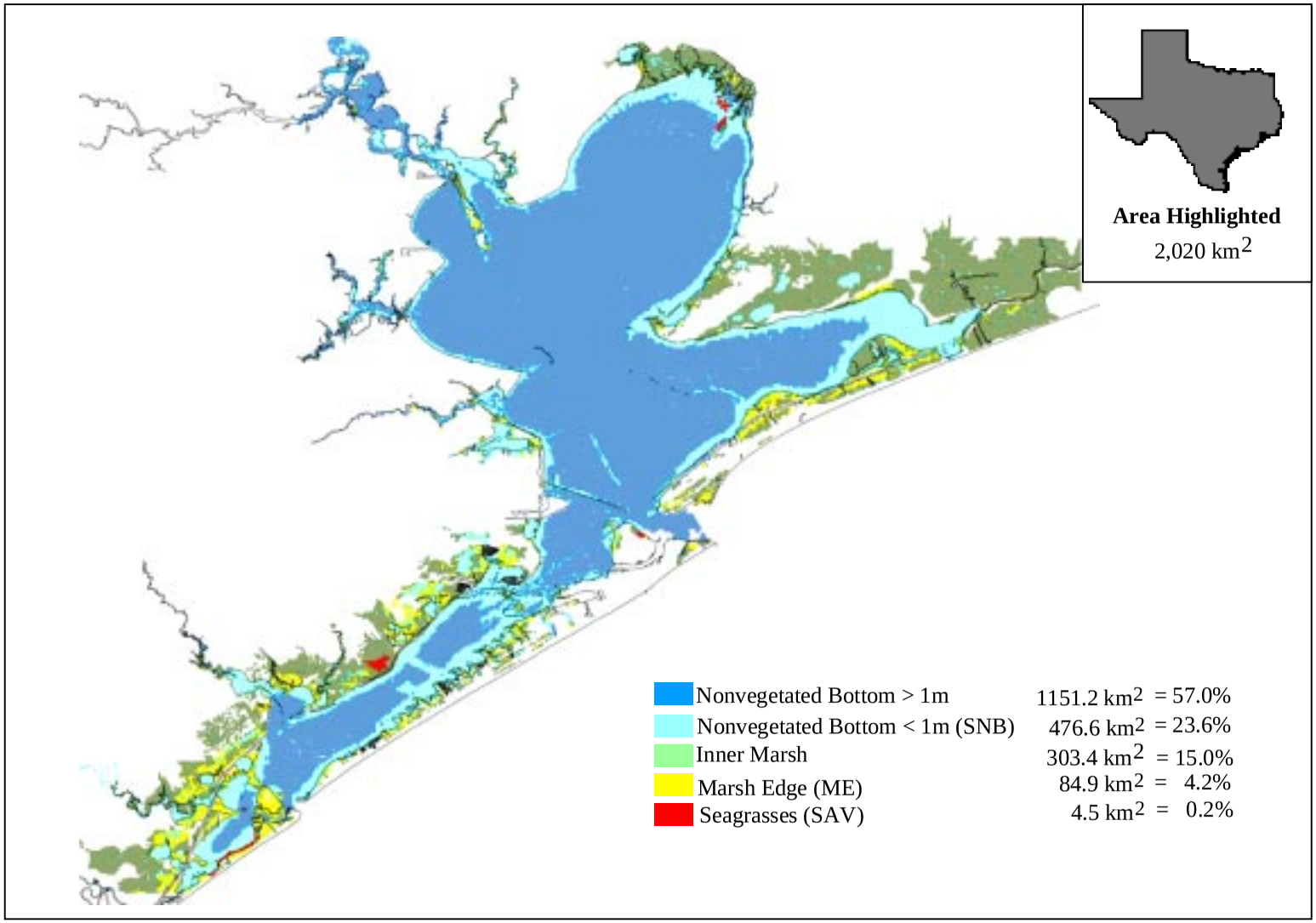


Figure 8. *Distribution and area of Galveston Bay shallow water habitats. ME is all intertidal regularly flooded vegetation and Inner Marsh is all irregularly flooded vegetation as classified in the National Wetland Inventory (NWI).*

the calculated prediction model (regression coefficients) to the composite of geographies to compute estimated nekton density across the Galveston Bay complex. All habitat and environmental covers were developed in geographic coordinate system.

Validation

NMFS drop sample data from Matagorda, San Antonio, and Aransas Bays were used to validate prediction models from Galveston Bay (Figures 9-11; Table 1) and to test the application of the models in a broader geographic context. Density data from each bay system were averaged in the same manner as the Galveston Bay data. Density estimates were then generated for each bay using the Galveston Bay model and compared to the observed density estimates using linear regression. Using this approach, the assumption was made that species modeled in Galveston Bay respond similarly to the range of biotic/abiotic factors in the validation bays. It was also assumed that the set of possible habitat combinations (salinity, temperature, vegetation type, etc.) were similar for all estuarine systems in this study.

Table 1. *Sample statistics for neighboring estuaries used in model validation.*

Validation Bay	# of Samples	Months Sampled	Habitats Sampled
Aransas Bay	192	May, Sept	ME, SAV, SNB
Matagorda Bay	336	May, June, Aug-Nov	ME, SNB
San Antonio Bay	232	May, Sept-Nov	ME, SAV, SNB

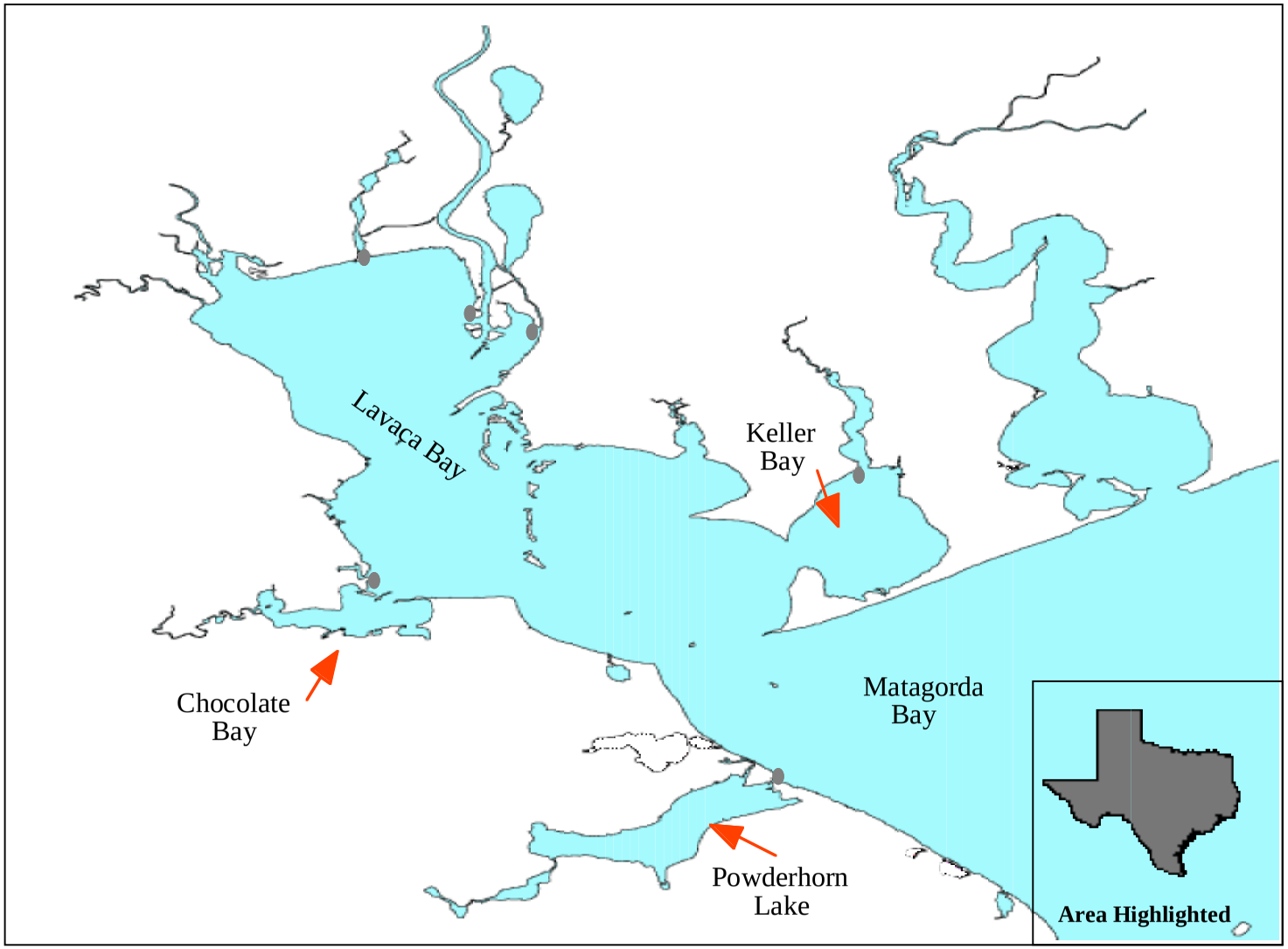


Figure 9. *Sampling locations – Matagorda Bay.*

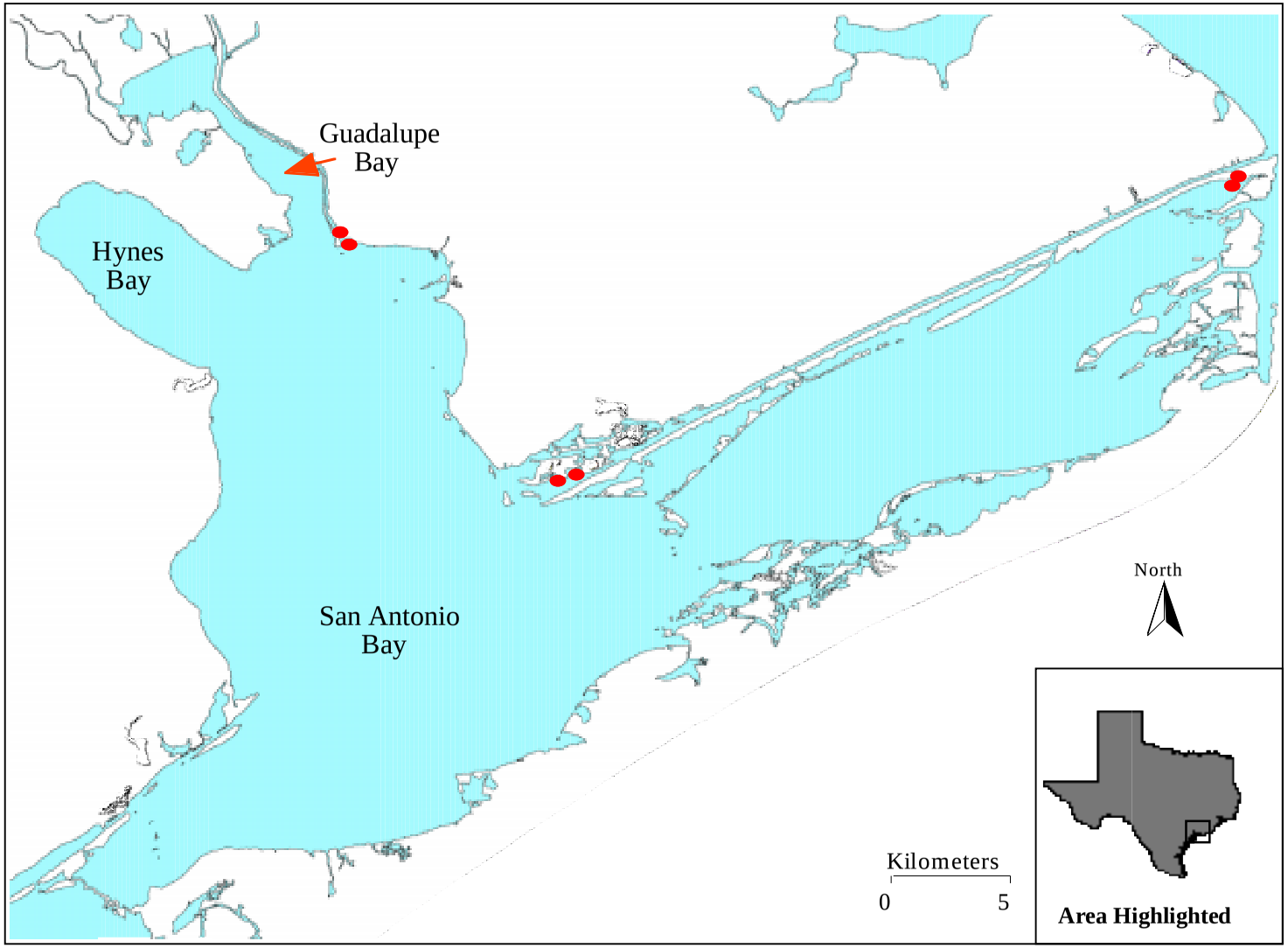


Figure 10. *Sampling locations – San Antonio Bay*.

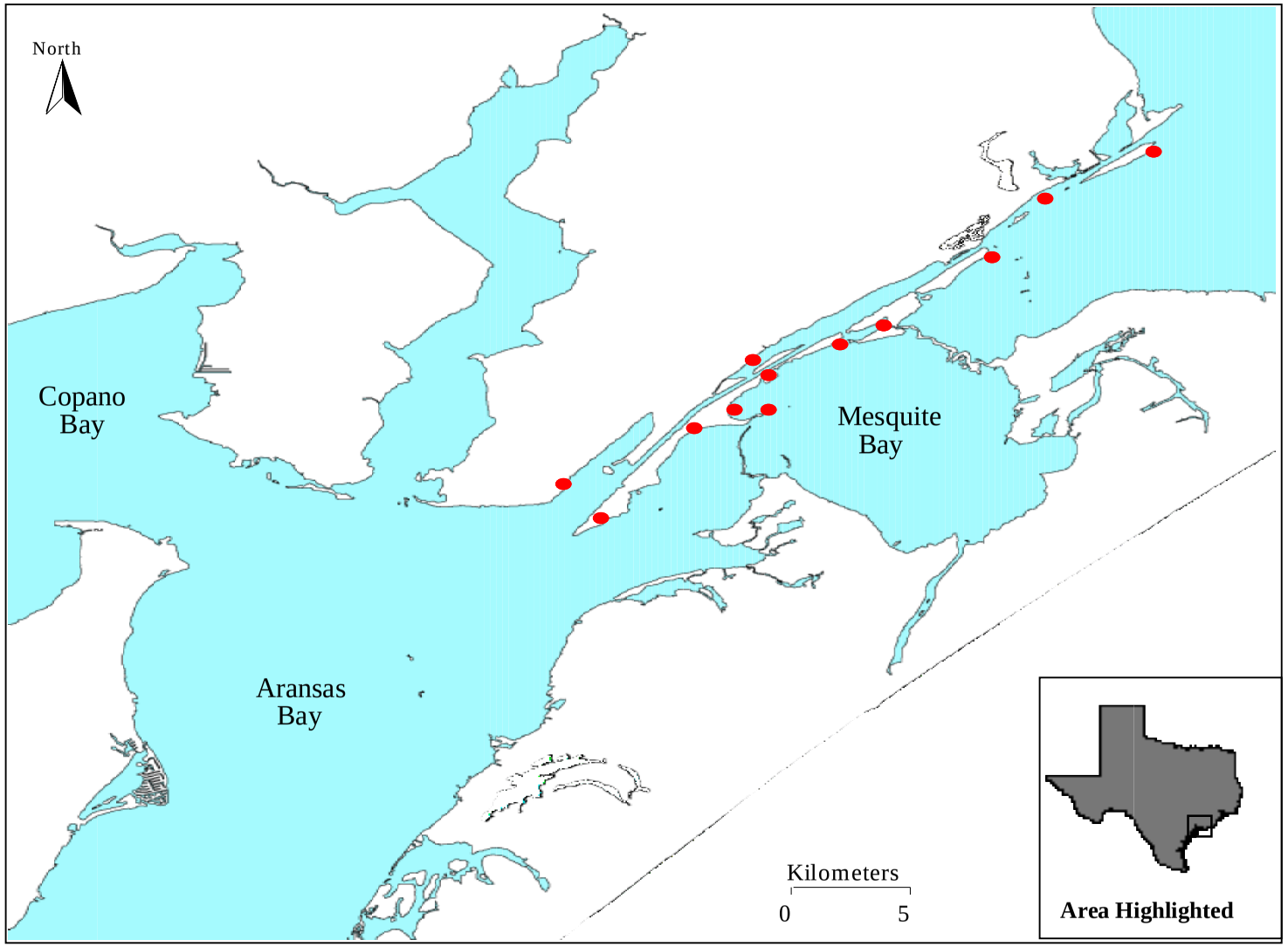


Figure 11. *Sampling locations – Aransas Bay.*

RESULTS

Geographic Data

To test whether the annualized salinity geographies used in the spatially explicit models were representative of actual salinities, mean *in situ* salinities from sampling locations were compared with annualized salinities (Figure 12). A strong correlation existed between mean *in situ* salinity (collected with drop samples) and annual salinity, $r^2=0.89$, $p<0.0001$.

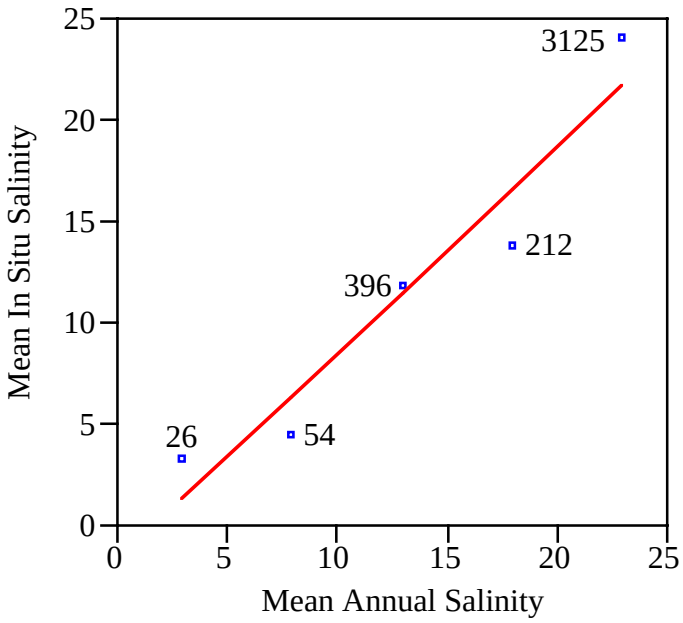


Figure 12. *Comparison of mean in situ salinity observations from NMFS sampling stations and mean annual salinity in Galveston Bay. Numbers by each point indicate number of samples taken within each salinity zone.*

Submerged nonvegetated bottom (SNB) to 1 m depth was the most evenly distributed habitat type included in the analysis, and the most abundant - approximately 476 km^2 (Table 2). There was slightly less SNB available in the western reaches of upper Galveston Bay relative to the remainder of the system. Marsh edge (ME) habitat was most abundant in East and West Bays. ME was relatively sparse in the remainder of the system. Total estimated ME habitat available to nekton was 84.96 km^2, or approximately 17% that of SNB. Submerged aquatic vegetation (SAV) was extremely sparse (4.5 km^2), with the majority distributed within West Bay. Several small patches totaling 1.2 km^2 were mapped in Upper Trinity Bay (Figure 7, Table 2). Inner marsh habitats were most abundant in East Bay and the northern shore of West Bay; this habitat totaled approximately 303 km^2.

