

An Efficient Sampling Survey Design to Estimate Pink Shrimp Population Abundance in Biscayne Bay, Florida

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Abstract.—We developed an efficient sampling design-based approach using fishery-independent surveys to estimate population abundance of pink shrimp *Penaeus duorarum* over time in Biscayne Bay, Florida. We initially implemented quarterly stratified random sampling (StRS) using nine habitat strata and determined that average pink shrimp density (numbers/m²) was highest in late fall and lowest in spring and late summer. Coefficient of variation of the quarterly surveys, expressed as percent standard error/mean density, ranged from 5.8% to 14.3%. We found StRS to be more efficient (i.e., with lower variance) than simple random sampling (SRS) in most seasons. Statistical analyses suggested that pink shrimp densities were dependent on the biophysical habitat variables of bottom substrate, depth, and salinity. We also noted ontogenetic shifts in these relationships that were particularly pronounced at the onset of sexual maturation. Poststratification analysis was used to further evaluate several alternative habitat-based sampling schemes. Results showed that a five-strata composite design that used all three habitat variables was similar in performance, but less complex, than the original nine-strata design. In addition, the composite design outperformed both SRS and all other StRS designs indexed on single habitat variables. The new five-strata composite design was implemented in late summer 1997 and achieved a significant reduction in coefficient of variation compared with the late summer 1996 survey. This new design did not perform as well as expected in late fall 1997, which we attribute to a mismatch between our seasonal sample allocation strategy and the timing of pink shrimp recruitment into Biscayne Bay in 1997. Finally, we show how statistical sampling designs that use stratifications based on relevant habitat covariates can yield high-precision abundance estimates at low costs and provide a robust quantitative methodology for identifying habitat essential to fisheries production.

Traditional management approaches for marine fisheries have mainly focused on regulating fishing effects on the exploited phase of a single stock. However, new directives, such as conserving marine biodiversity (Bohnsack and Ault 1996) and the need to better understand the linkages between fish stock productivity and habitat that are emphasized in the “essential fish habitat” provisions of the reauthorized Magnuson–Stevens Fishery Conservation and Management Act (NOAA 1996), require a more holistic understanding of harvested populations and ecosystem dynamics. The case of pink shrimp *Penaeus duorarum* in the southeastern United States offers compelling support for this new management approach. Adult and juvenile life stages are segregated spatially, a common feature of tropical penaeid species (Garcia and Le Reste 1981). Adults reside in the soft bottoms of offshore

shelf regions where they support intense and lucrative food fisheries (Iversen et al. 1993; NOAA 1993). Major U.S. fishing grounds are located in the Dry Tortugas off southwestern Florida and the Atlantic ocean off northeastern Florida and North Carolina (Kennedy and Barber 1981; Bielsa et al. 1983). Juvenile pink shrimp inhabit coastal bays and estuaries, with important nursery areas located along the Gulf and Atlantic coasts of Florida and the Atlantic coasts of Georgia and the Carolinas (Williams 1955; Costello and Allen 1966; Sheridan 1992, 1997; Wenner and Beatty 1993). Pink shrimp juveniles occupy a key trophic position in the estuarine ecosystem as a primary food source for juveniles of important food fishes (Hettler 1989), including many coral reef species that have an estuarine juvenile phase (e.g., gray snapper *Lutjanus griseus*). In some areas, such as Biscayne Bay in south Florida, juvenile pink shrimp are targeted by a live-bait fishery (Costello and Allen 1970). This may have ramifications for the sustainability of the adult offshore fishery. Increasing

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fishing effort on large adult reef fishes, (e.g., snappers and groupers) fuels demand for juvenile pink shrimp as bait, which in turn reduces the available food base for prerecruit juveniles of many of the targeted reef species. Thus, sustainability of important south Florida reef fishes, some of which are currently overfished (Ault et al. 1998), and sustainability of pink shrimp are interrelated. In addition, the nearshore habitats of juvenile pink shrimp are potentially threatened by human activities unrelated to fishing (e.g., dredging, shoreline construction, pollutant discharge, and alteration of freshwater inflows to coastal bays from land; South Atlantic Fishery Management Council 1993; U.S. Army Corps of Engineers 1999).