Table 2. *Estimated area (km^2) of each habitat/salinity combination in Galveston Bay, Texas. ME is NWI classification of all regularly flooded emergent vegetation and Inner Marsh is all irregularly flooded emergent vegetation.*

Habitat/Salinity	(0-1)	(1-5)	(5-15)	(15-25)	(>25)	Σ
ME (NWI)	1.36	6.77	9.35	33.64	33.84	84.96
SAV	0.19	1.03	0.01	0	3.27	4.50
SNB (to 1m)	19.54	60.52	140.41	87.16	168.64	476.27
Inner Marsh (NWI)	20.59	98.34	85.61	57.93	40.95	303.42
Σ	41.68	166.66	235.38	178.73	246.7	869.15

Brown shrimp - *Farfantepenaeus aztecus*

Densities of brown shrimp were highest during April through September (Figure 13), and data from these months were used to model habitat use patterns. A total of 38,249 individuals were captured exhibiting a mean length of 28.4 mm within the subset. The model included season, habitat type, and salinity zone as statistically significant regressors, all of which were discrete. The model can then be expressed as:

Y-Intercept$_{(o)}$		**Season**		**Habitat**		**Salinity**
						-0.532 (0-1 ppt)
		-0.137 (FA)		0.135 (ME)		-0.066 (1-5 ppt)
0.501	+	0.109 (SP)	+	0.153 (SAV)	+	0.068 (5-15 ppt)
		0.028 (SU)		-0.288 (SNB)		0.194 (15-25 ppt)
						0.335 (>25 ppt)

where the additive regressor coefficients are included for each variable; SP=spring (April, May); SU=summer (June-August); FA=fall (September); ME=marsh edge; SAV=submerged aquatic vegetation; SNB=submerged nonvegetated bottom; and salinity (parenthetical corresponds to NOS's Estuarine Living Marine Resources salinity classification). Analysis of variance for the whole model fit is summarized in Table 3. The model predicts highest brown shrimp densities within the >25 ppt salinity zone (Figure 14). SAV yields the highest estimates within this zone (11.5/m^2) as well as the highest overall model estimates. ME predictions were similar to those observed in SAV, and the highest predicted densities were in the >25 ppt salinity zone (11/m^2). SNB estimates were significantly lower than SAV and ME in this zone, yielding a maximum density of 3.5/m^2. Highest density estimates occurred during the spring (April-May) and the spatial distribution revealed highest densities within SAV and ME habitats in Christmas and West Bays (Figure 15). Christmas and West Bay exhibit mean annual

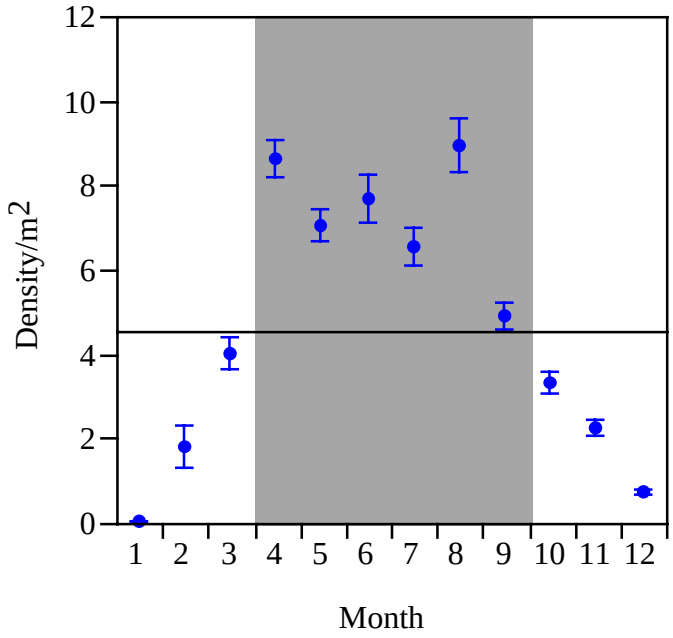


Figure 13. *Monthly brown shrimp (Farfantepenaeus aztecus) mean density and standard error in Galveston Bay, Texas (1982-1997). Shaded area (April-September) selected as time frame most appropriate to subsample data for the development of predictive models.*

salinities > 25 ppt and support the greatest area of ME and SAV habitat in the bay. All habitats exhibited a general decline in estimated density as salinity decreased.

Table 3. *Analysis of variance for least squares multiple regression model to predict seasonal brown shrimp density in Galveston Bay, Texas. Statistical significance at α=0.05 denoted by asterisk.*

SUMMARY OF FIT: R^2 adjusted = 0.83 Observations (Sum Weights) = 35(2252)
Mean = 0.68 Root Mean Square Error = 1.00

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	8	173.49	21.69	21.61
Error	26	26.09	1.00	**Prob>F**
Total	34	199.58		<0.0001*

EFFECTS TEST

Source	**DF**	**Sum of Squares**	**F Ratio**	**Prob>F**
Season	2	18.79	9.36	<0.0001*
Habitat	2	98.96	49.30	0.0009*
Salinity	4	52.41	13.05	<0.0001*

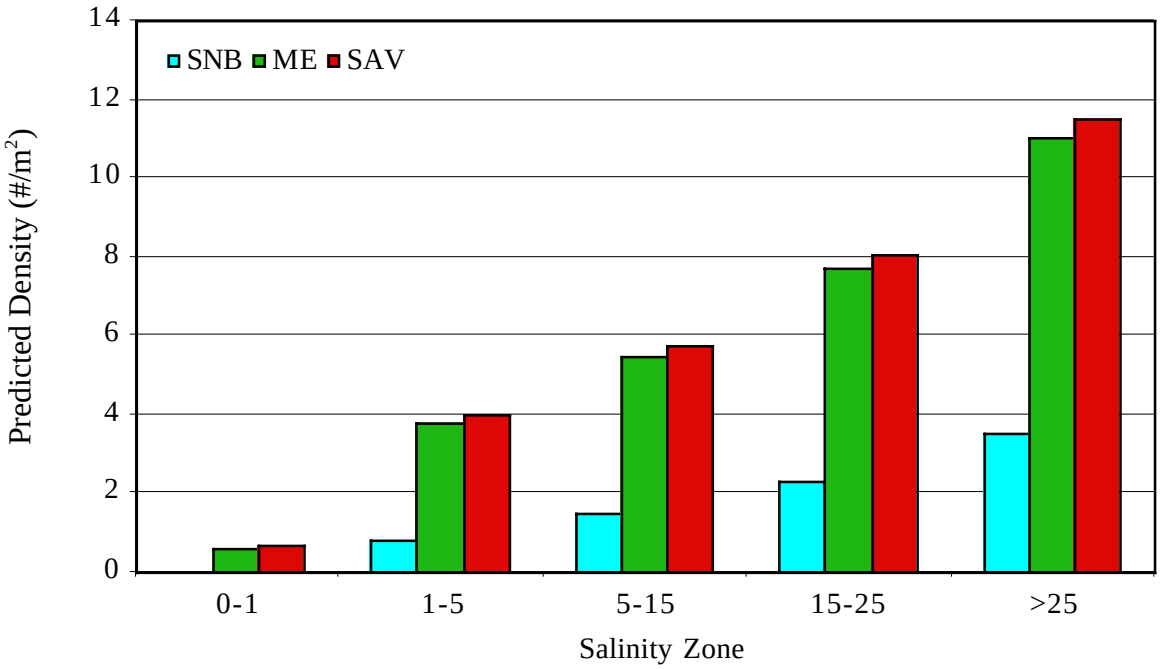


Figure 14. *Highest seasonal predicted brown shrimp density (spring, April-May) by habitat/salinity zone.*

Inner marsh mean density patterns were similar to the model results with highest densities in the >25 ppt salinity zone (1-5 zone – 0.27/m^2; 5-15 zone – 2.5/m^2; 15-25 zone – 1.8/m^2; >25 zone – 3/m^2). No data were available for 0-1 ppt salinity zone.

<u>White shrimp (*Litopenaeus setiferus*)</u>

White shrimp exhibited peak densities in shallow habitats during late summer/early fall, while mean densities were severely reduced during the winter and spring (Figure 16). Comparison with the median of monthly mean densities indicated that June–November should be used in model development. During this period 30,529 white shrimp were captured having a mean length of 31.5 mm. The resulting model

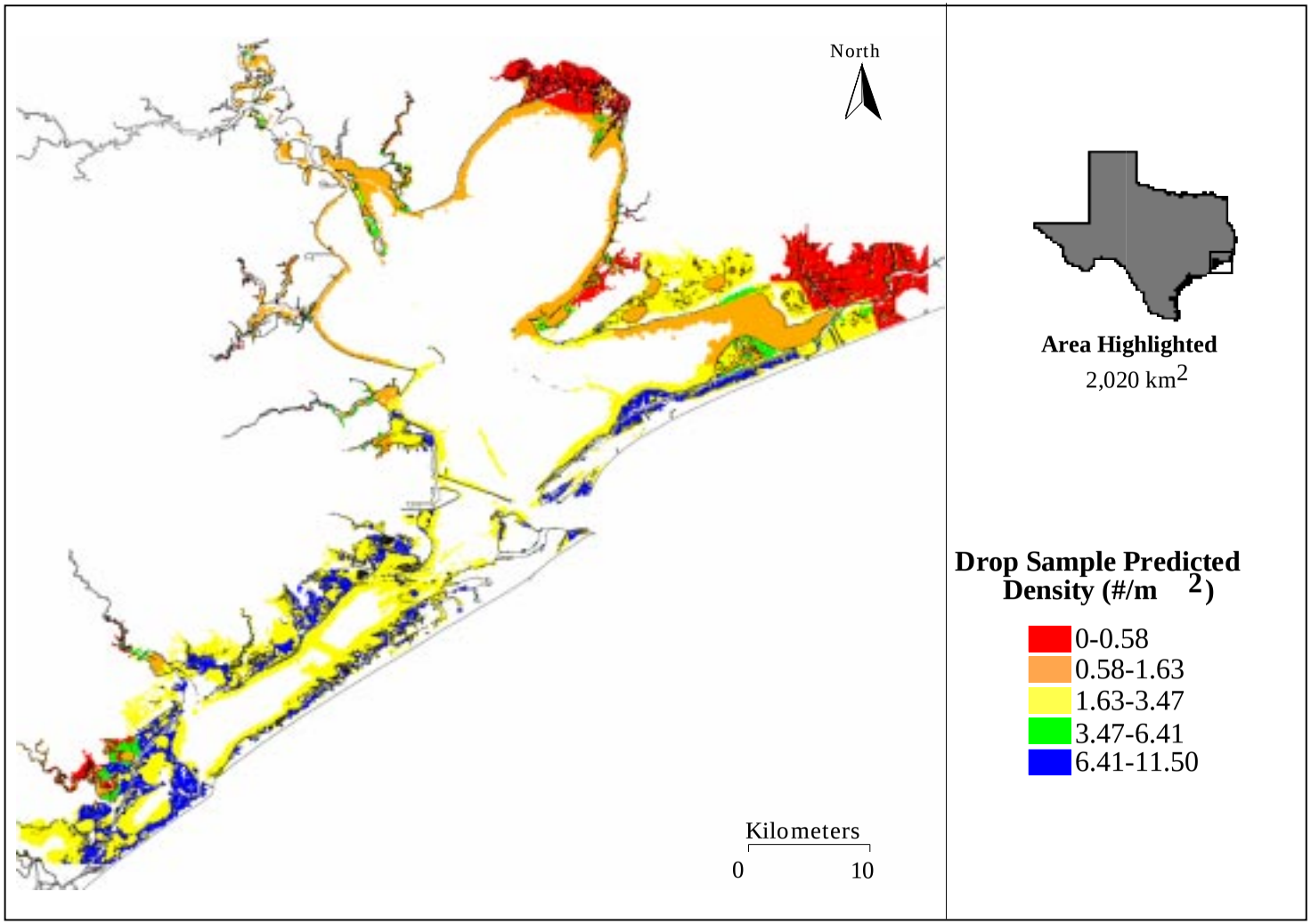


Figure 15. *Spatial distribution of predicted brown shrimp density from NMFS drop samples. Data were plotted using highest seasonal estimates – spring (April-May).*

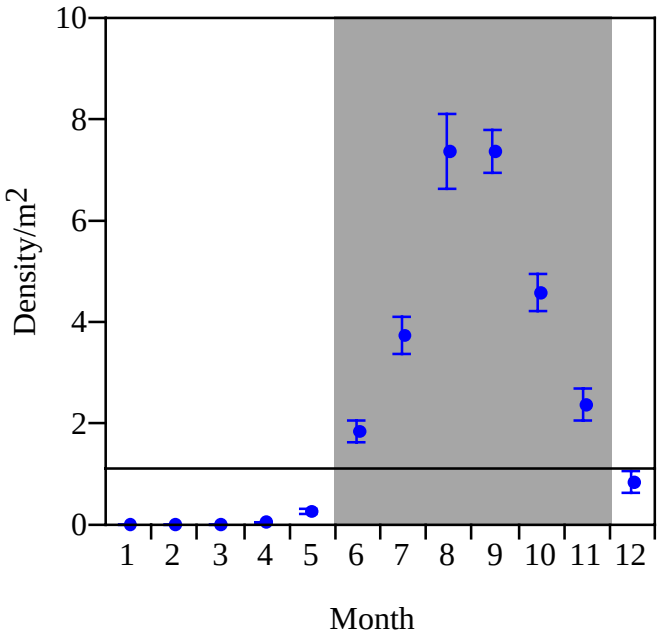


Figure 16. *Monthly white shrimp (Litopenaeus setiferus) mean density and standard error in Galveston Bay, Texas (1982-1997). Shaded area (June-November) selected as time frame most appropriate to subsample data for the development of predictive models.*

produced from the subset yielded only two significant discrete regressors, habitat type and month.

The model is expressed as:

Y-Intercept$_{(o)}$		**Habitat**		**Month**
0.437	+	0 (ME) -0.341 (SAV) -0.288 (SNB)	+	0 (June) 0.166 (July) 0.446 (August) 0.416 (September) 0.252 (October) 0.024 (November)

where the additive regressor coefficients are included for each variable; ME = marsh edge; SAV = submerged aquatic vegetation; SNB = submerged non-vegetated bottom. Analysis of variance for the whole model fit is summarized in Table 4. White shrimp

distribution or abundance was not significantly related to salinity although densities were generally higher in the midbay region. White shrimp densities were not significantly different between seasons (summer = June, July, August; fall = September, October, November), however, when seasons were broken out into their monthly components a temporal response was statistically evident. Density estimates for white shrimp were highest in ME while SNB and SAV density estimates were comparable with SAV being

Table 4. *Analysis of variance for least squares multiple regression model to predict seasonal white shrimp density in Galveston Bay, Texas. Statistical significance at α=0.05 denoted by asterisk.*

SUMMARY OF FIT: R^2 adjusted = 0.80 Observations (Sum Weights) = 18(1957)
Mean = 0.51 Root Mean Square Error = 1.22

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	110.54	15.79	10.65
Error	10	14.83	1.48	**Prob>F**
Total	17	125.37		0.0006*

EFFECTS TEST

Source	DF	Sum of Squares	F Ratio	Prob>F
Month	5	55.84	7.53	0.0036*
Habitat	2	42.47	14.32	0.0012*

slightly lower (Figure 17). White shrimp within SAV were mainly found in Christmas Bay. White shrimp densities within SNB exhibited no clear spatial trends with the exception of no catch in the oligohaline (0-0.5 ppt) salinity zone. Model estimates were mapped using the highest monthly estimates - August: ME = 6.5/m^2, SNB = 2.9/m^2, and SAV = 2.4/m^2 (Figure 18). Mean densities for inner marsh were low across the bay and highest values of 1/m^2 were observed in the lower bay.

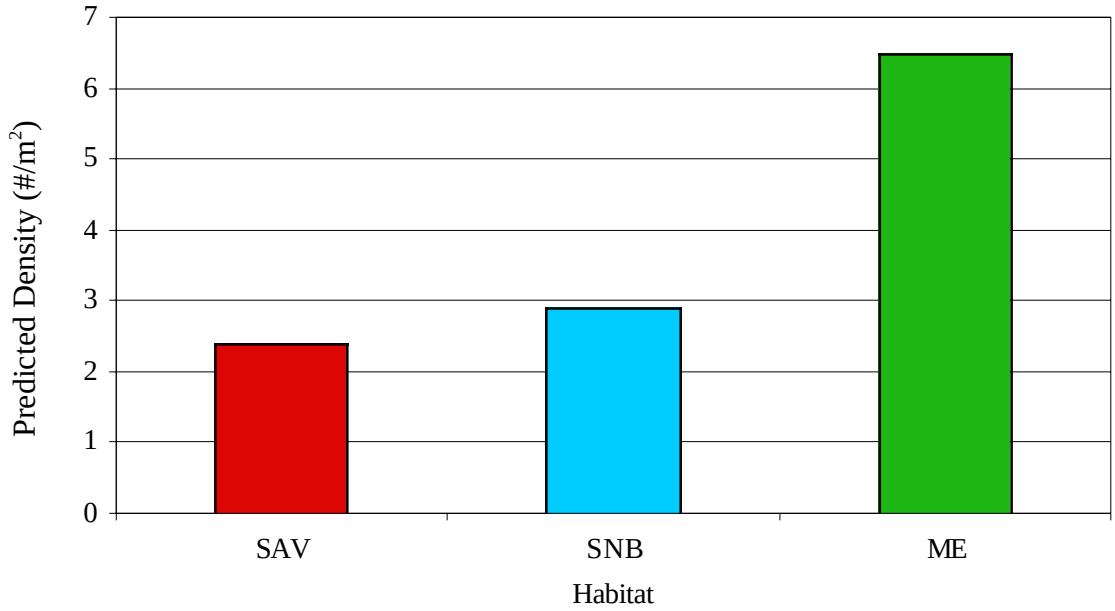


Figure 17. *Highest monthly (August) predicted white shrimp density by habitat*.