Proper management of exploited species and their habitats requires co-occurrent information on both. The basic demographic data on stock abundance, age, size structure, growth, and reproduction that are required for assessment and management of harvested species can be obtained via fishery-dependent or fishery-independent approaches. Fishery-independent population surveys possess at least two distinct advantages over fishery-dependent data collection methods: sampling can be directed at both exploited and unexploited age- and size-classes of a target population and sampling can be conducted in a random manner (Gunderson 1993). A third advantage has often been underappreciated: the enhanced ability to simultaneously collect information on animal abundance and relevant biological and physical habitat features at specific points in space. These data are the foundation for describing species' habitats (see Rubec and O'Hop 1996, Rubec et al. 1999) and for developing population assessment models that are dynamic in both time and space (see Ault et al., in press).

In this paper, we design and implement a fishery-independent stratified random sampling survey that incorporates habitat information to estimate pink shrimp population abundance in Biscayne Bay. We describe an iterative sampling and analysis methodology that can be used to assess essential fish habitat in addition to providing abundance estimates.

Methods

Field sampling.—Sampling was conducted from Rickenbacker Causeway to Long Arsenicker Key in Biscayne Bay, Florida (Figure 1), at depths greater than 1 m. Because pink shrimp burrow into bottom sediments during the day (Hughes 1968), sampling was carried out exclusively at night. We

employed the standard roller frame trawl used in the southern Florida commercial live-bait shrimp fishery. The trawl consists of a 10-mm square-mesh net attached to a 3-m wide by 0.5-m high metal frame outfitted with a slotted roller along the lower portion. At a given sampling station, two nets are towed simultaneously on either side of the sampling vessel. A station tow distance of 200 m yields an average tow area ($\bar{T}$) of 600 m² for each trawl net. Upon completion of a tow, captured animals were processed separately for each trawl net. Pink shrimp were sorted from the total catch of fish and other macroinvertebrates and brought back to the laboratory, where each individual was sexed and carapace length (CL) was recorded as the distance from the postorbital margin to the posterior margin of the carapace (Penn 1980). Water temperature, salinity, dissolved oxygen, and depth were measured at each sampling station.

Pink shrimp density (D) in animals/m² was computed by dividing number captured by area trawled (T). We performed preliminary experiments to examine aspects of station tow duration and distance with respect to the capture of pink shrimp. Trawl durations of 5 and 10 min yielded similar pink shrimp densities; consequently, we chose the shorter 5-min tow, which enabled us to (1) sample almost twice as many stations during a nighttime trawl session, (2) minimize gear saturation effects resulting from the net filling up with drift algae, and (3) minimize the chances of trawling over different bottom substrate types during a given tow (Lenarz and Adams 1980; Pennington and Vølstad 1991). We used an onboard global positioning system unit equipped with a differential-beacon receiver during survey operations to control individual tow lengths to a fixed distance of 200 m, the approximate distance covered in 5 min. We also conducted separate trawl net "covered cod end" experiments (Sparre and Venema 1992) and Leslie-type depletion experiments (Leslie and Davis 1939; Joll and Penn 1990; Zhang et al. 1993) to assess size-selectivity and capture efficiency of the roller frame trawl, respectively (G. A. Diaz and J. S. Ault, unpublished data). Pink shrimp density (D_j) at each station (j) was obtained by averaging densities for the two trawl nets and then correcting for gear size selectivity and capture efficiency.