Pinfish (*Lagodon rhomboides*)

Peak pinfish densities in shallow Galveston Bay habitats occurred during February-April (Figure 19). Pinfish began leaving shallow habitats in May and were almost absent from these habitats from August-January. The period from February-July was selected as the most appropriate months to develop predictive models. A total of 7,757 pinfish were captured in drop samples during February-July with a mean length of 37.3 mm standard length. The model produced from this subset included season, salinity zone, and habitat as significant discrete regressors and is expressed as:

Y-Intercept$_{(o)}$		**Season**		**Habitat**		**Salinity**
						0 (0-1 ppt)
		0.070 (SP)		-0.012 (ME)		0.098 (1-5 ppt)
0.011	+	-0.029 (SU)	+	0.207 (SAV)	+	0.264 (5-15 ppt)
		-0.041 (WI)		-0.195 (SNB)		0.288 (15-25 ppt)
						0.209 (>25 ppt)

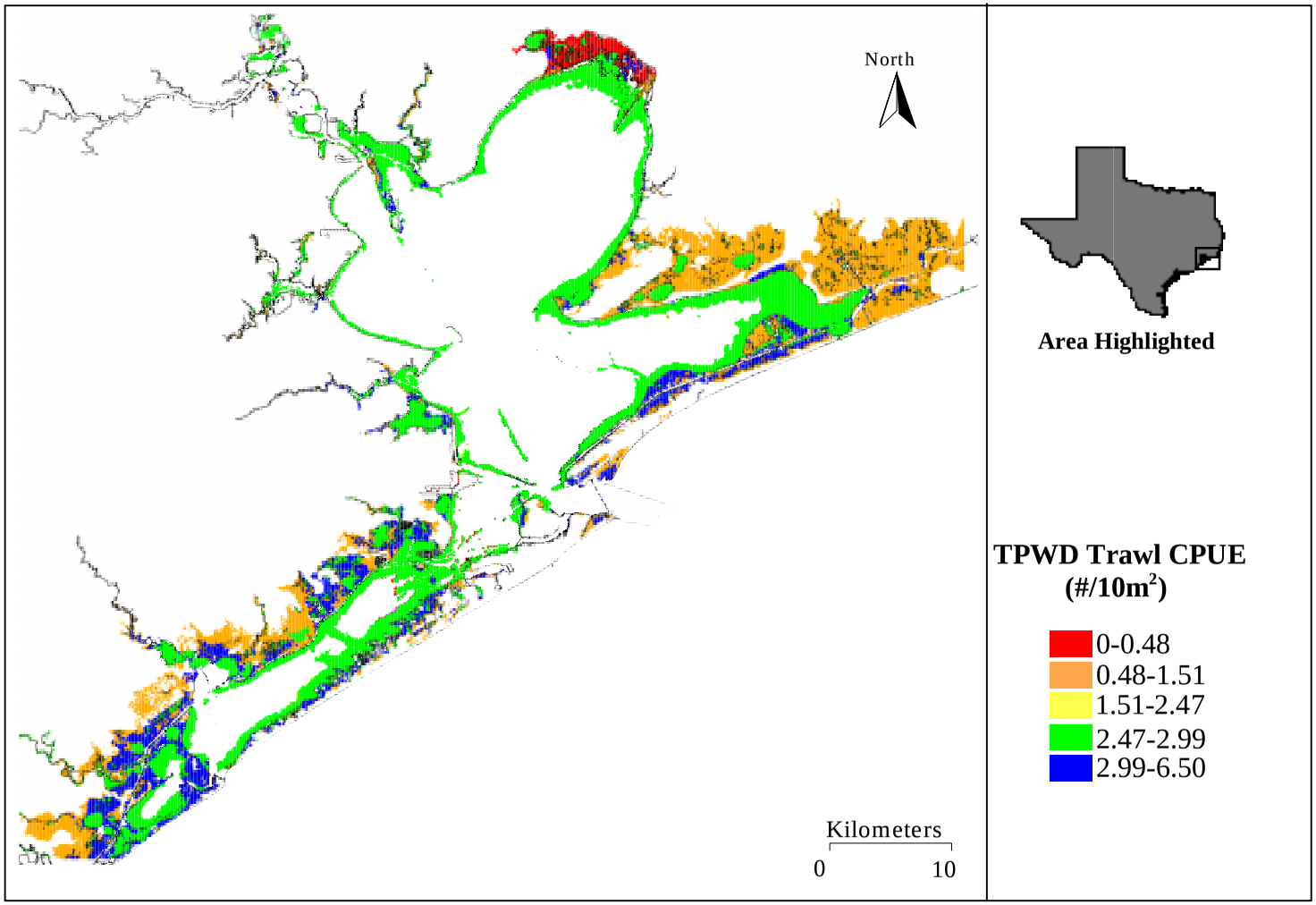


Figure 15. *Spatial distribution of predicted white shrimp density from NMFS drop samples. Data were plotted using highest monthly estimates – August.*

where the additive regression coefficients are included for each variable; WI=winter (February); SP=spring (March, April, May); SU=summer (June, July). Analysis of variance for the whole model fit is detailed in Table 5. The model predicted highest pinfish densities within 15-25 ppt SAV habitat. Density estimates in SAV within the 5-15 ppt and >25 ppt salinity zones were slightly lower (2.5 and 2.1/m^2, respectively); all three zones were in the upper 20th percentile of the data distribution (Figure 20). Pinfish density estimates in ME were considerably lower than SAV; densities were highest in the 15-25 ppt salinity zone (1.2/m^2) and slightly lower in the 5-15 ppt (1.1/m^2) and >25 ppt salinity zones (0.9/m^2). All SNB density estimates were no greater than 0.5/m^2 and estimates for SNB in waters <5 ppt were zero. Mean pinfish densities in inner marsh habitats were low and were greatest in the 15-25 salinity zone (0.19/m^2). Highest density estimates during spring were used to map pinfish spatial distribution (Figure 21).

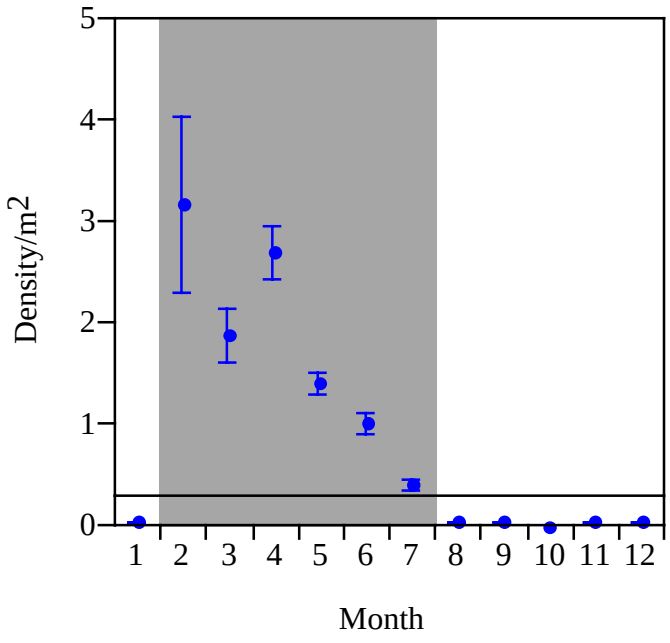


Figure 19. *Monthly pinfish (Lagodon rhomboides) mean density and standard error in Galveston Bay, Texas (1982-1997). Shaded area (February-July) selected as time frame most appropriate to subsample data for the development of predictive models.*

Table 5. *Analysis of variance for least squares multiple regression model to predict seasonal pinfish density in Galveston Bay, Texas. Statistical significance at α=0.05 denoted by asterisk.*

SUMMARY OF FIT: R^2 adjusted = 0.66 Observations (Sum Weights) = 35(2060)
Mean = 0.22 Root Mean Square Error = 0.78

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	45.77	5.72	9.39
Error	26	15.83	0.61	**Prob>F**
Total	34	61.61		0.0001*

EFFECTS TEST

Source	DF	Sum of Squares	F Ratio	Prob>F
Season	2	4.74	3.90	0.0331*
Salinity	4	7.15	2.93	0.0397*
Habitat	2	32.70	26.84	<0.0001*

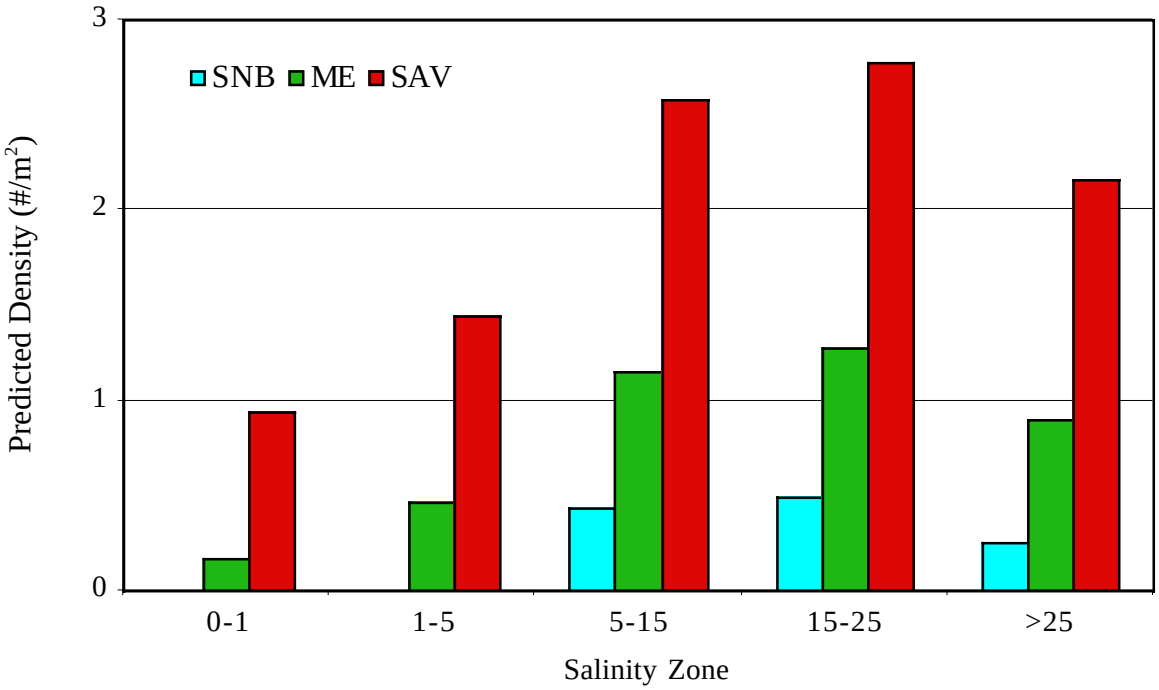


Figure 20*. Highest seasonal predicted pinfish density (spring, March-May) by habitat/salinity zone.*

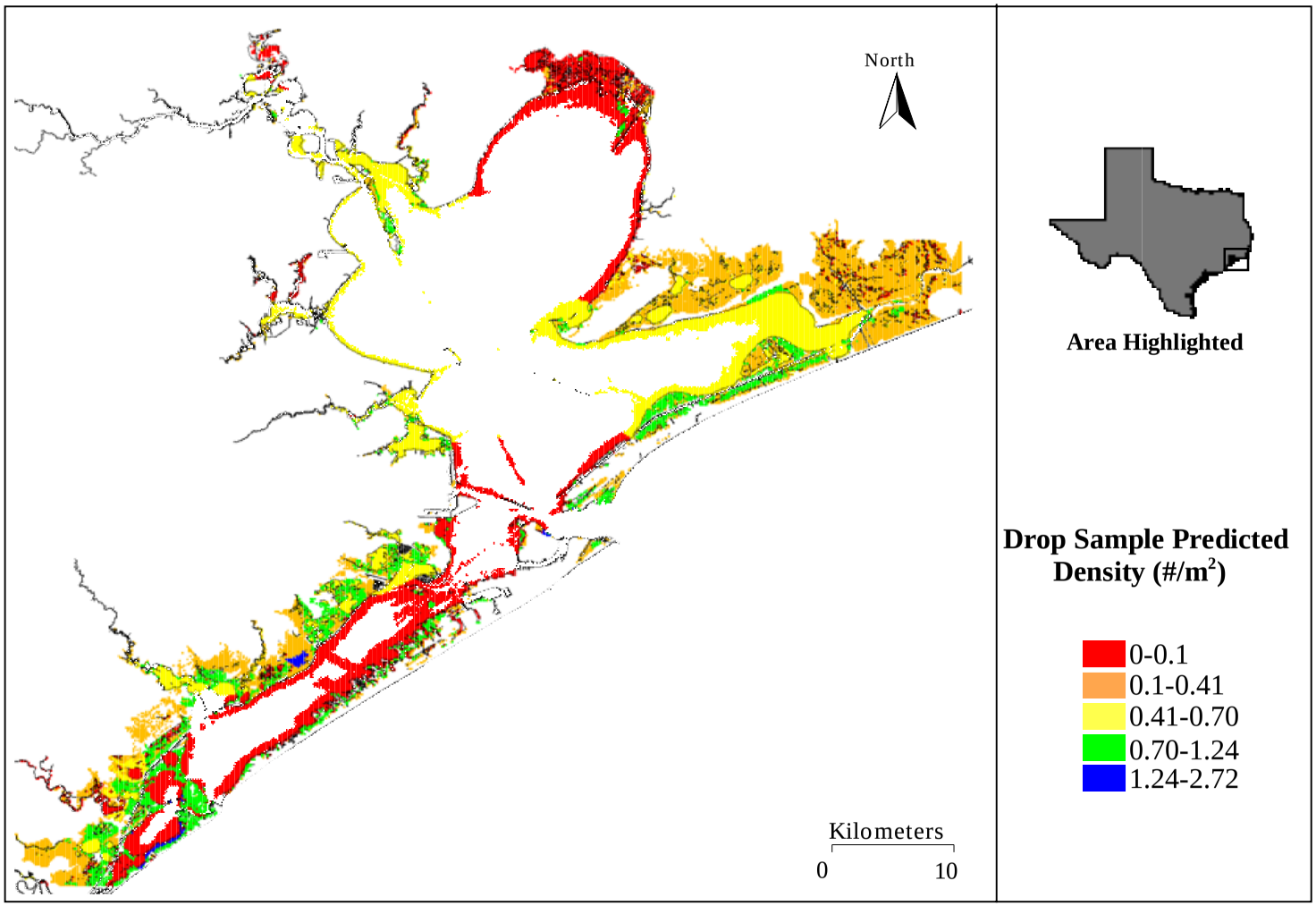


Figure 21. *Spatial distribution of predicted pinfish density from NMFS drop samples. Data were plotted using highest seasonal estimates – spring (March-May).*

Validation - *Brown shrimp*

Densities predicted in Matagorda, San Antonio, and Aransas Bays based on the Galveston Bay model were closely related to observed densities in these bays (r^2= 0.61, p< 0.0001) (Figure 22). Independently, Matagorda Bay had the tightest fit, - (r^2= 0.712, p= <0.0001), followed by Aransas Bay, - (r^2= 0.67, p= 0.0043), and San Antonio Bay, - (r^2= 0.654, p= <0.0001). Highest densities were observed within high salinity (>15 ppt) SAV habitats in Aransas and San Antonio Bays, while ME habitats in waters >15 ppt supported higher densities in Matagorda Bay (no SAV habitats were sampled within this system).

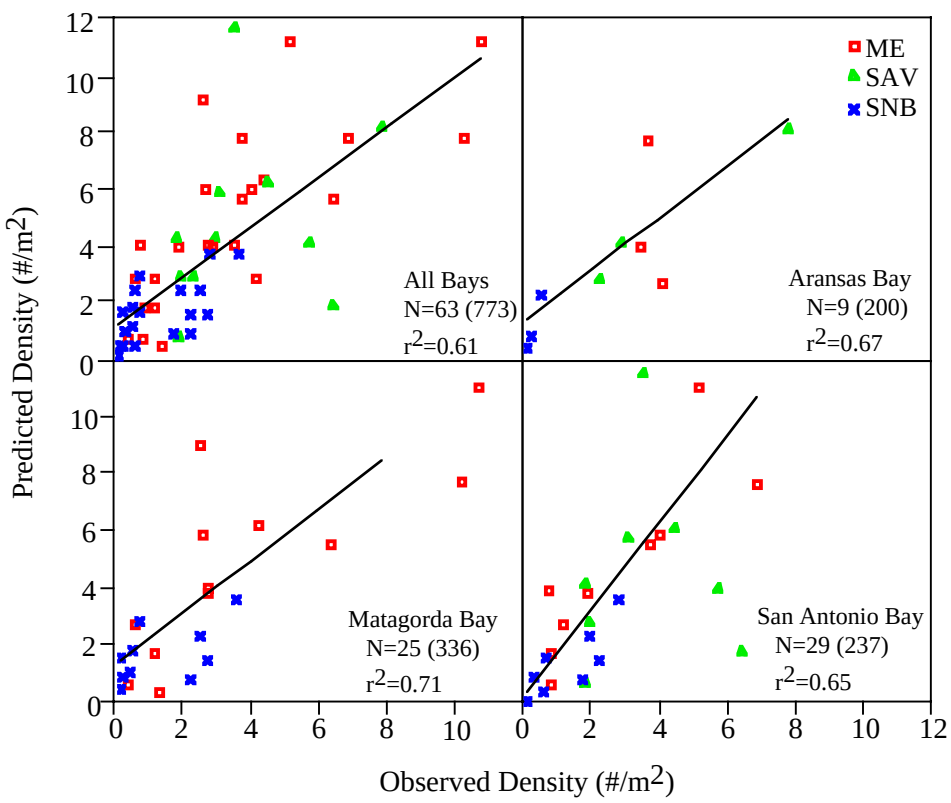


Figure 22. *Relationships between observed densities of brown shrimp in validation bays and predicted densities using model derived in Galveston Bay. For each relationship, the r^2 is shown for the least squares regression with the number of observations (N) and the total number of samples in parentheses.*

White shrimp

The model developed for Galveston Bay white shrimp yielded a significant fit with the composite validation dataset (p= 0.007) although the variance explained was low, r^2= 0.35 (Figure 23). Independently, Matagorda Bay provided the best fit with the Galveston model (p= 0.0027, r^2= 0.76). White shrimp densities in Matagorda Bay were highest in ME habitats while no data were available for SAV comparisons. White shrimp were not abundant in San Antonio Bay, and the model did not fit well (p= 0.6384, r^2= 0.03).

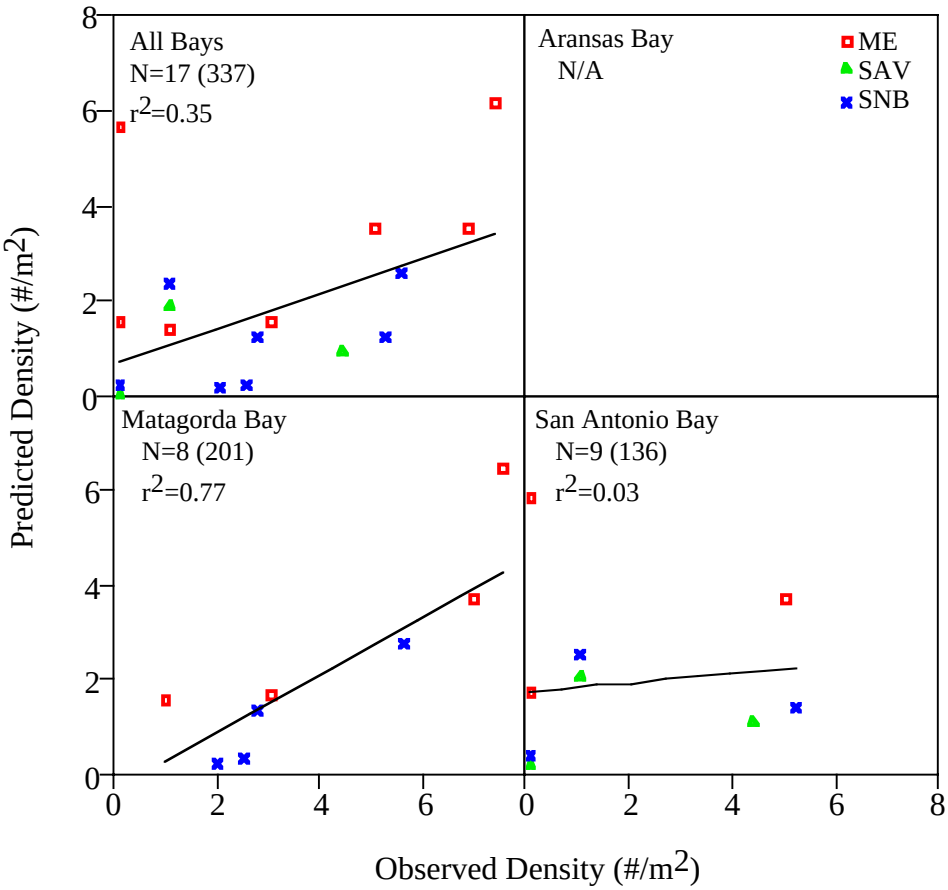


Figure 23. *Relationships between observed densities of white shrimp in validation bays and predicted densities using model derived in Galveston Bay. For each relationship, the r^2 is shown for the least squares regression with the number of observations (N) and the total number of samples in parentheses.*

Aransas Bay was excluded from the validation analysis because only three observations overlapped with the temporal subset from the Galveston model.