Design statistics.—We implemented a stratified random sampling (SIRS) design following procedures described in Cochran (1977). A glossary of sampling design statistics is given in Table 1. Sam-

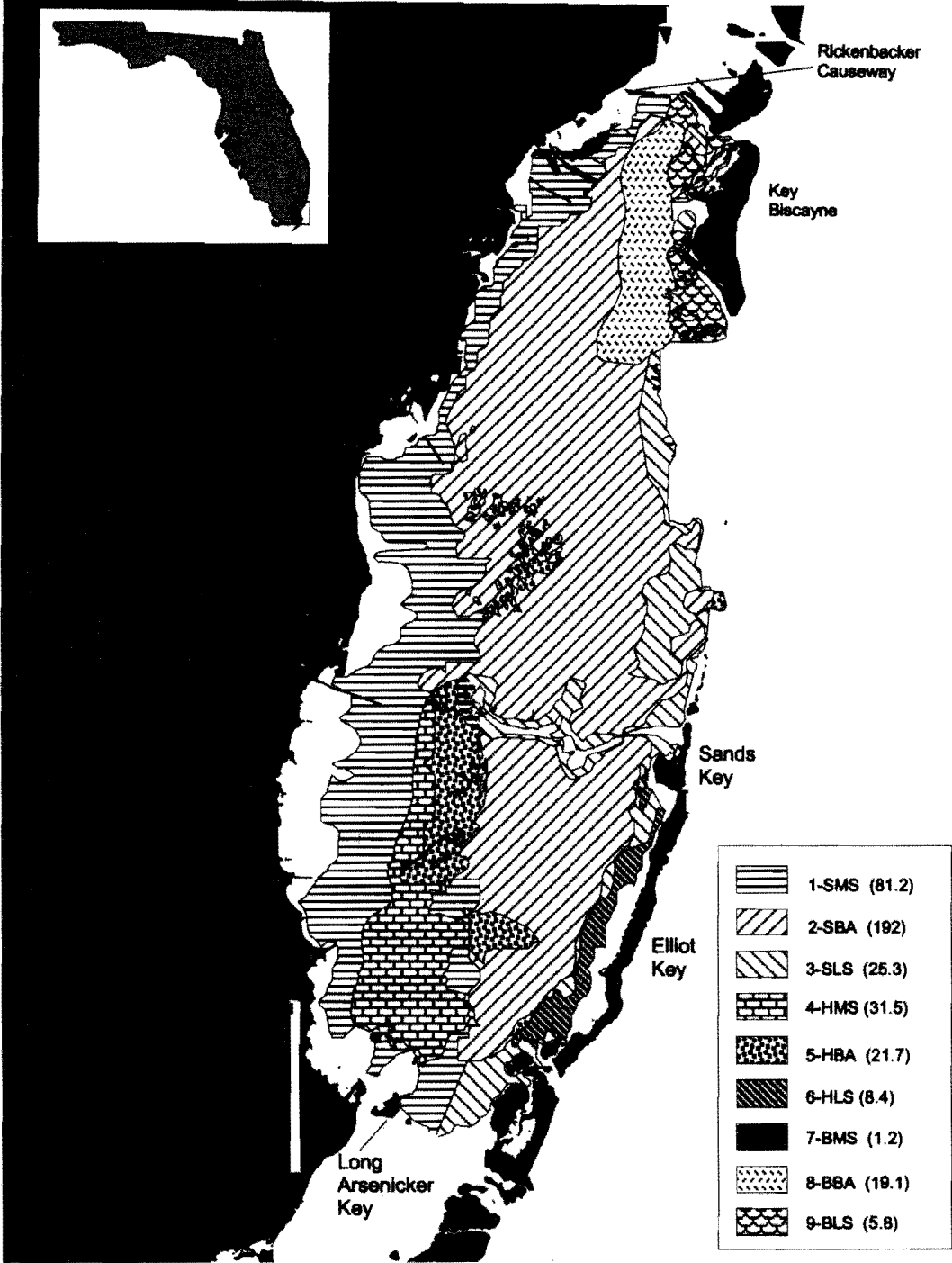


FIGURE 1.—Map of Biscayne Bay, Florida, showing the nine habitat strata for pilot sampling surveys. Stratum codes follow Lindeman (1997): seagrass mainland subtidal (SMS, 1–2 m depth); seagrass basin axis (SBA, > 2 m depth); seagrass leeward subtidal (SLS, 1–2 m depth); hard-bottom mainland subtidal (HMS); hard-bottom basin axis (HBA); hard-bottom leeward subtidal (HLS); bare-bottom mainland subtidal (BMS); bare-bottom basin axis (BBA); bare-bottom leeward subtidal (BLS). White areas within the bay denote regions shallower than 1 m that were not sampled due to vessel constraints. Stratum areas in km² are given in parentheses.