Pinfish

The model derived for pinfish fit well in Matagorda and San Antonio Bays. Aransas Bay was not included in the analysis due to limited samples within the temporal overlap of the datasets. The model fit significantly ($p=<0.0001$, $r^2=0.46$) with the composite density data from Matagorda and San Antonio Bays (Figure 24). Individually,

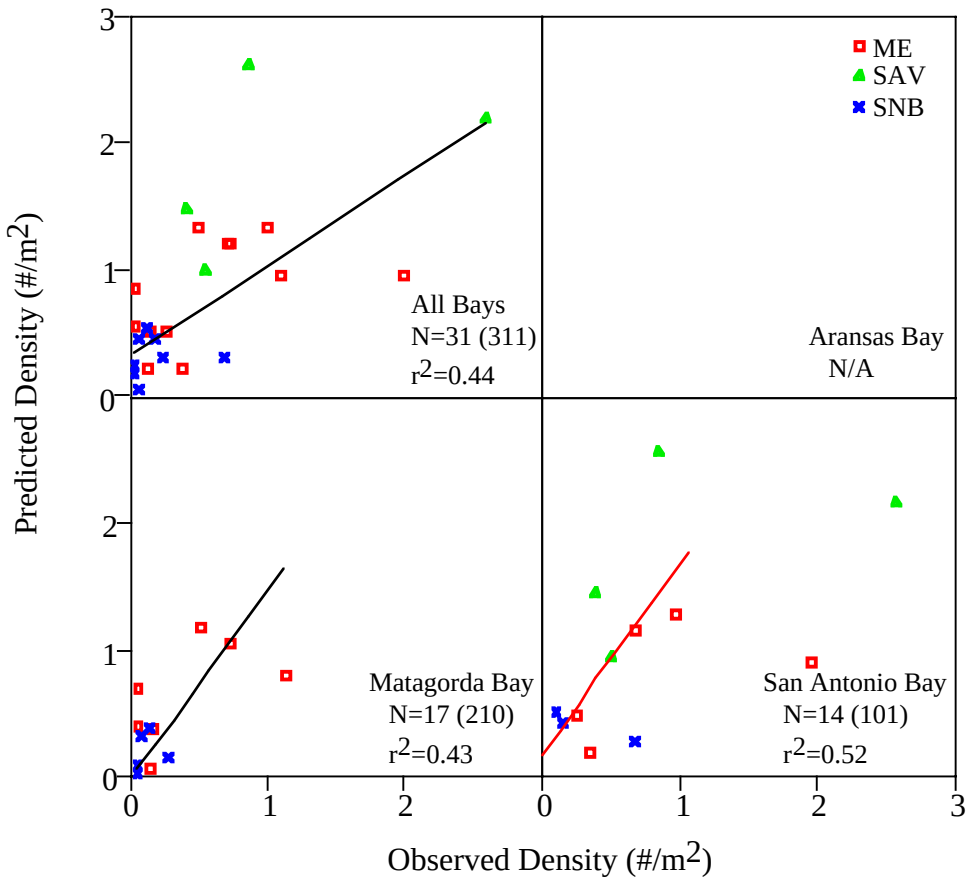


Figure 24. *Relationships between observed densities of pinfish in validation bays and predicted densities using model derived in Galveston Bay. For each relationship, the r^2 is shown for the least squares regression with the number of observations (N) and the total number of samples in parentheses.*

the model fit best in San Antonio Bay ($p=0.0023$, $r^2=0.55$), and explained variance was slightly lower in Matagorda Bay ($p=0.0025$, $r^2=0.47$). Highest densities were observed in high salinity (>25 ppt isohaline) ME habitat in both Matagorda and San Antonio Bays. Densities were comparable but slightly lower in San Antonio Bay high salinity SAV.

DISCUSSION

Previous attempts to define linkages between nekton and habitats included the development of Habitat Suitability Index (HSI) models by the U.S. Fish and Wildlife Service (FWS 1980a, 1980b, 1981). These models were developed using qualitative methods based on expert opinion but with little or no field validation. Brown et al. (1997) and Christensen et al. (1997) developed HSI models for various species that were integrated into a GIS to produce a spatial view of relative suitability in geographic space through time. Florida Marine Research Institute (FMRI) and NOS/NCCOS/CCMA cooperatively developed more quantitative HSI models using fisheries-independent monitoring data (trawls, etc.) as an approach to define EFH in Florida estuaries (Rubec et al. 1999). However, the above attempts to quantify HSI models have been based on sampling gear that were not appropriate for the highly structured habitats found in shallow estuarine areas (Rozas and Minello 1997). The intent of this study was to elucidate spatial patterns of habitat use by analyzing density data collected with enclosure gear from shallow estuarine habitats within Galveston Bay. Distribution patterns were further discriminated by determining how physical processes (salinity and temperature) influence habitat utilization. These data should provide evidence that not all habitats within a system are equally essential in supporting fishery species.

Various factors are considered important in defining nursery areas for juvenile estuarine-dependent organisms. Specific combinations of physico-chemical conditions and cyclic primary production that are related to food availability, growth, and sanctuary from predation often define optimal environments (Miller and Dunn 1980). Barry et al. (1996) considered prey availability to be a necessary component defining the nursery function of estuarine habitats. Shrimp and blue crab production has been correlated with the availability of salt marsh habitat in estuaries (Turner 1977; Zimmerman et al. 2000). ME and SAV availability was greatest in Christmas and West Bays where maximum densities of brown shrimp and pinfish occurred. Brown shrimp utilized both habitats similarly, while pinfish selected SAV and white shrimp selected ME. Inner marsh was not highly utilized by white shrimp or pinfish and brown shrimp exhibited moderate utilization (2.5-3/m^2) in salinities > 15 ppt.

Most estuarine nekton are adaptable to the highly dynamic environmental conditions exhibited within estuaries. Estuarine organisms are commonly found in a wide range of salinities and temperatures and are most affected by sudden changes in these environmental conditions (Longley 1994; Christensen et al. 1998). Metabolism, activity, and reproductive endocrine function have been reported to be affected by salinity (Holliday 1971; Thomas and Boyd 1989), and some organisms, such as the Eastern oyster, *Crassostrea virginica*, depend on salinity variability to control predators (Longley 1994). Salinity effects were significant in brown shrimp and pinfish models. Brown shrimp were captured throughout the bay but highest densities were observed in the lower bay. White shrimp were abundant throughout the bay except in the lowest (0-0.5 ppt) salinity zone. Pinfish distribution was restricted to the mid and lower bay.

These species and others are noted for their ability to accommodate low salinities (Zein-Eldin 1989; Gifford1962; Tagatz 1971), and other factors or combination of factors may be more important in influencing their distribution. Important prey items such as benthic infauna are most abundant in lower Galveston Bay (Zimmerman et al. 1990) and are important dietary components for brown shrimp, white shrimp (Zein-Eldin and Renaud 1986; McTigue and Zimmerman 1991, 1998), and pinfish (Stoner 1980; Stoner and Livingston 1984). It appears that indirect salinity affects and the greater availability of vegetated habitats in the lower bay may work synergistically to provide attractive nursery areas for brown shrimp and pinfish. Both brown shrimp and pinfish selected SAV, which was most abundant in the lower bay.

White shrimp did not exhibit a significant response to salinity in Galveston Bay, however, densities were generally greatest in the midbay region. Gunter et al. (1964) concluded that white shrimp were most abundant in waters < 10 ppt and salinity was the limiting factor to their abundance and distribution. Other authors (Perez-Farfante 1969; Zein-Eldin and Griffith 1969; Lindner and Cook 1970; Copeland and Bechtel 1974) observed no relationship between abundance and salinity. Zimmerman et al. (1990) suggest that salinity may have an indirect role in determining white shrimp abundance and that rich deposits of organic material transported from the upper bay support high abundance's of midbay nekton and infauna populations. As such, midbay habitats would provide adequate trophic resources and reduce competition with brown shrimp. Competitive pressures between the two penaeids are alleviated by staggered temporal utilization of estuarine habitats. Also, white shrimp are omnivorous and rely more on plant material (McTigue and Zimmerman 1991, 1998) than do brown shrimp. In

laboratory experiments, Giles and Zamora (1973) observed white shrimp displacement from vegetated habitats by brown shrimp. This direct competitive displacement may have an affect on white shrimp utilization patterns in areas where the species are sympatric, although Minello and Zimmerman (1985) did not observe this displacement behavior. All three species exhibited a pronounced decline in the utilization of habitats in the less saline portions of the bay (< 5 ppt). Forage organisms in this area are significantly reduced compared to middle and lower bay populations due to prolonged exposure to low salinity (Zimmerman et al. 1990). Moreover, vegetated habitats are extremely limited in this portion of the Galveston Bay system.

Currently, estuarine EFH for most federally managed species in the Gulf of Mexico exists as mapped estimates of relative abundance developed from the NOS Biogeography Program's Estuarine Living Marine Resources (ELMR) database (Monaco and Christensen 1998). ELMR provides relative abundance distributions for 44 fish and invertebrate species in Gulf of Mexico estuaries, which are ranked: not present, rare, common, abundant, and highly abundant. Relative abundance across seasonal salinity gradients were assigned based on literature review, fishery independent monitoring CPUE data, and expert review (Christensen and Monaco 1998; GMFMC 1998). EFH for these species was selected to consist of those areas mapped as common, abundant, and highly abundant. Presently, the entire Galveston Bay System is considered EFH for brown shrimp and white shrimp (Figures 25-26). An FMP for pinfish does not exist, but EFH for this species would also consist of the entire bay system (Figure 27). Models generated using density data in this report result in a more spatially resolved delineation of EFH (in waters <1 m depth). In comparison, the mapped density estimates

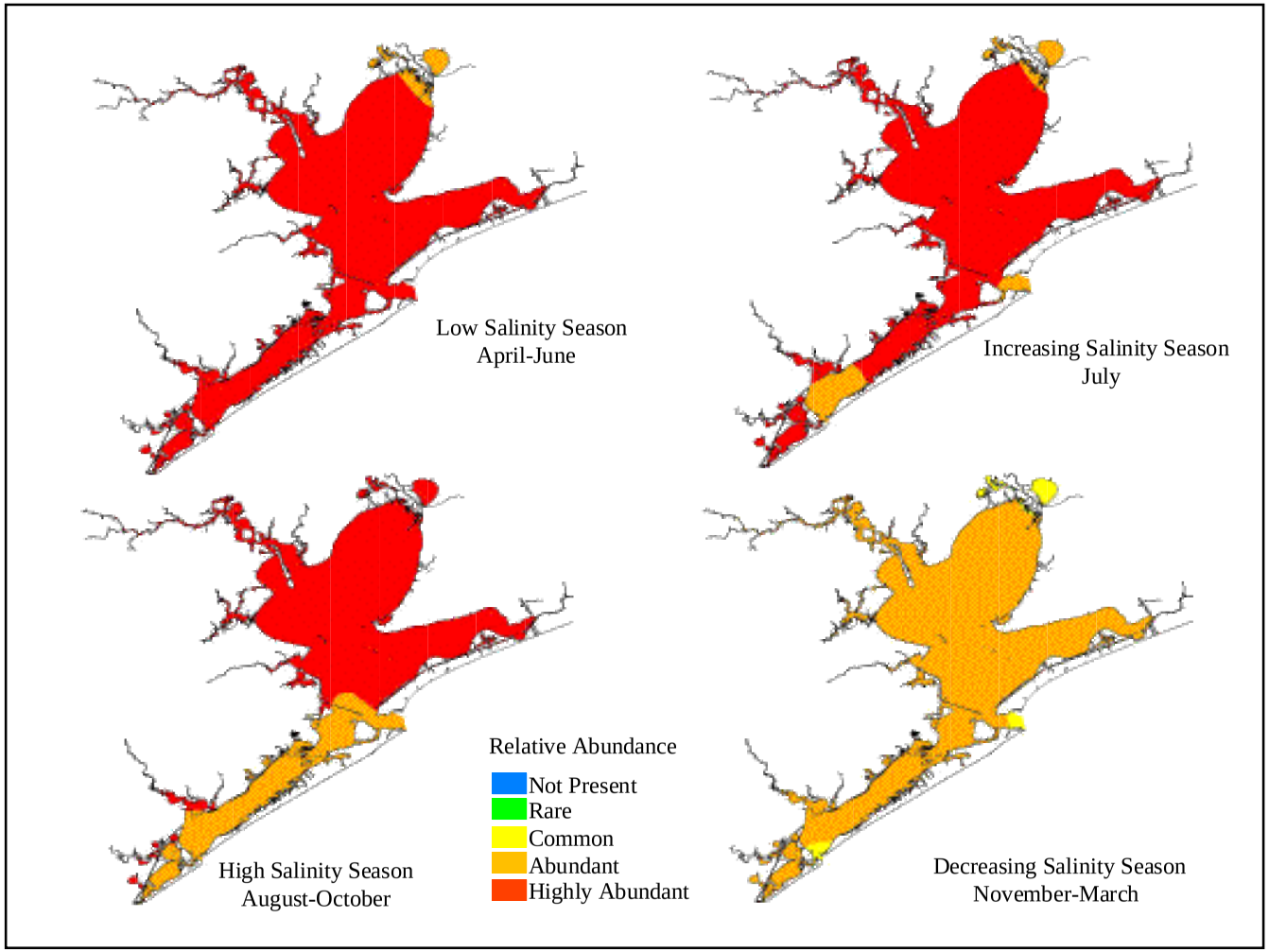


Figure 25. *EFH delineation for juvenile brown shrimp in Galveston Bay. EFH was defined by the GMFMC for areas where a species relative abundance was ranked, using ELMR Program data, as common, abundant, or highly abundant (GMFMC, 1998).*

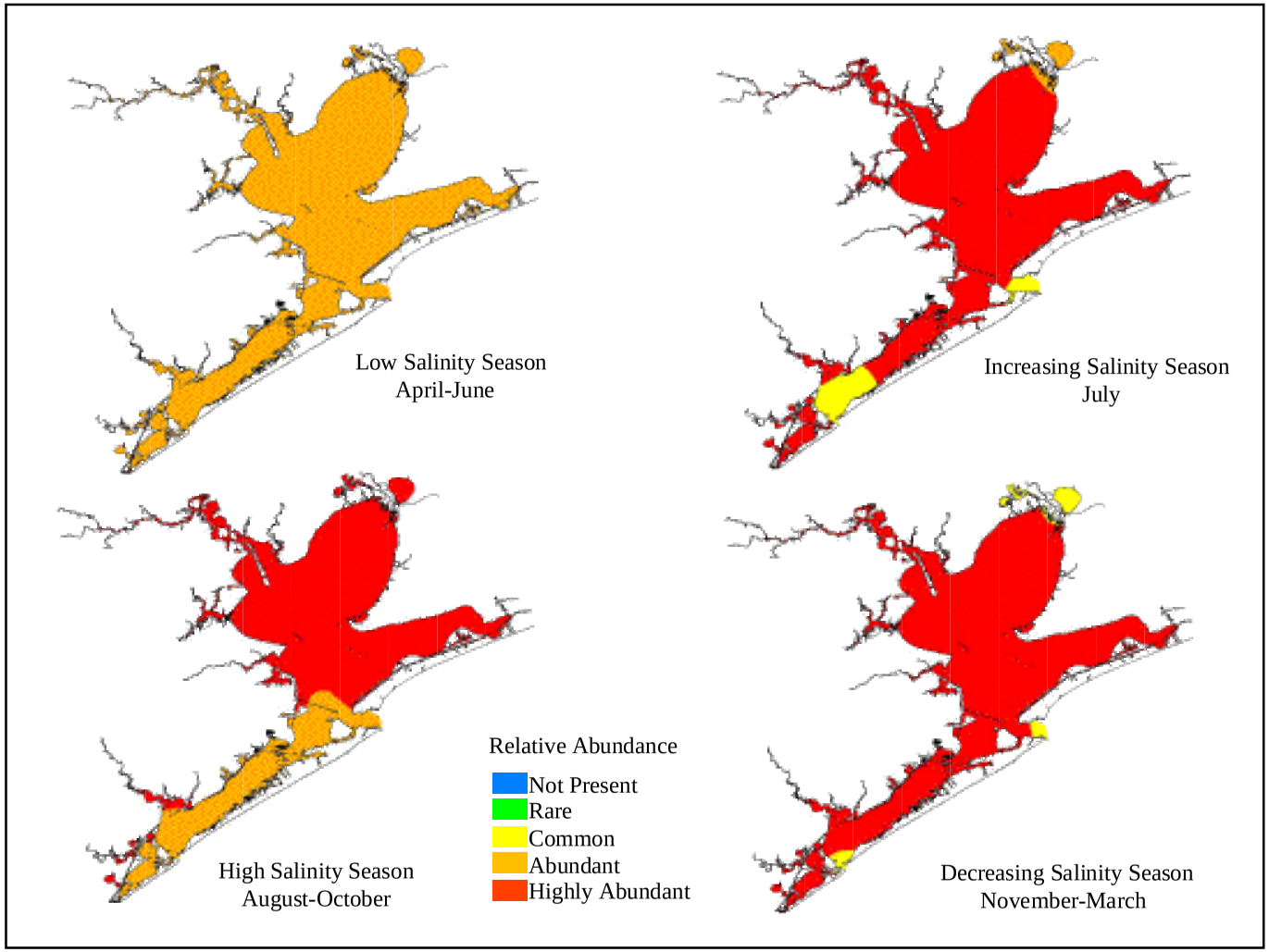


Figure 26. *EFH delineation for juvenile white shrimp in Galveston Bay. EFH was defined by the GMFMC for areas where a species relative abundance was ranked, using ELMR Program data, as common, abundant, or highly abundant (GMFMC 1998).*

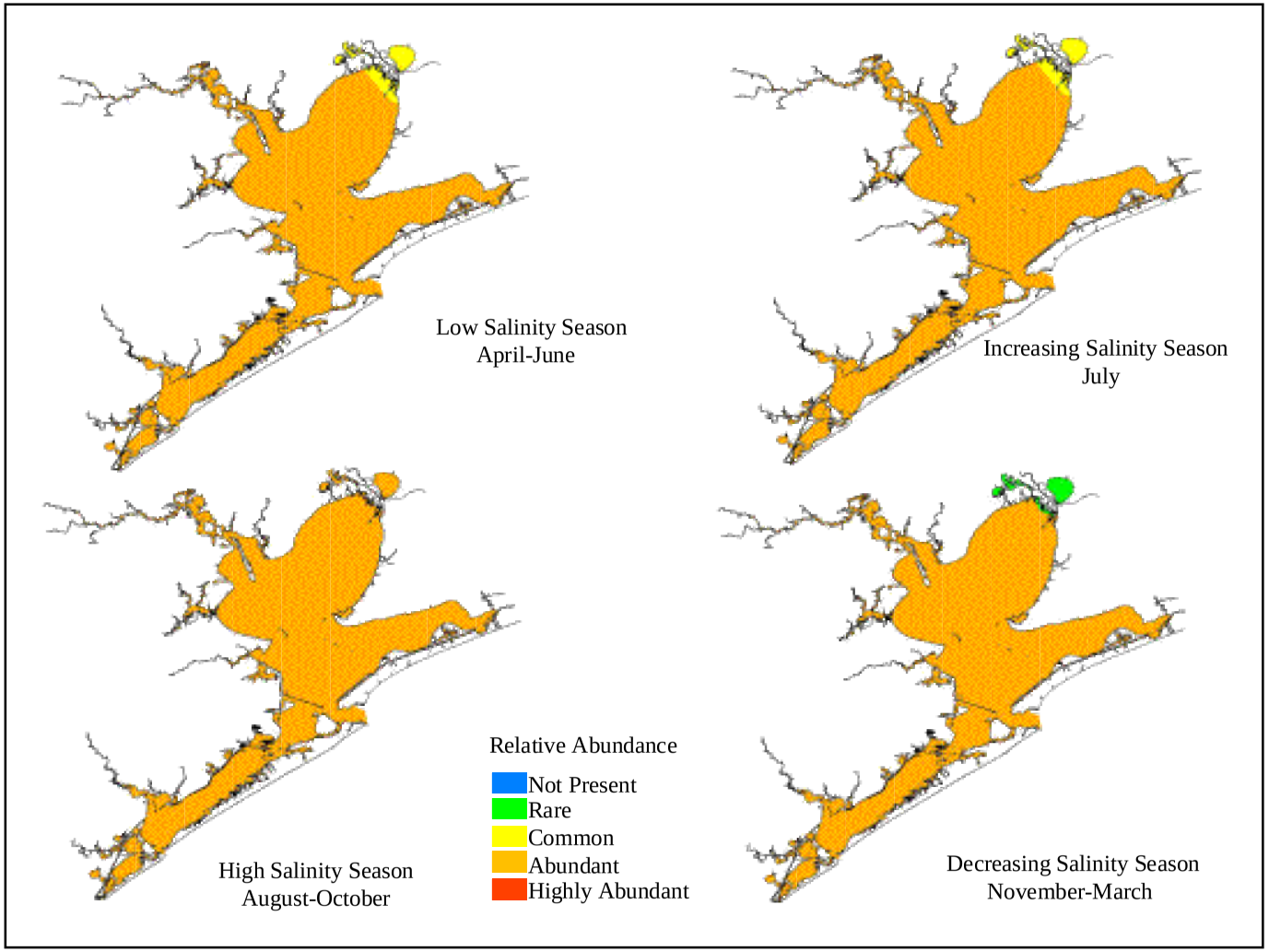


Figure 27. *Estuarine Living Marine Resources (ELMR) relative abundance distribution map for juvenile pinfish in Galveston Bay.*

for these taxa are significantly reduced from the maps based on ELMR data.