TABLE 1.—Glossary of sampling design statistical symbols.

Symbol	Description	Units
j	Trawl station subscript	
h	Stratum number	
A_h	Stratum area	m^2
w_h	Stratum weighting factor	
N_h	Number of total possible samples in stratum h	
N	Number of total possible samples in all strata combined	
n_h	Number of samples in stratum h	
n	Number of samples in all strata combined	
n^*	Number of samples required to achieve a specified variance	
T_j	Tow area at station j	m^2
$\bar{T}_h$	Mean tow area in stratum h	m^2
D_j	Density at station j	animals/ m^2
$\bar{D}_h$	Mean density in stratum h	animals/ m^2
$\bar{D}_{st}$	Mean density for a stratified random survey	animals/ m^2
$\bar{D}_{ran}$	Mean density for a simple random survey	animals/ m^2
s_h^2	Sample variance of density in stratum h	
P_h	Population abundance in stratum h	number of animals
P	Population abundance in all strata combined	number of animals
$var[]$	Variance of an estimate	
$SE[]$	Standard error of an estimate	
$CV[]$	Coefficient of variation of an estimate	%
V	Target variance for a future survey	
ζ	Relative efficiency of a sampling design	%

ple mean ($\bar{D}$) and variance (s^2) of pink shrimp density in stratum h are computed as

$$\bar{D}_h = \frac{1}{n_h} \sum_{j=1}^{n_h} D_{hj} \quad (1)$$

and

$$s_h^2 = \frac{1}{n_h - 1} \sum_{j=1}^{n_h} (D_{hj} - \bar{D}_h)^2, \quad (2)$$

where n_h is the number of sampling stations j in stratum h . The survey total stratified mean shrimp density was then estimated by

$$\bar{D}_{st} = \sum_h w_h \bar{D}_h, \quad (3)$$

with stratum weighting factor (w_h) defined as

$$w_h = \frac{N_h}{N}, \quad (4)$$

where N_h is the total possible samples in a stratum, and N is the total possible samples in all strata combined. We estimated N_h by dividing stratum surface area (A_h) by average tow area ($\bar{T}_h$),

$$N_h = \frac{A_h}{\bar{T}_h}. \quad (5)$$

Variance of $\bar{D}_{st}$ was estimated by

$$var[\bar{D}_{st}] = \sum_h \frac{w_h^2 s_h^2}{n_h} - \sum_h \frac{w_h s_h^2}{N}. \quad (6)$$

Our practice of controlling tow area to approximately 600 m^2 maintained consistency of stratum weighting factors (w_h ; equations 4 and 5) among surveys. We thus considered w_h as a fixed constant in variance computations. The design feature of controlling tow distance to a fixed length also helped control variation in station density (D_j) by keeping the covariance between station catch (number of shrimp) and tow area (T_j) close to zero (see the discussion of ratio estimators in Cochran 1977).

Samples were allocated among strata based on our estimates of stratum size and variance,

$$n_h = n \frac{w_h s_h}{\sum_h w_h s_h}, \quad (7)$$

where $s_h = \sqrt{s_h^2}$. Equation (7) is generally known as an "optimal" or Neyman sample allocation scheme (Cochran 1977), with a key assumption being that costs of obtaining samples are equal among strata.

Pink shrimp population size (P_h) or abundance in stratum h was obtained by multiplying stratum mean density by stratum area

$$P_h = \bar{D}_h A_h. \quad (8)$$

Variance of P_h was estimated as

$$var[P_h] = \frac{A_h^2 s_h^2}{n_h} \left(\frac{N_h - n_h}{N_h} \right). \quad (9)$$

Total population abundance (P) and associated variance, $var[P]$, were obtained by summing equations (8) and (9) over all strata.