Comparisons of the Galveston Bay models with observed data from Matagorda, San Antonio, and Aransas Bays yielded variable results. Brown shrimp and pinfish models fit well in all estuarine systems, suggesting that the empirical models are not estuary-specific. However, these models are still probably constrained within a larger geographic construct (i.e. regional). This conclusion is consistent with Rubec et al. (1999), who used NOS Biogeography Program's spatial Habitat Suitability Modeling (HSM) methodologies to demonstrate the transferability of HSM models across estuaries. These results are promising, as previous efforts to predict nekton abundance with empirical models have proven difficult. Darnell and McEachran (1989) were unsuccessful in applying empirical predictive models for larval and juvenile nekton abundance in locations within the same estuary. The white shrimp model fit well only in Matagorda Bay, but the results may be misleading due to limited observations. The lack of fit that was observed in San Antonio Bay may reflect differences in population size between the two systems and spatial and temporal utilization dynamics. The center of white shrimp abundance has been reported to extend eastward from Galveston Bay to Mobile Bay (Muncy 1984), and white shrimp may be naturally less abundant along the mid and southern coast of Texas. San Antonio Bay's southerly location may promote different seasonal patterns that affect timing of recruitment or emigration. Several authors have positively correlated white shrimp abundance with freshwater inflow (Gunter and Hildebrand 1954; Gunter and Edwards 1969; Mueller and Matthews 1987), and significant differences in freshwater inflow are apparent between the two systems (Orlando et al. 1993). For these reasons, great care should be taken in applying the

model results to different estuarine systems.

Enclosure data used to build the predictive models were restricted to shallow waters (generally < 1 m). Thus, utilization patterns of deeper bay waters were not modeled. These deeper waters are generally inhabited by larger individuals, which have left the shallow nurseries and are preparing to emigrate from the bay system (Zilberg 1966; Cameron 1969; Lindner and Cook 1970; Minello et al. 1989). In addition, density data from oyster reefs and inner marsh were limited and not used in the models. These habitats are abundant throughout the bay and may provide essential habitat for managed fishery species (Wenner et al. 1996; Coen et al. 1999; Minello 1999).

Relative abundance and distribution patterns in open bay waters were analyzed from catch-per-unit-effort (CPUE in animals/10 m^2 of area swept) data from Texas Parks and Wildlife Department (TPWD) trawl surveys were mapped along with predictive model results for Galveston Bay. These trawls (3.8 cm stretched mesh) do not efficiently capture small size classes (< 50 mm TL) of nekton, thus, the trawl analysis only provides information on larger size classes (0 = 89 mm). However, few individuals in smaller size classes of shrimp or pinfish are likely to inhabit deeper bay waters; density estimates of small nekton including shrimp decline rapidly with depth (Mock 1966; Baltz et al. 1993; Rozas 1994; Rozas and Zimmerman in press). These CPUE estimates of animals/10 m^2 are likely underestimates of nekton density; catch efficiency for shrimp in trawls can be roughly estimated at 20% (Zimmerman et al. 1984; Rozas and Minello 1997). Assuming that this catch efficiency is stable, actual densities of large juveniles and subadult shrimp would be around five times larger than the values shown in Figures 28 and 29. Despite these difficulties in data analysis, the trawl data indicate that brown

shrimp in deeper waters of the bay were most abundant during May-July and did not display an obvious spatial distribution pattern (Figure 28). White shrimp caught in trawls were most abundant in September-November and generally appeared to be more abundant in lower salinity areas of the bay (Figure 29). Similar patterns were observed in TPWD trawl data from San Antonio Bay, TX; white shrimp were significantly more abundant in fresher (<15 ppt) waters of that system (Longley 1994). Additionally, larger penaeids (>50 mm) were captured most frequently on mud substrate (Lee et al. 1990) in San Antonio Bay. Pinfish were poorly represented in trawl samples, but those captured were almost exclusive to West Bay (Figure 30). Abundance estimates from TPWD trawl data were much lower than densities measured in shallow water habitats with enclosure samplers, and this difference may be partially due to low trawl catch efficiency for these species (Rozas and Minello 1997). A close up view of Figures 28-30 are provided in Appendices 1-9.

Ideally, EFH efforts should be based on a large comprehensive density database for estuarine habitats and associated environmental data created for Gulf of Mexico estuaries. This database can be integrated into a user-friendly GIS system to display and analyze the data. When consultations on project impacts are needed, habitats can be visualized in a GIS and managers can assess the possible extent of site-specific impacts to the habitat and the organisms that utilize it to provide a basis for management decisions. As such, the modeling approach discussed here will serve as a useful assessment tool for fishery and habitat managers. This approach also can be used to assess system-wide responses to anthropogenic activities, including: 1) freshwater flow diversions and reservoir construction, which significantly alter the volume and/or timing of freshwater

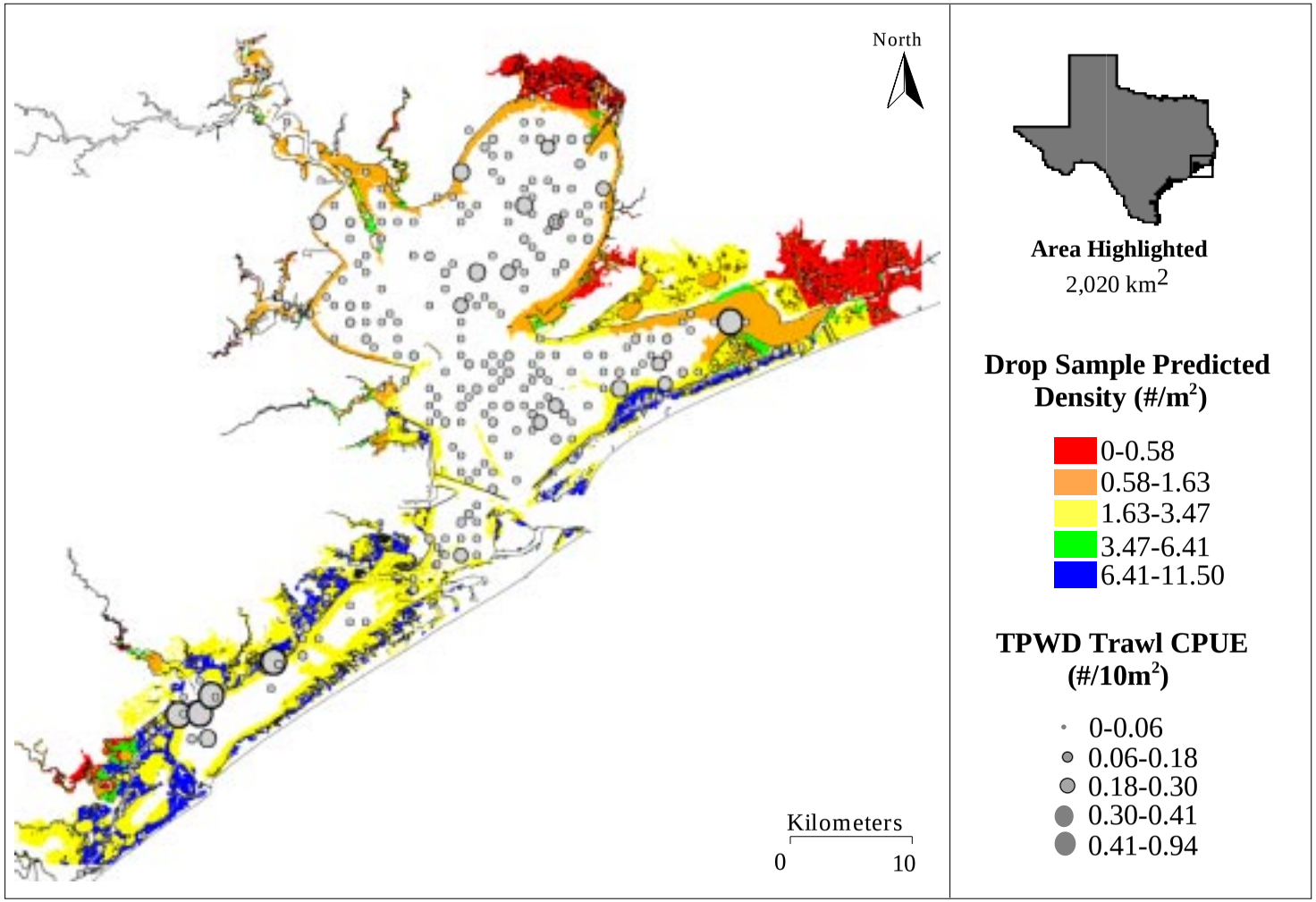


Figure 28. *Spatial distribution of predicted brown shrimp density from NMFS drop samples and observed TPWD otter trawl CPUE.*

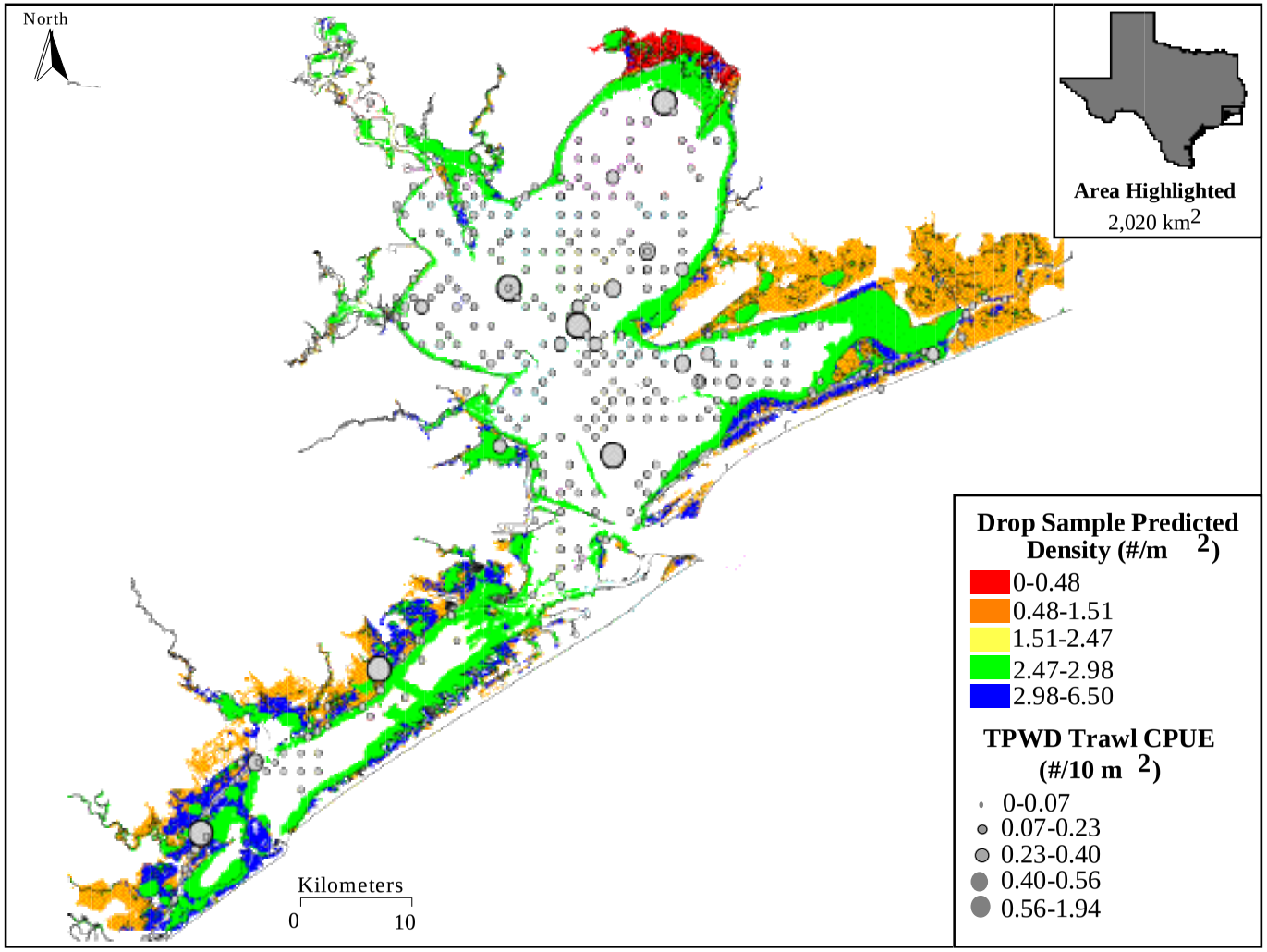


Figure 29. *Spatial distribution of predicted white shrimp density from NMFS drop samples and observed TPWD otter trawl CPUE.*

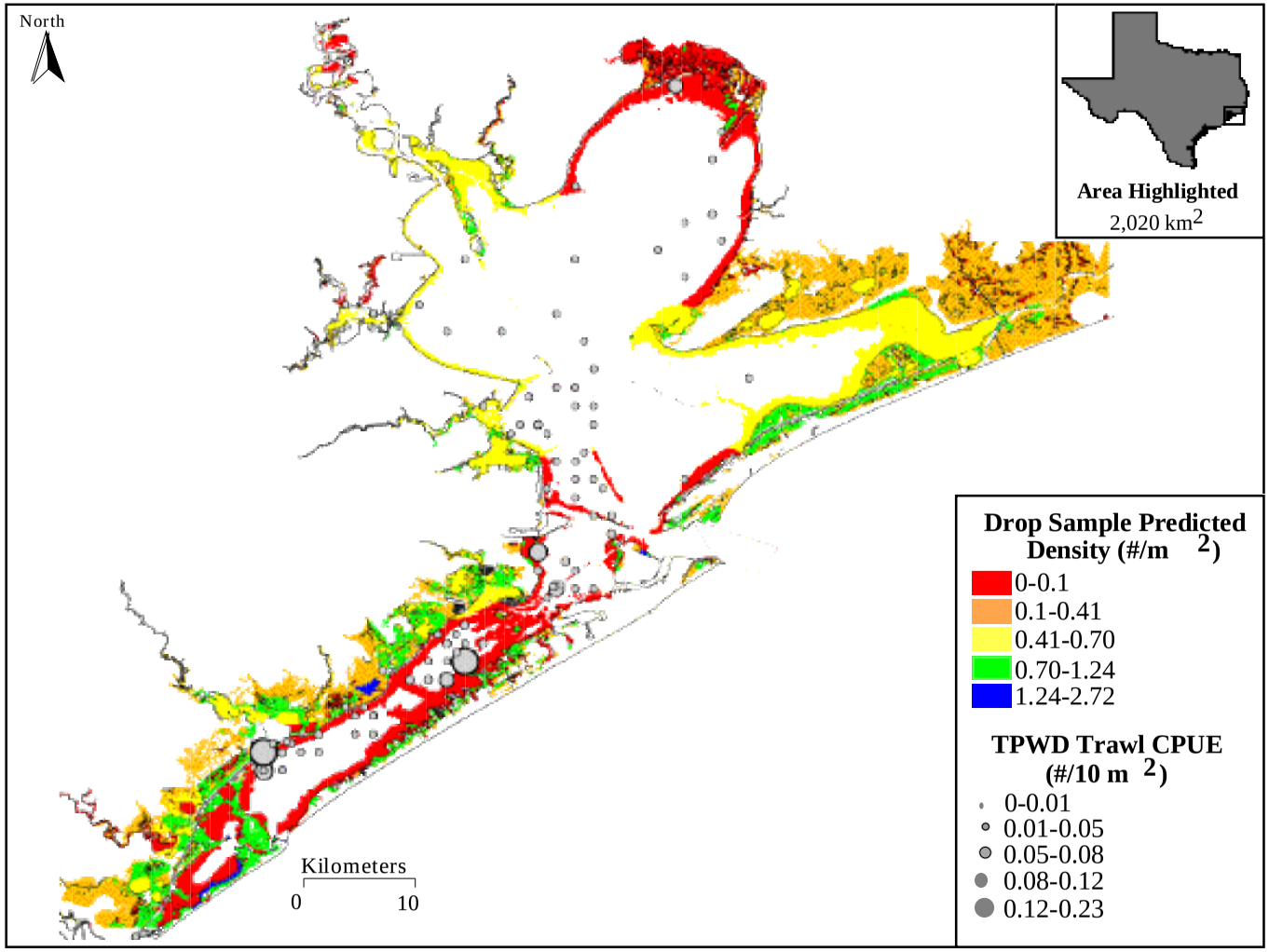


Figure 30. *Spatial distribution of predicted pinfish density from NMFS drop samples and observed TPWD otter trawl CPUE.*

delivery to an estuary; 2) creation or deepening of navigation channels; and 3) large-scale dredge material disposal site construction (Orlando et al. 1993). The success of transferring the brown shrimp model to adjacent estuarine systems indicates that these models can possibly act as "simulated" data in systems that lack sufficient density data. Continued monitoring in Galveston Bay and other Gulf estuaries is necessary to refine existing models and generate data for other federally managed species. Continued research and the collection of additional density data from other estuaries will further support the EFH mandate. Level 3 data, which evaluates how particular habitats influence survival, growth and reproductive dynamics of estuarine organisms, are needed to effectively define EFH as provisioned in the MFSCMA. In addition, more inter-estuary comparative studies are needed to determine, if and how, habitat utilization patterns differ throughout a species range. For example, some Florida estuaries contain mangroves, calcium carbonate rock formations, and sponge communities that may be important habitats for managed species.