Design performance measures.—We evaluated the performance of sampling designs according to several measures. Coefficient of variation (CV) of a particular design is determined as the standard error of mean density, $SE[\bar{D}_{st}]$, expressed as a proportion of the mean (i.e., $CV[\bar{D}_{st}] = SE[\bar{D}_{st}]/\bar{D}_{st}$, where $SE[\bar{D}_{st}]$ is the square root of equation 6).

TABLE 2.—Results of nine-strata sampling design for pilot surveys. Symbols and units are defined in Table 1. Juveniles are individuals less than 18 mm carapace length (CL) and subadults are greater than or equal to 18 mm CL (Eldred et al. 1961).

Survey period	<i>n</i>	$\bar{D}_{st}$	$CV[\bar{D}_{st}]$	ζ	Juveniles (%)	Subadults (%)
Spring 1996	118	0.269	9.4	126	59.2	40.8
Late summer 1996	93	0.289	14.3	93	94.9	5.1
Late fall 1996	151	0.758	5.8	183	69.8	30.2
Late winter 1997	125	0.475	6.7	147	70.3	29.7

The relative efficiency (ζ) of a StRS design with respect to simple random sampling (SRS) is defined as

$$\zeta = \frac{\text{var}[\bar{D}_{ran}]}{\text{var}[\bar{D}_{st}]}, \quad (10)$$

where $\text{var}[\bar{D}_{ran}]$ is the variance of mean density that would have resulted had a SRS survey been conducted rather than a StRS survey. An estimate of $\text{var}[\bar{D}_{ran}]$ from a StRS survey using the formula in Cochran (1977:136) is computed as

$$\text{var}[\bar{D}_{ran}] = \frac{(N-n)}{n(N-1)} \left[\left(\frac{1}{N} \sum_h \frac{N_h}{n_h} \sum_j D_{hj}^2 \right) - (\bar{D}_{st})^2 + \text{var}[\bar{D}_{st}] \right]. \quad (11)$$

The required sample size n^* to achieve a specified variance in a future survey, a key performance measure, is determined by

$$n^* = \frac{\left(\sum_h w_h s_h \right)^2}{V + \frac{1}{N} \sum_h w_h s_h^2}, \quad (12)$$

where V is the desired variance, which can be expressed as

$$V = (CV[\bar{D}_{st}] \cdot \bar{D}_{st})^2, \quad (13)$$

using a target CV of stratified shrimp density.

Habitat and strata measures.—The spatial areas comprising each of the sampling strata were constructed in a geographical information system (GIS) using georeferenced data on bottom substrates, depth, and salinity. Digital maps of bottom substrates in Biscayne Bay were provided by the Dade County Department of Environmental Resources Management. We grouped these data into three basic substrate types: seagrass, hard bottom, and bare bottom. Seagrass consisted of sandy or silt-clay sediments vegetated by the seagrasses

Thalassia spp., *Halodule* spp., or *Syringodium* spp. Hard bottom was characterized by a foundation of oolitic limestone covered by a thin sediment layer populated with a variety of soft coral and sponge species. Bare bottom was substrate generally devoid of large benthic organisms. Additional depth and salinity information was obtained to supplement data collected during trawling operations for pink shrimp. The National Ocean Service supplied gridded bathymetry data used to create depth contours. Salinity values with high spatial and temporal resolution were simulated from a two-dimensional finite-element hydrodynamic model of Biscayne Bay (Wang et al. 1988). Calculations of stratum areas (A_h) and random allocations of sampling stations within strata were performed with the GIS.

Results

Pilot Surveys

To evaluate both the temporal and spatial aspects of our sampling design, we conducted four seasonal pilot surveys: spring 1996 (April 3–May 16), late summer 1996 (August 12–25), late fall 1996 (November 4–December 2), and late winter 1997 (March 4–12). The number of trawl stations in the pilot surveys ranged from 93 to 151 (Table 2). The sampling domain was stratified using animal density and habitat relationships reported from studies conducted on pink shrimp in Florida Bay (Costello et al. 1986) and fish predators of shrimp in Biscayne Bay (Campos 1985; Lindeman 1997). We delineated nine sampling strata (Figure 1) by combining three bottom substrates (seagrass, hard bottom, bare bottom) with three east–west depth gradients (western Bay, 1–2 m; central Bay, >2 m; eastern Bay, 1–2 m) following Lindeman (1997). For the initial survey in spring 1996, the number of sampling stations was allocated among strata according to stratum size only (i.e., s_h was set to a value of 1 in equation 7) because no information on stratum variability of shrimp density was available. In the subsequent pilot surveys,

TABLE 3.—Percent sample allocation among strata for pilot surveys. Stratum numbers correspond to the map shown in Figure 1. Total sample sizes (n) for each survey are given in Table 2.

Stratum	Spring 1996 (%)	Late summer 1996 (%)	Late fall 1996 (%)	Late winter 1997 (%)
1	23.8	17.2	21.2	36.8
2	44.9	23.7	49.7	41.6
3	10.2	17.2	6.0	7.2
4	9.3	11.8	7.3	4.0
5	4.2	5.4	6.6	3.2
6	1.7	5.4	2.0	1.6
7		2.1	1.3	1.6
8	4.2	8.6	4.6	2.4
9	1.7	8.6	1.3	1.6

sample allocation was based on results obtained from the preceding survey (Table 3).

Average pink shrimp density ($\bar{D}_{st}$) was highest in late fall and lowest in spring and late summer (Table 2). We made separate density estimates for two carapace length-classes delineated by the size

at onset of sexual maturity (Eldred et al. 1961). Juveniles (<18 mm CL) dominated samples during late summer, whereas subadults (≥ 18 mm CL) made up a significant portion of the population during the other survey periods (Table 2). The spatial distribution of shrimp was heterogeneous during each sampling season (Figure 2). However, highest densities consistently occurred in stratum 1 (Figure 2), the shallow seagrass region in the western bay (Figure 1).

Estimates of $\bar{D}_{st}$ were fairly precise, with the coefficient of variation ranging from 5.8% to 14.3% (Table 2). The stratified random sampling design proved to be more efficient than simple random sampling (SRS) in most cases (Table 2, where the base reference point of relative efficiency for SRS is 100%). This increased efficiency of StRS is supported by the results shown in Figure 2: the nine-strata design was moderately effective in partitioning Biscayne Bay into subregions of differing variances, one of the main objectives of