NEXT STEPS

Refinements to the models are currently being explored. Possible interactions between salinity and habitat are being examined. In addition, a substrate layer has been developed for Galveston Bay and utilization patterns within substrate types are being tested. A method is also being developed to more accurately delineate habitat types within the NWI E2EM1N classification. Evidence exists that marsh edge habitats are used more frequently by some estuarine organisms than inner marsh habitat (Minello et al. 1991; Baltz et al. 1993; Peterson and Turner 1994), thus a more accurate

representation of these habitats are needed. Edge marsh is impossible to delineate using the NWI data due to the size of the minimum mapping unit. To estimate marsh edge, NWI data will be geo-referenced to USGS Digital Orthophoto Quarter Quadrangle (DOQQ) files, which have one meter resolution. Subsequently, area estimates for ME, inner marsh and SNB can be calculated. Randomly selected 1/4-hectare subsamples from within the DOQQ's are classified and categorized as to habitat type. These subsamples are then superimposed on the NWI layer for delineation. A preliminary analysis of the NWI emergent wetlands located at Elmgrove Point in East Bay indicated that these wetlands were composed of 42% ME, 30% SNB, and 28% inner marsh. Completion of this analysis will allow precise calculations of population estimates. Using the habitat area estimates from the NWI based habitat coverages, brown shrimp population size was determined by multiplying habitat area estimates (Table 2) by the respective density predictions from the model. This calculation estimated the total brown shrimp population in shallow water habitats at approximately 2.2 billion.

Historically, the management of marine fisheries habitat has been a secondary concern of state and federal fisheries management councils and commissions (Haddad 1997). The methods described here have provided evidence that estuarine habitats are discriminately utilized by the target species. The inclusion of stochastic processes, such as salinity, can be useful in developing predictive models but more data are needed to determine how other parameters may influence EFH. Although this method exhibits great promise, more comparative studies are needed for other habitats and other managed species to better understand the linkage between habitat utilization and fishery production.

REFERENCES

BALTZ, D.M., C. RAKOCINSKI, AND J.W. FLEEGER.
1993. Microhabitat use by marsh-edge fishes in a Louisiana estuary. Environ. Biolog. Fish. 36:109-126.

BARRY, J.P., M.M. YORKLAVICH, G.M. CAILLIET, D.A. AMBROSE, AND B.S. ANTRIM.
1996. Trophic ecology of the dominant fishes in Elkhorne Slough, California, 1974-1980. Estuaries 19:115-138.

BROWN, S.K., K.R. BUJA, S.H. JURY, M.E. MONACO, AND A. BANNER.
1997. Habitat suitability index models in Casco and Sheepscot Bays, Maine. Silver Spring, MD: National Oceanic and Atmospheric Administration, and Falmouth, ME: U.S. Fish and Wildlife Service. 86 p.

CAMERON, J.N.
1969. Growth, respiratory metabolism and seasonal distribution of juvenile pinfish (*Lagodon rhomboides* Linnaeus), in Redfish Bay, Texas. Contrib. Mar. Sci. 14:19-36.

CAPONE, T.A., AND J.A. KUSHLAN.
1991. Fish community structure in dry-season stream pools. Ecology. 72(3): 983-992.

CHRISTENSEN, J.D.
1996. Ichthyofaunal community structure at a coal-combustion by-product reef and a natural oyster reef in Galveston Bay, Texas. M.S. Thesis. Texas A&M University, College Station, TX. 113 p.

CHRISTENSEN, J.D., AND M.E. MONACO.
1998. Gulf-wide information system: Methodological briefing on the development and spatial integration of NOAA SEA Division's Living Marine Resource Data for G-WIS. NOAA/NOS Strategic Environmental Assessments Division, Silver Spring, MD. 20 p.

CHRISTENSEN, J.D., M.E. MONACO, AND T.A. LOWERY.
1997. An index to assess the sensitivity of Gulf of Mexico species to changes in estuarine salinity regimes. Gulf Res. Rep. 9(4):219-229.

CHRISTENSEN, J.D., T.A. BATISTA, M.E. MONACO, AND C.J. KLEIN.
1997. Habitat suitability modeling and GIS technology to support habitat management: Pensacola bay, Florida Case Study. NOAA/NOS Strategic Environmental Assessments Division, Silver Spring, MD. 58 p.

COPELAND, B.J. AND T.J. BECHTEL.
1974. Some environmental limits of six Gulf coast estuarine organisms. Contrib. Mar. Sci. 18:169-204.

COWARDIN, L.J., V. CARTER, F.C. GOLET, AND E.T. LAROE.
1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish Wildl. Serv. Biol. Serv. Program FWS/OBS-79/31. 131 p.

COEN, L.D., M.W. LUCKENBACH, AND D.L. BREITBURG.
1999. The role of oyster reefs as essential fish habitat; a review of current knowledge and some new perspectives. Pages 438-454 *in* L.R. Benaka, editor. Fish habitat; essential fish habitat, and rehabilitation. American Fisheries Society, Symposium 22, Bethesda, Maryland.

CZAPLA, T.E.
1991. Diets and prey selection of pinfish and southern flounder in a *Halodule wrightii* seagrass meadow. Doctoral dissertation. Texas A&M University, College Station.

DARNELL, R.M. AND J.D.MCEACHRAN.
1989. Larval recruitment of estuarine-related fishes and invertebrates of the Texas coast. Report to Texas Parks and Wildlife Department, by Departments of Oceanography and Wildlife and Fisheries Sciences, Texas A&M University, College Station, TX. 107 p.

FWS (U.S. FISH AND WILDLIFE SERVICE).
1980a. Habitat as a basis of environmental assessment. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, D.C., ESM Report 101 (4-80).

FWS (U.S. FISH AND WILDLIFE SERVICE).
1980b. Habitat evaluation procedures. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, D.C., ESM Report 102 (2-80).

FWS (U.S. FISH AND WILDLIFE SERVICE).
1981. Standards for the development of habitat suitability index models for use with habitat evaluation procedures. U.S. Department of the Interior, U.S. Fish and Wildlife Service, Division of Ecological Services, Washington D.C., ESM Report 103 (1-81).

GIFFORD, C.A.
1962. Some aspects of osmotic and ionic regulation in the blue crab, *Callinectes sapidus* and the ghost crab, *Ocypode albicans*. Publ. Inst. Mar. Sci. 8:97-125.

GILES, J.H. AND G. ZAMORA.
1973. Cover as a factor in habitat selection by juvenile brown (*Penaeus aztecus*) and white (*P. setiferus*) shrimp. Trans. Am. Fish. Soc. 102:144-145.

GMFMC (GULF OF MEXICO FISHERY MANAGEMENT COUNCIL).
1998. Generic amendment for addressing essential fish habitat requirements. Prepared by the GMFMC, October 1998.

GUNTER, G.
1941. Death of fishes due to cold on the Texas coast, January, 1940. Ecology 22:203-208.

GUNTER, G.
1961. Some relations of estuarine organisms to salinity. Limnol. Oceanogr. 6:182-190.

GUNTER, G. AND J.C. EDWARDS.
1969. The relation of rainfall and freshwater drainage to the production of penaeid shrimps (*Penaeus fluviatilis* Say and *Penaeus aztecus* Ives) in Texas and Louisiana waters. FAO Fish. Rep. 57(3):875-892.

GUNTER, G. AND H.H. HILDEBRAND.
1954. The relation of rainfall of the state and catch of the marine shrimp (*Penaeus setiferus*) in Texas waters. Bull. Mar. Sci. Gulf Caribb. 4:95-103.

GUNTER, G., J.Y. CHRISTMAS, AND R. KILLEBREW.
1964. Some relations of salinity to population distributions of motile estuarine organisms, with special reference to penaeid shrimp. Ecology 45:181-185.

HADDAD, K.
1997. Integration of state fisheries and habitat management with ASMFC and fishery management councils. pp. 12-15 *in* Management of Atlantic coastal marine habitat: Proceedings of a workshop for habitat managers, Philadelphia, PA. Atlantic States. Mar. Fish. Comm. Habitat Manag. Ser. No. 2.

HECK, K.L., JR., K.W. ABLE, S.G. MORGAN, AND R.K. ZIMMER-FAUST.
1994. Recruitment and habitat utilization by the blue crab, *Callinectes sapidus*: the importance of juvenile nursery habitats to the fishery. Marine Fisheries Initiative (MARFIN) final report to NOAA National Marine Fisheries Service, St. Petersburg, Florida. 95 p.

HILDEBRAND, H.H. AND G. GUNTER.
1953. Correlation of rainfall with Texas catch of white shrimp, *Penaeus setiferus* (Linnaeus). Trans. Am. Fish. Soc. 82:151-155.

HOLLIDAY, F.G.T.
1971. Salinity-animals-fishes. Pages 997-1083 *in* O. Kinne, ed. Marine Ecology. Vol. I. Pt. II Environmental factors. John Wiley, New York, NY. 1244 p.

JOHNSON, G.D.
1978. Development of fishes of the Mid-Atlantic Bight: an atlas of egg, larval and juvenile stages. Vol. VI. Carangidae through Ephippidae. U.S. Fish Wildl. Serv., Biol. Serv. Prog. FWS/OBS-78/12, 314 p.

KANA, J.C., J.A. DAILY, B. FULS, AND L.W.MCEACHRAN.
1993. Trends in relative abundance and size of selected finfishes and shellfishes along the Texas Coast: November 1975-December 1991. Texas Parks and Wildlife Department. Management Data Series No. 103.

KEEFE, M.L. AND K.W. ABLE.
1994. Contributions of abiotic and biotic factors to settlement in summer flounder, *Paralichthys dentatus*. Copeia 2:458-465.

LEE, W.Y., A.W. GREEN, AND G.C. MATLOCK.
1990. Salinity and substrate preferences of juvenile brown and white shrimp in the inshore environment of the San Antonio Bay system, Texas. Report to Texas Water Development Board, by Texas Parks and Wildlife Department, Austin, TX. 26 p.

LINDNER, M.J. AND H.L. COOK.
1970. Synopsis of biological data on the white shrimp *Penaeus setfierus* (Linnaeus) 1767. FAO Fish. Synop. 101. FAO Fish. Rep. 4:1439-1469.

LONGLEY, W.L.
1994. Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs. Texas Water Development Board and Texas Parks and Wildlife Department, Austin, TX.

MCTIGUE, T.A., AND R.J. ZIMMERMAN.
1991. Carnivory versus herbivory in juvenile *Penaeus setfierus* (Linnaeus) and *Penaeus aztecus* (Ives). J. Exp. Mar. Biol. Ecol. 15:1-16.

MCTIGUE, T.A., AND R.J. ZIMMERMAN.
1998. The use of infauna by juvenile *Penaeus aztecus* (Ives) and *P. setiferus* (Linnaeus). Estuaries 21: 160-175.

MILLER, J.M., AND M.L. DUNN.
1980. Feeding strategies and patterns of movement in juvenile estuarine fishes. Pages 437-448 *in* V. S. Kennedy, ed. Estuarine perspectives, Academic Press, New York.

MINELLO, T.J.
1999. Nekton densities in shallow estuarine habitats of Texas and Louisiana and the identification of Essential Fish Habitat. *In* Beneka, L., ed. Fish habitat: Essential fish habitat and rehabilitation, The American Fisheries Society, Bethesda, MD. (in press).

MINELLO, T.J., AND J.W. WEBB, JR.
1997. Use of natural and created *Spartina alterniflora* salt marshes by fishery species and other aquatic fauna in Galveston Bay, Texas, USA. Mar. Ecol. Prog. Ser. 151:165-179.

MINELLO, T.J., AND R.J. ZIMMERMAN.
1985. Differential selection for vegetative structure between juvenile brown shrimp (*Penaeus aztecus*) and white shrimp (*P. setiferus*), and implications in predator-prey relationships. Est. Coast. Shelf Sci. 20: 707-716.

MINELLO, T.J., AND R.J. ZIMMERMAN.
1992. Utilization of natural and transplanted Texas salt marshes by fish and decapod crustaceans. Mar. Ecol. Prog. Ser. 90:273-285.

MINELLO, T.J., J.W. WEBB, JR., R.J. ZIMMERMAN, R.B. WOOTEN, J.L. MARTINEZ, T.J. BAUMER, AND M.C. PATILLO.
1991. Habitat availability and utilization by benthos and nekton in Hall's Lake and West Galveston Bay. NOAA Tech. Mem. NMFS-SEFC-275:37.

MINELLO, T.J., R.J. ZIMMERMAN, AND R. MEDINA.
1994. The importance of edge for natant macrofauna in a created salt marsh. Wetlands 14:184-198.

MOCK, C.R.
1966. Natural and altered estuarine habitats of penaeid shrimp. Proceedings of the Gulf and Caribbean Fisheries Institute, 19th Annual Session: 86-98.

MOLES, A., AND B.L. NORCROSS.
1995. Sediment preference in juvenile Pacific flatfishes. Neth. Jour. Sea Res. 34:177-182.

MUELLER, A.J., AND G.A. MATTHEWS.
1. Freshwater inflow needs of the Matagorda Bay system, with focus on penaeid shrimp. National Marine Fisheries Service, U.S. Department of Commerce. Technical Memorandum NMFS-SEFC-189. 97 p.

MONACO, M.E. AND J.D. CHRISTENSEN.
1997. Biogeography Program: Coupling species distributions and habitat. *In* Boehlert, G.W. and J.D. Schumacher (ed.). Changing oceans and changing fisheries: Environmental data for fisheries research and management. NMFS Tech. Memo., NOAA-TM-NMFS-SWFSC-239, April 1997, Pacific Grove, CA.

MUNCY, R.J.
1984. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Gulf of Mexico)-white shrimp. U.S. Fish Wildl. Serv. FWS/OBS-82/11.20 U.S. Army Corps of Engineers, TR EL-82-4. 19 p.

NMFS (NATIONAL MARINE FISHERIES SERVICE).
1997. Magnuson-Stevens Act provisions: essential fish habitat: interim final rule and request for comments. Federal Register [Docket 961030300-7238-04; I.D. 120996A]: 66531-66559.

NOAA (NATIONAL OCEANIC AND ATMSOPHERIC ADMINISTRATION).
1989. Estuaries of the United States: Vital statistics of a natural resource base. Strategic Environmental Assessments Division, Rockville, MD. 79 p.

ODUM, W.E., C.C. MCIVOR, AND T.J. SMITH III.
1982. The ecology of the mangroves of south Florida: a community profile. U.S. Fish Wildl. Serv. Biol. Serv. Program FWS/OBS-81/24. 144 p.

ORLANDO, S.P. JR., L.P. ROZAS, G.H. WARD, AND C.J. KLEIN.
1993. Salinity characteristics of Gulf of Mexico Estuaries. Silver Spring, MD: National Oceanic and Atmospheric Administration, Office of Ocean Resources Conservation and Assessment. 209 p.

PEREZ-FARFANTE, I.
4. Western Atlantic shrimps of the genus *Penaeus*. U.S. Fish and Wildl. Serv. Fish. Bull. 67(3):461-591.

PEREZ-FARFANTE, I. AND B. KENSLEY.
1997. Penaeoid and sergestoid shrimps and prawns of the world; keys and diagnoses for the families and genera. Mamoires du MusAum National d'Histoire Naturelle, Tome 175, 233p.

PETERSON, G.W., AND R.E. TURNER.
1994. The value of salt marsh edge vs. interior as a habitat for fish and decapod crustaceans in a Louisiana tidal marsh. Estuaries 17:235-262.

REID, G.K., JR.
1954. An ecological study of the Gulf of Mexico fishes, in the vicinity of Cedar Key, Florida. Bull. Mar. Sci. Gulf Caribb. 4(1);43-91.

ROZAS, L.P., AND T.J. MINELLO.
1998. Nekton use of salt marsh, seagrass, and nonvegetated habitats in a south Texas (USA) estuary. Bull. Mar. Sci. 63(3):481-501.

ROZAS, L.P., AND D.J. REED.
5. Nekton use of marsh-surface habitats in Louisiana (USA) deltaic salt marshes undergoing submergence. Mar. Ecol. Prog. Ser. 96:147-157.

ROZAS, L.P., AND R.J. ZIMMERMAN
IN PRESS. Small-scale patterns of nekton use among marsh and adjacent shallow nonvegetated areas of the Galveston Bay estuary, Texas (USA). Mar. Ecol. Prog. Ser.

RULIFSON, R.A.
1981. Substrate preferences of juvenile penaeid shrimps in estuarine habitats. Contrib. Mar. Sci. 24:35-52.

RUBEC, P.J., J.C.W. BEXLEY, H. NORRIS, M.S. COYNE, M.E. MONACO, S.G. SMITH, AND J.S. AULT.
1999. Suitability modeling to delineate habitat essential to sustainable fisheries. American Fisheries Society Symposium 22:108-133.

SHERIDAN, P.F.
1992. Comparative habitat utilization by estuarine macrofauna within the mangrove ecosystem of Rookery Bay, Florida. Bull. Mar. Sci. 50:21-39.

SOKAL, R.R., AND F.J. ROHLF.
1995. Biometry. (Third Edition). San Francisco. W.H. Freeman and Co.

ST. AMANT, L.S., K.C. CORKUM, AND J.G. BROOM.
1962. Studies on growth dynamics of the brown shrimp, *Penaeus aztecus*, in Louisiana waters. Proceedings of the Gulf and Caribbean Fishery Institute 18:1-16.

STONER, A.W.
1980. Feeding ecology of *Lagodon rhomboides* (Pices: Sparidae): variation and functional responses. Fish. Bull., U.S. 78:337-352.

STONER, A.W., AND R.J. LIVINGSTON.
1984. Ontogenetic patterns in diet and feeding morphology in sympatric sparid fishes from seagrass meadows. Copeia 1984:174-187.

STRANGE, E.M., P.B. MOYLE, AND T.C. FION.
1992. Interactions between stochastic and deterministic processes in stream fish community assembly. Environ. Biol. Fish. 36: 1-15.

TAGATZ, M.E.
1971. Osmoregulatory ability of blue crabs in different temperature-salinity combinations. Ches. Sci. 12:14-17.

THOMAS, P., AND N. BOYD.
1989. Salinity requirements for reproduction and larval development of several important fishes in Texas estuaries. Part 1: Reproduction in spotted seatrout and Atlantic croaker. Report to Texas Water Development Board, by Marine Science Institute, University of Texas at Austin, Port Aransas, TX. 45 p.

THOMAS, J.L., R.J. ZIMMERMAN, AND T.J. MINELLO.
1990. Abundance patterns of juvenile blue crabs (*Callinectes sapidus*) in nursery habitats of two Texas bays. Bull. Mar. Sci. 46:115-125.

TURNER, R.E.
1977. Intertidal vegetation and commercial yields of penaeid shrimp. Trans. Am. Fish. Soc. 106:411-416.

VALENTINE, J.F., K.L. HECK, P. HARPER, AND M. BECK.
1994. Effects of bioturbation in controlling turtlegrass (*Thalassia testudinum* Banks *ex* Konig) abundance: evidence from field enclosures and observations in the northern Gulf of Mexico. J. Exp. Mar. Biol. Ecol. 22:171-178.

WENNER, E., H.R. BEATTY, AND L. COEN.
1996. A method for quantitatively sampling nekton on intertidal oyster reefs. J. Shell. Res. 15:769-775.

WHITE, W.A., T.A. TREMBLAY, E.G. WERMUND, JR., AND L.R. HANDLEY.
1993. Trends and status of wetland and aquatic habitats in the Galveston Bay System, Texas. Galveston Bay National Estuary Program, 1993. 225 p.

WILLIAMS, A.B.
1958. Substrates as a factor in shrimp distribution. Limnol. Oceanogr. 3(3):283-290.

WILLIAMS, A.H., L.D. COEN, AND M.S. STOELTING.
1990. Seasonal abundance, distribution, and habitat selection of juvenile *Callinectes sapidus* (Rathbun) in the northern Gulf of Mexico. J. Exp. Mar. Biol. Ecol. 137:165-183.

ZEIN-ELDIN, Z.P.
1963. Effect of salinity on growth of postlarval penaeid shrimp. Biol. Bull. (Woods Hole) 125:188-196.

ZEIN-ELDIN, Z.P.
1989. Growth and survival of postlarval *Penaeus setiferus* and *P. aztecus* under controlled temperature and salinity combinations. (unpublished manuscript) 25 p.

ZEIN-ELDIN, Z.P., AND G.W. GRIFFITH.
1969. An appraisal of the effect of salinity and temperature on growth and survival of postlarval penaeids. FAO Fish. Rep. 57:1015-1026.

ZEIN-ELDIN, Z.P., AND M.L. RENAUD.
1986. Inshore environmental effects on brown shrimp, *Penaeus aztecus*, and white shrimp, *P. setiferus*, populations in coastal waters, particularly Texas. Mar. Fish. Rev. 48:9-19.

ZILBERG, M.H.
1966. Seasonal occurrence of fishes in a coastal marsh of northwest Florida. Publ. Inst. Mar. Sci. Univ. Tex. 11:126-134.

ZIMMERMAN, R.J., AND T.J. MINELLO.
1984. Densities of *Penaeus aztecus*, *P. setiferus* and other natant macrofauna in a Texas salt marsh. Estuaries 7:421-433.

ZIMMERMAN, R.J., T.J. MINELLO, AND G. ZAMORA.
1984. Selection of vegetated habitat by *Penaeus aztecus* in a Galveston Bay salt marsh. Fish. Bull. 82:325-336.

ZIMMERMAN, R.J., T.J. MINELLO, T.J. BAUMER, AND M.C. CASTIGLIONE.
1989. Oyster reef as habitat for estuarine macrofauna. NOAA Tech. Memo., NMFS-SEFC-249.

ZIMMERMAN, R.J., T.J. MINELLO, M.C. CASTIGLIONE, AND D.L. SMITH.
1990a. The use of *Juncus* and *Spartina* marshes by fisheries species in Lavaca Bay, Texas, with reference to effects of floods. NOAA Tech. Memo., NMFS-SEFC-251.

ZIMMERMAN, R.J., T.J. MINELLO, M.C. CASTIGLIONE, AND D.L. SMITH.
1990b. Utilization of marsh and associated habitats along a salinity gradient in Galveston Bay. NOAA Tech. Memo., NMFS-SEFC-250.

ZIMMERMAN, R.J., T.J. MINELLO, AND L.P. ROZAS.
2000. Salt marsh linkages to productivity of penaeid shrimps and blue crabs in the northern Gulf of Mexico. *In* Weinstein, M.P. and D.A. Kreeger (ed.). Concepts and controversies in tidal marsh ecology. New Jersey Sea Grant (in press).

APPENDICES

Appendix 1. Zoom in of predicted brown shrimp density and observed TPWD otter trawl CPUE – West Galveston Bay.

Appendix 2. Zoom in of predicted brown shrimp density and observed TPWD otter trawl CPUE – East Galveston Bay.

Appendix 3. Zoom in of predicted brown shrimp density and observed TPWD otter trawl CPUE – Galveston and Trinity Bays.

Appendix 4. Zoom in of predicted white shrimp density and observed TPWD otter trawl CPUE – West Galveston Bay.

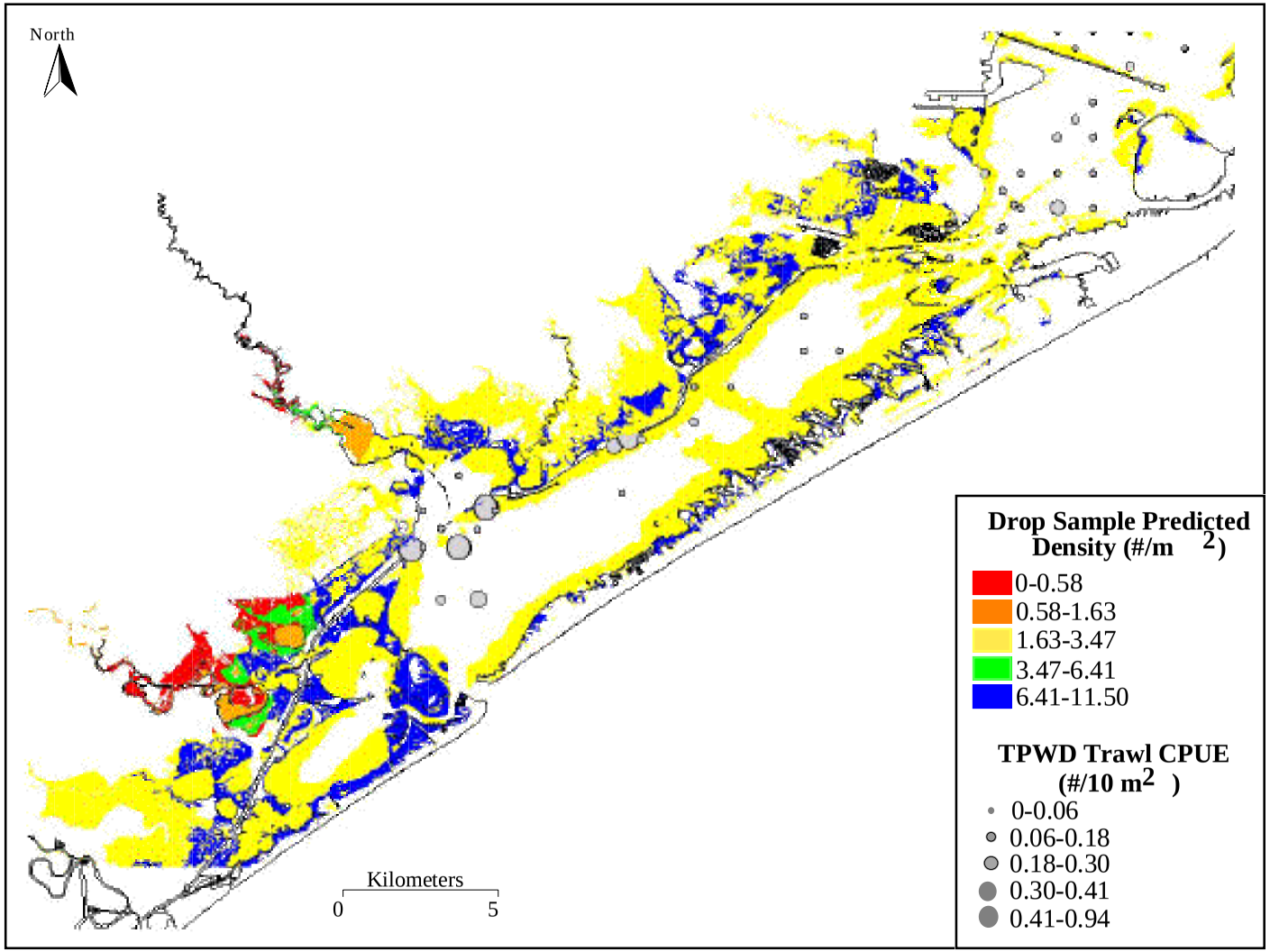
Appendix 5. Zoom in of predicted white shrimp density and observed TPWD otter trawl CPUE – East Galveston Bay.

Appendix 6. Zoom in of predicted white shrimp density and observed TPWD otter trawl CPUE – Galveston and Trinity Bays.

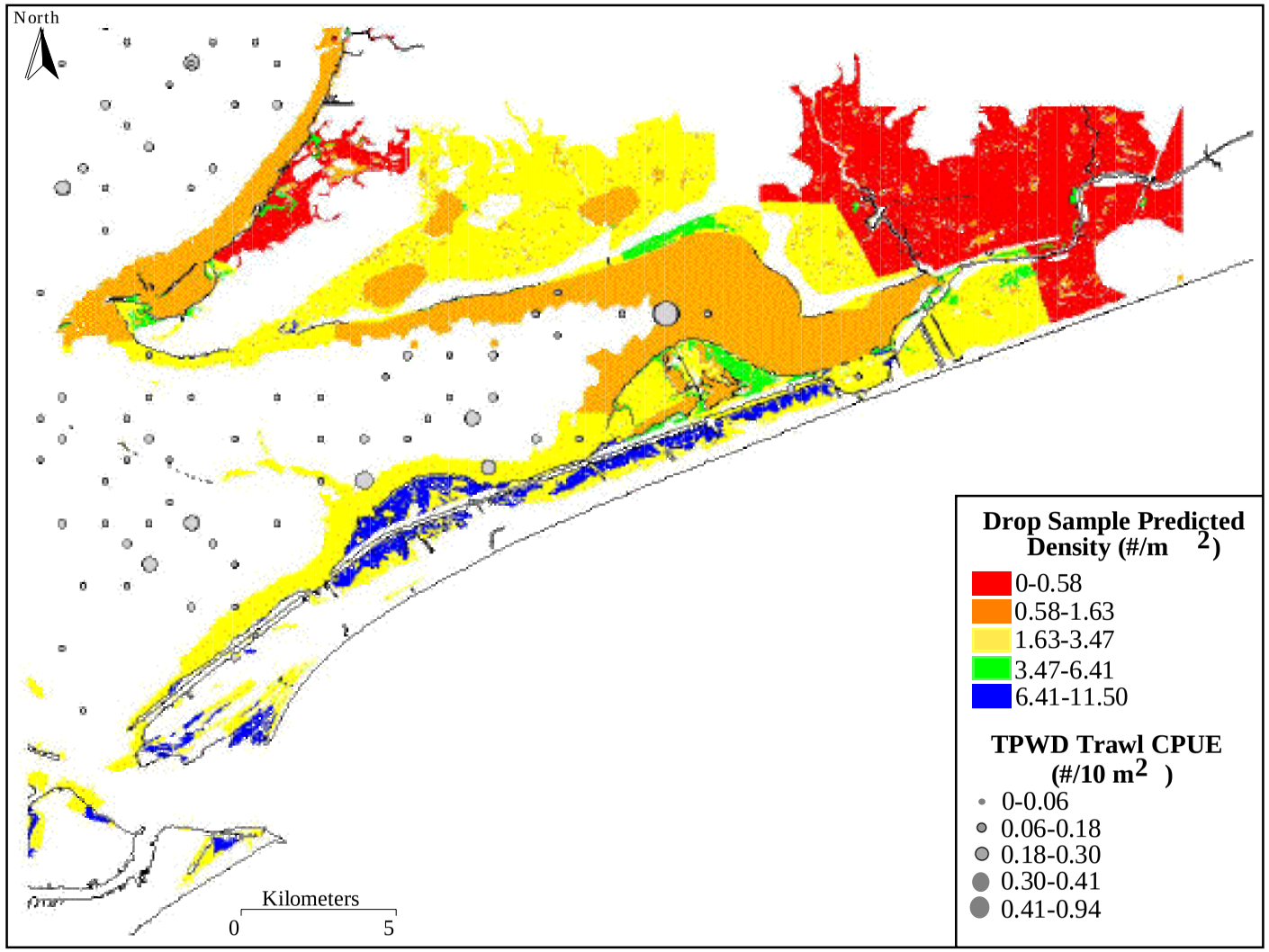
Appendix 7. Zoom in of predicted pinfish density and observed TPWD otter trawl CPUE – West Galveston Bay.

Appendix 8. Zoom in of predicted pinfish density and observed TPWD otter trawl CPUE – East Galveston Bay.

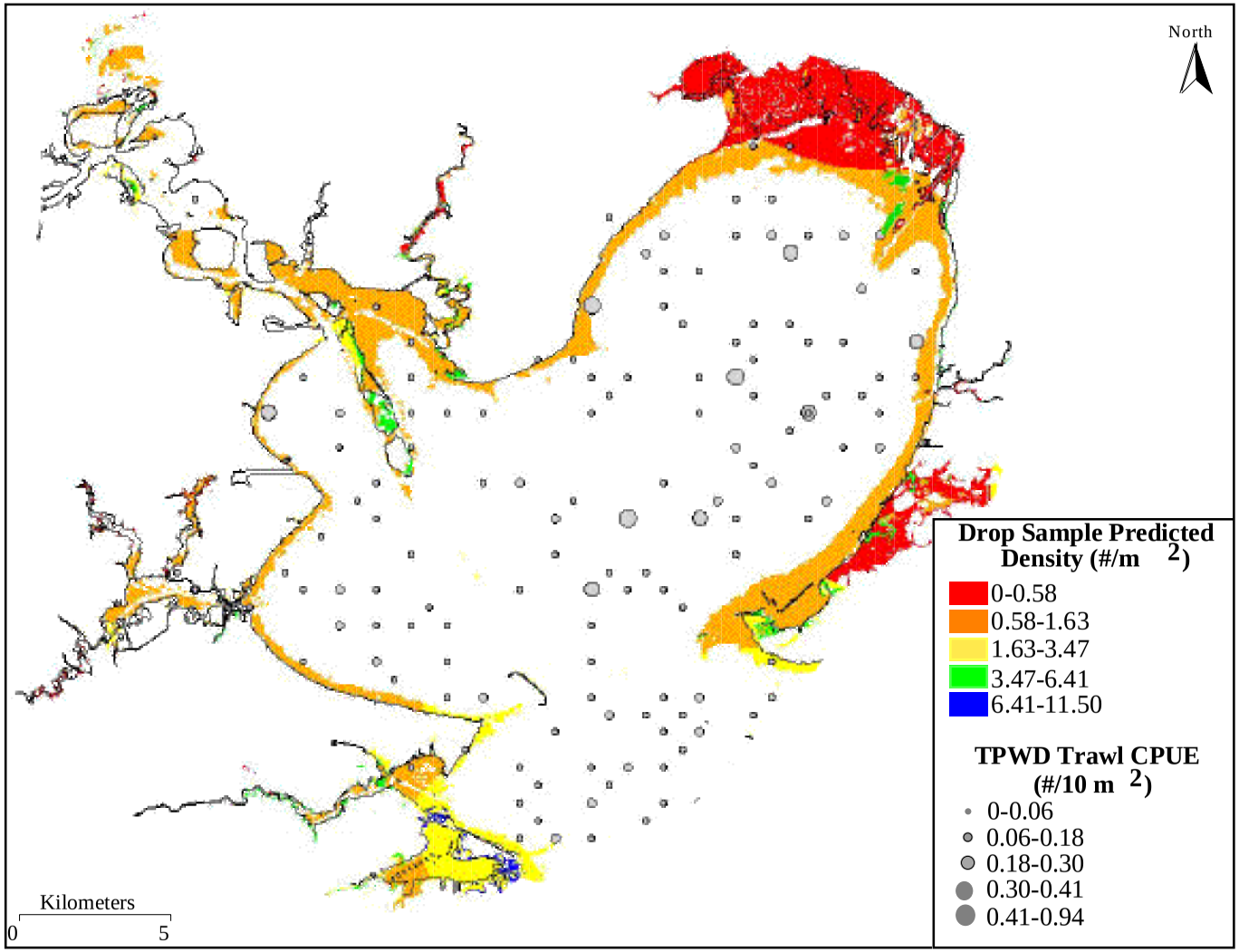
Appendix 9. Zoom in of predicted pinfish density and observed TPWD otter trawl CPUE – Galveston and Trinity Bays.



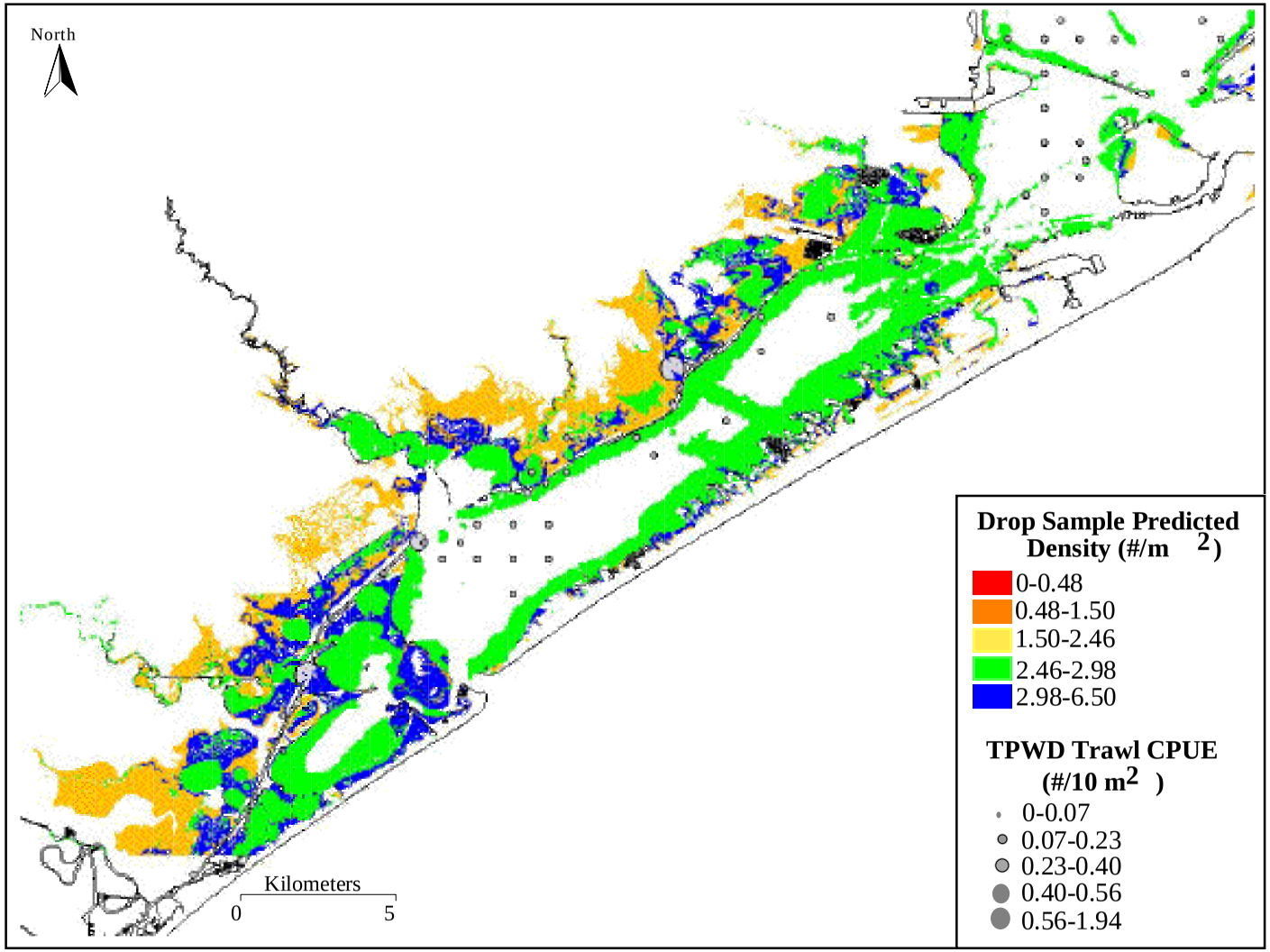
Appendix 1 *. Zoom in of predicted brown shrimp density and observed TPWD otter trawl CPUE - West Galveston Bay.*



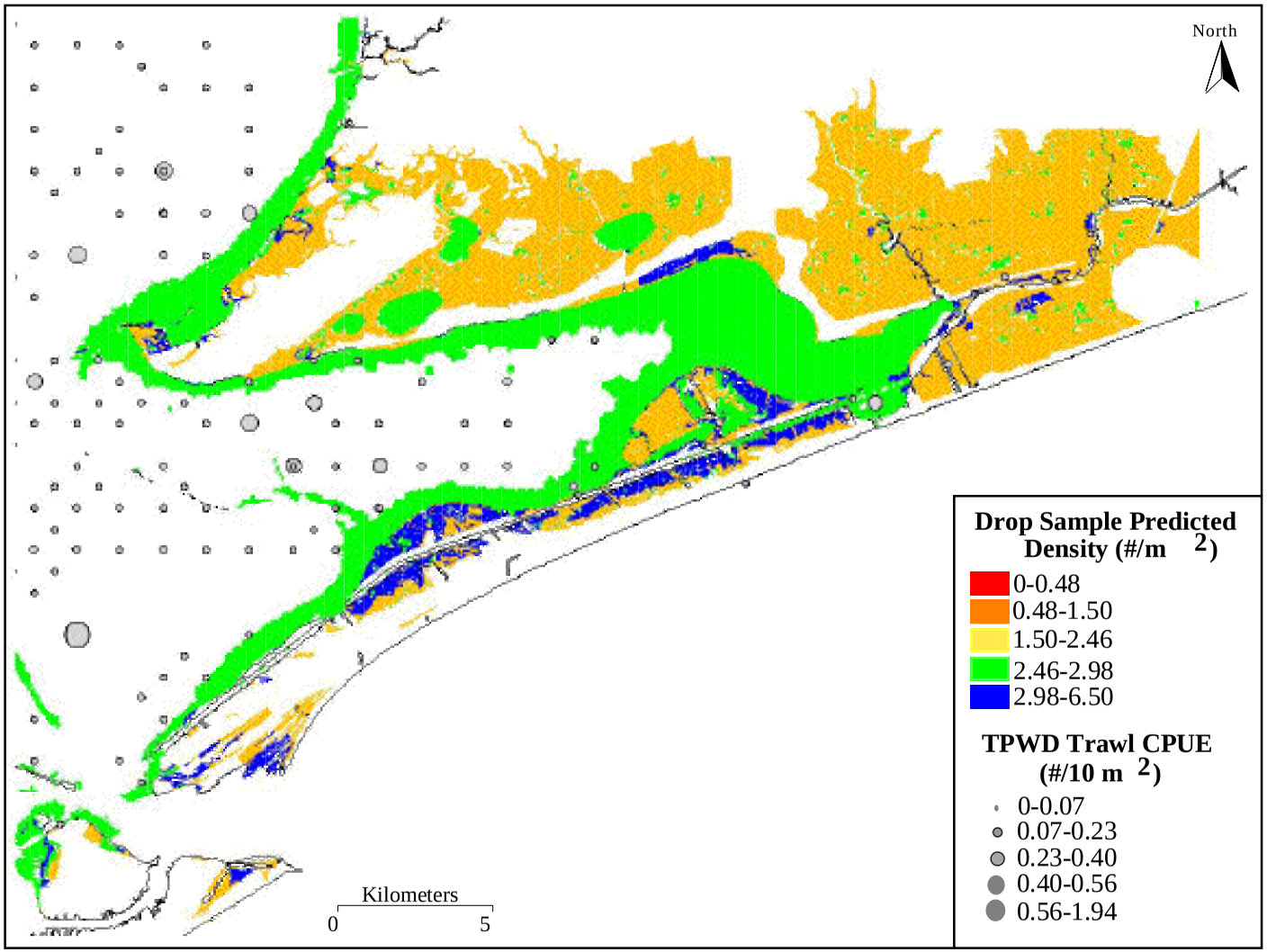
Appendix 2. *Zoom in of predicted brown shrimp density and observed TPWD otter trawl CPUE - East Galveston Bay.*



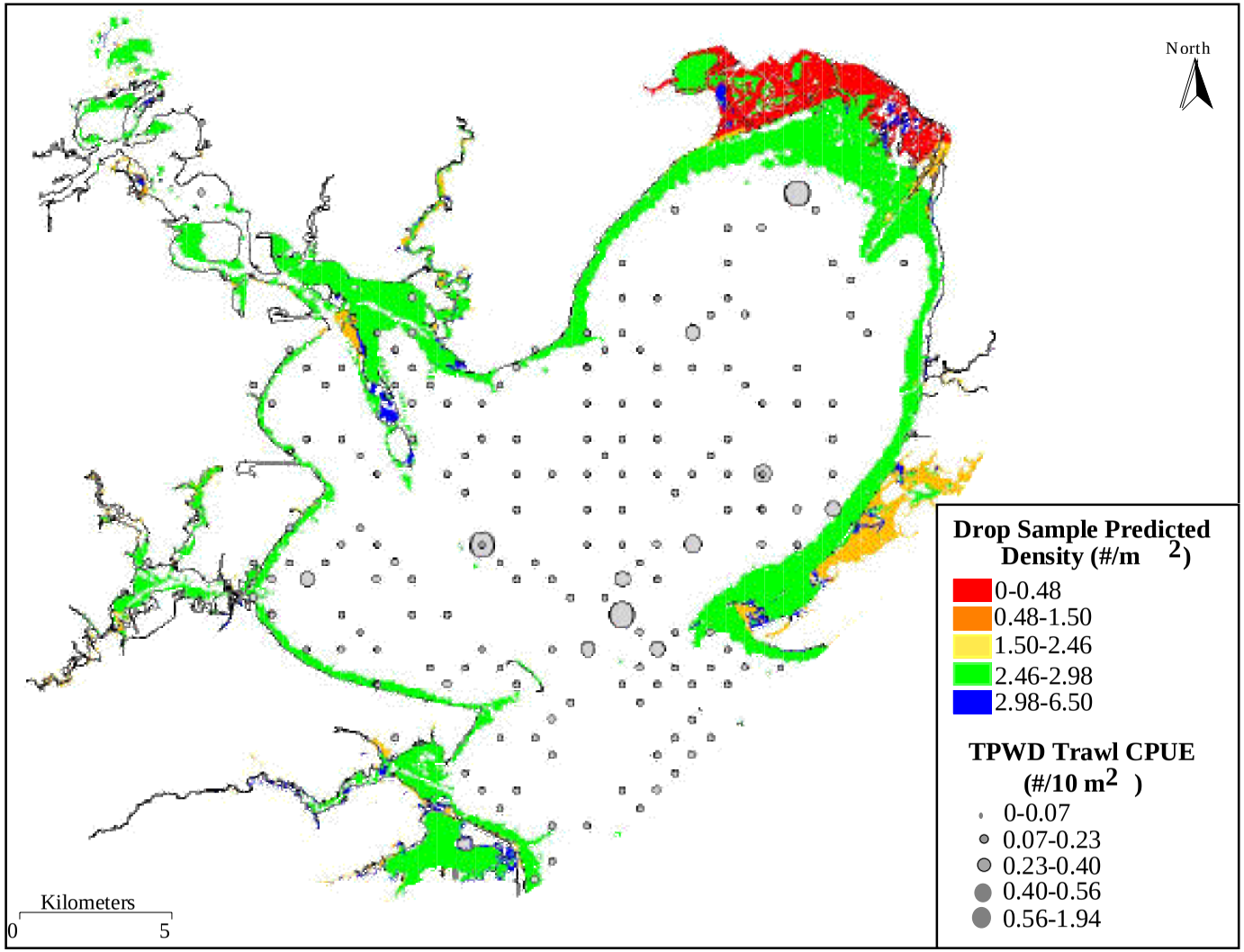
Appendix 3. *Zoom in of predicted brown shrimp density and observed TPWD otter trawl CPUE - Galveston and Trinity Bays.*



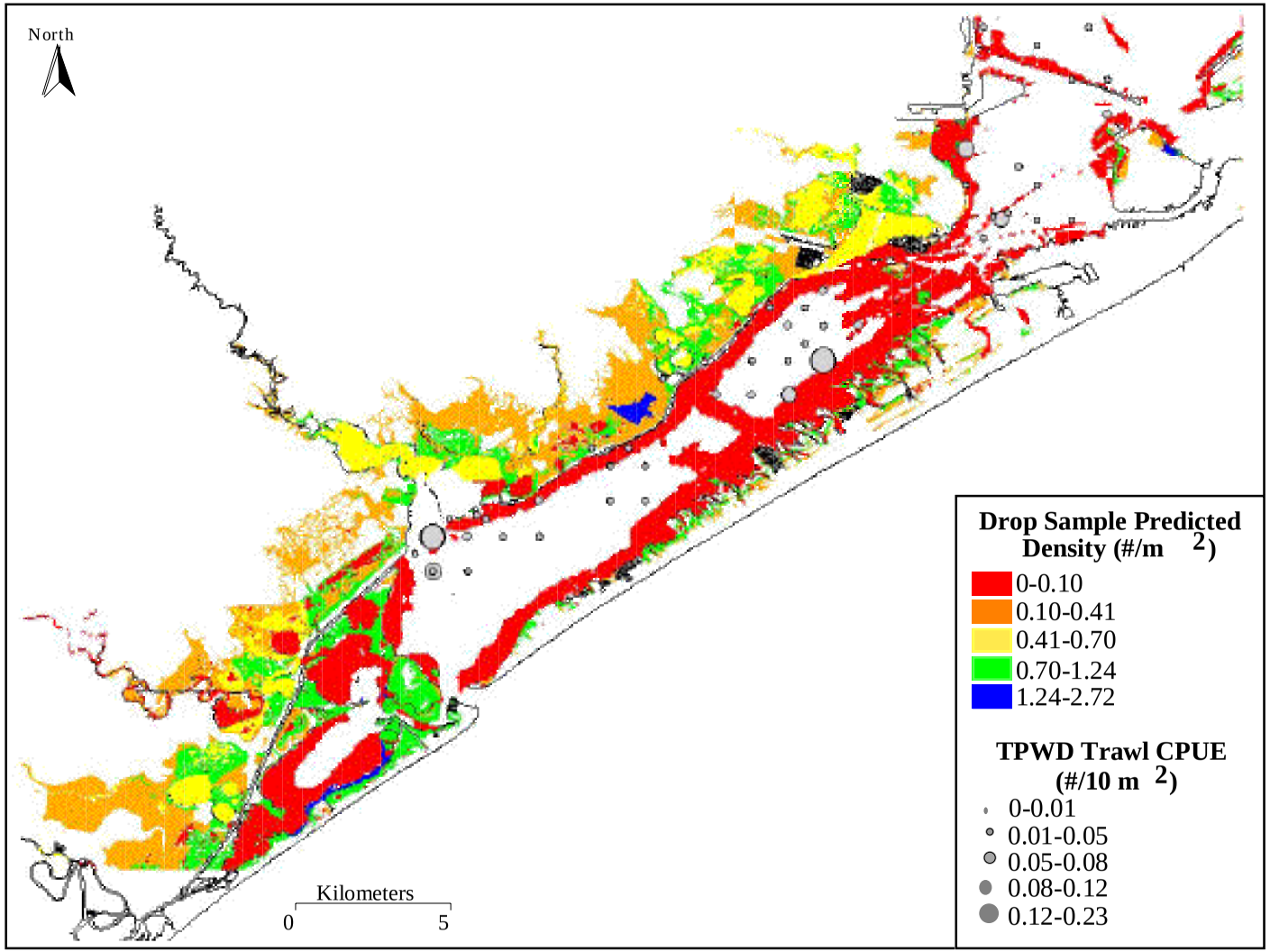
Appendix 4 *. Zoom in of predicted white shrimp density and observed TPWD otter trawl CPUE - West Galveston Bay.*



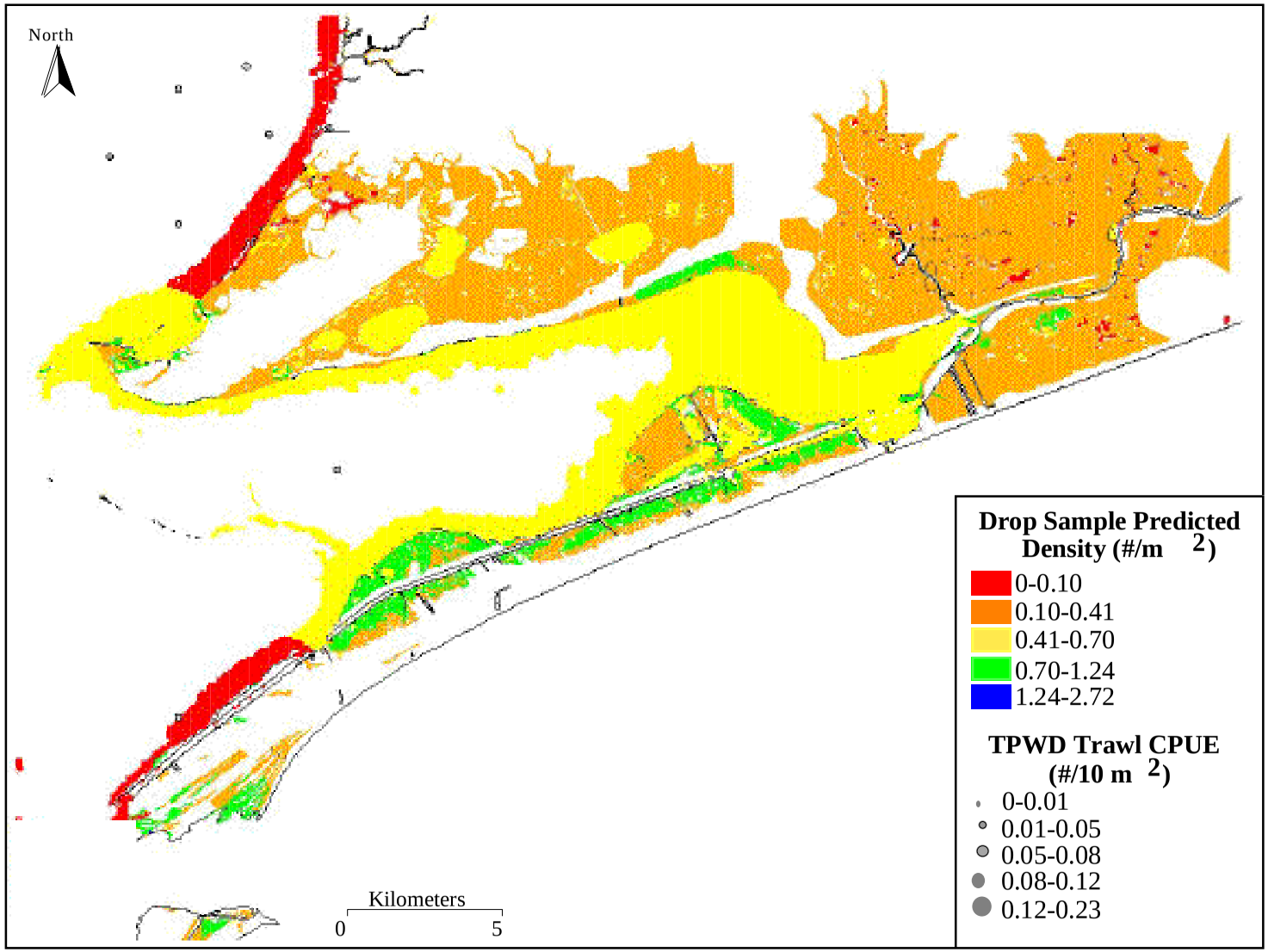
Appendix 5 . *Zoom in of predicted white shrimp density and observed TPWD otter trawl CPUE - East Galveston Bay.*



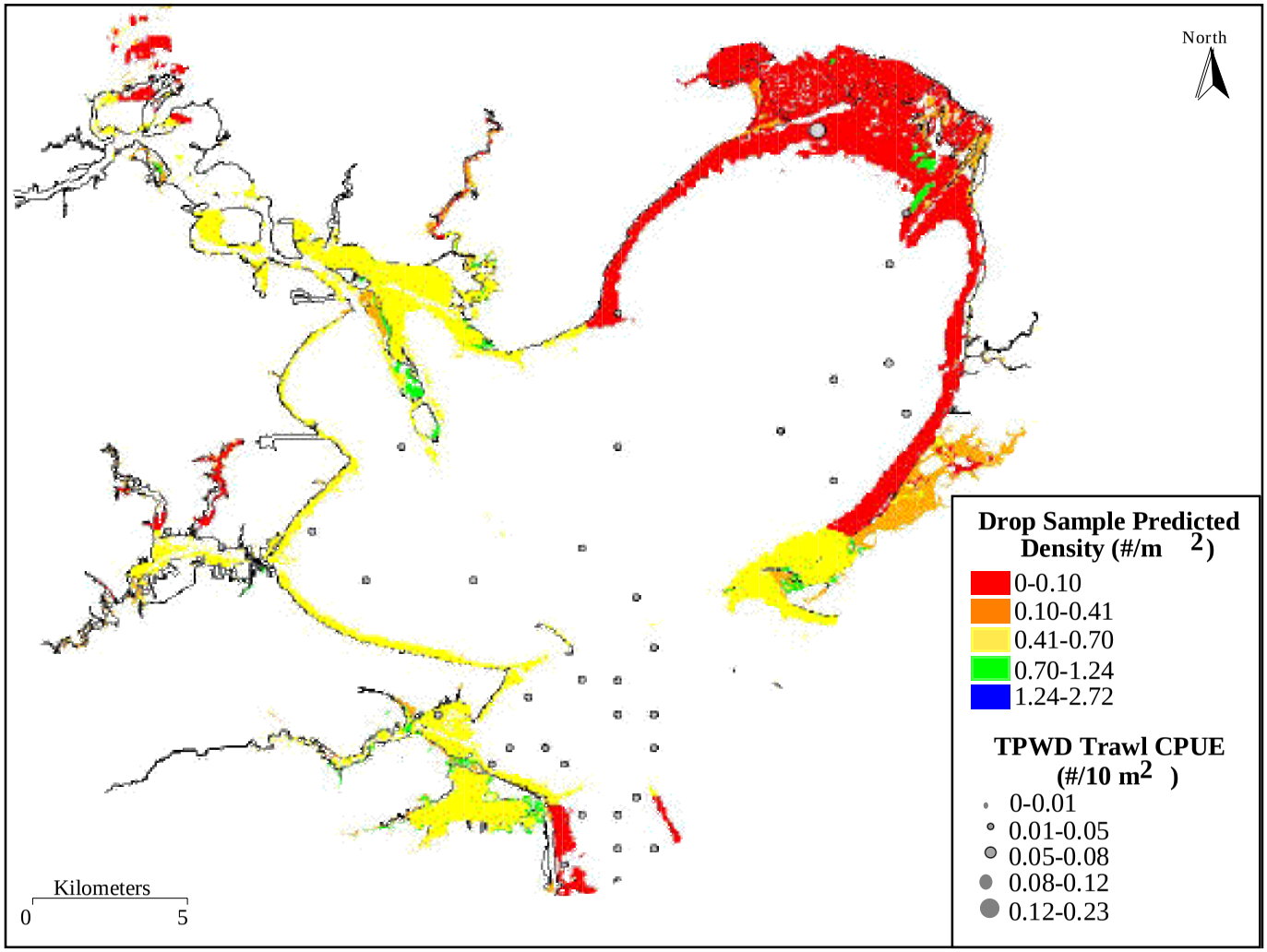
Appendix 6. *Zoom in of predicted white shrimp density and observed TPWD otter trawl CPUE - Galveston and Trinity Bays.*



Appendix 7 *. Zoom in of predicted pinfish density and observed TPWD otter trawl CPUE - West Galveston Bay.*



Appendix 8 *. Zoom in of predicted pinfish density and observed TPWD otter trawl CPUE - East Galveston Bay.*



Appendix 9. *Zoom in of predicted pinfish density and observed TPWD otter trawl CPUE - Galveston and Trinity Bays.*