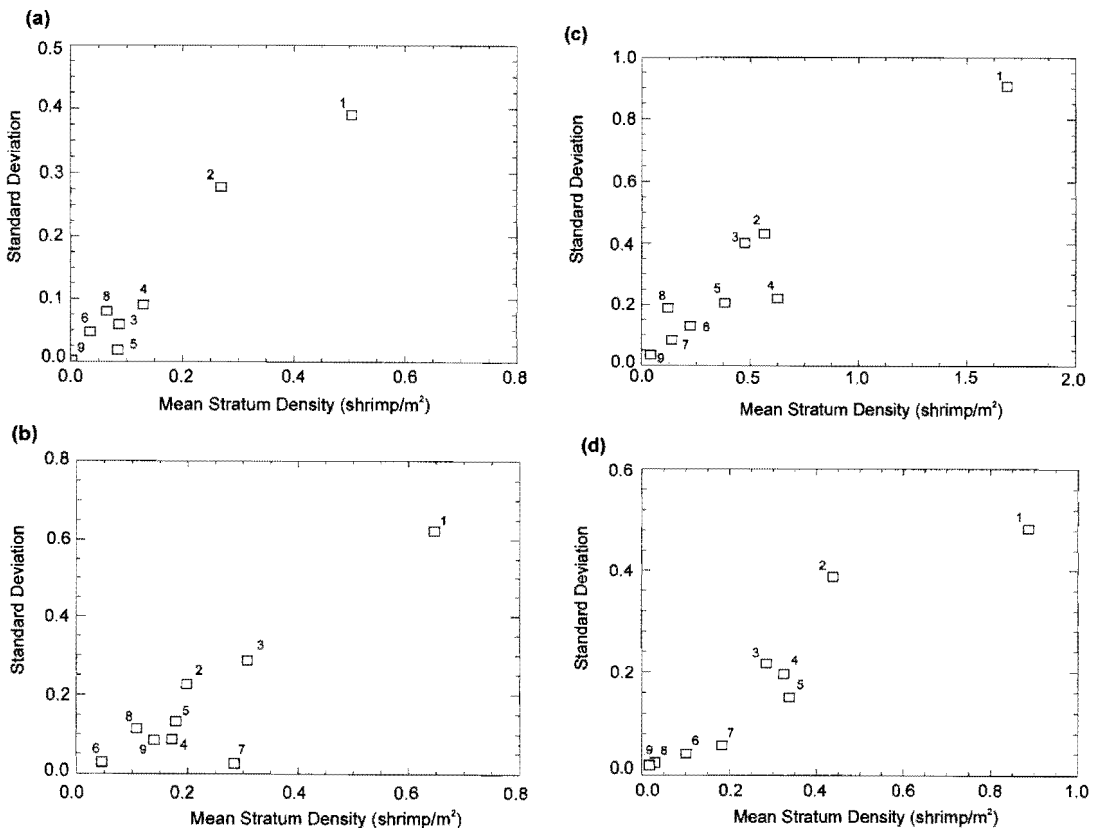


FIGURE 2.—Plots of stratum standard deviation (s_h) against mean density ($\bar{D}_h$) for pilot surveys conducted in (a) spring 1996, (b) late summer 1996, (c) late fall 1996, and (d) late winter 1997. Values are labeled with stratum numbers corresponding to the map in Figure 1.

stratification (Cochran 1977). Room for improvement in the sampling design was also indicated because variances (and SDs) were similar among some strata (Figure 2).

Density-Habitat Relationships

Although strata variances are the technical focus of survey design, the direct dependence between s_h and $\bar{D}_h$ exhibited in Figure 2 suggests that understanding relationships between mean pink shrimp density and habitat covariates may provide insight for constructing more efficient stratification schemes. Contour maps of station density (Figure 3a) and average carapace length (Figure 3b) for late fall 1996 show that areas of high animal density coincided with areas of small animal size, and vice versa. We observed similar density and size patterns in surveys conducted during spring 1996, late summer 1996, and late winter 1997, suggesting that these differences in spatial distribution between smaller juvenile and larger subadult pink shrimp persist throughout the year. No sex-specific differences in spatial distribution within each life stage were observed. Subsequent analyses were conducted separately for juvenile and subadult size-classes, with males and females combined within each size category.

We focused attention on three habitat variables: bottom substrate, depth, and salinity. Analyses are presented for the late fall season only; results for the other sampling seasons were essentially the same. Pink shrimp demonstrated an affinity for areas vegetated by seagrasses compared with hard-bottom or bare-bottom substrates (Figure 4a). Nonparametric analysis of variance (ANOVA; Kruskal-Wallis test, $p < 0.001$) indicated that bottom substrate explained at least some of the observed spatial differences in mean density for both juveniles and subadults. Parametric analyses (F -tests) were not used because density observations exhibited asymmetric, nonnormal frequency distributions (Shapiro-Wilk test, $p < 0.05$) and attempts to correct these departures from normality by log transformation were unsuccessful.

Although depth in our sampling domain only ranged from 1 to 5 m, juvenile pink shrimp density was significantly higher in shallow areas (1–2 m) than in relatively deeper (>2 m) areas (Figure 4b; Kruskal-Wallis test, $p < 0.001$). No depth preference was observed for subadult shrimp (Figure 4b). Seasonal salinity regimes were analyzed using the Biscayne Bay hydrodynamic model of Wang et al. (1988), which allowed us to readily identify two broad regions with respect to magnitude and

variability of salinity. The first area is located in the eastern bay adjacent to the Atlantic Ocean (stratum 5 in Figure 5) and is characterized by near-oceanic salinities (annual mean $\geq 34\text{‰}$) that only vary by several milligrams per liter over the course of weeks or months. The second is a lower-salinity region (annual mean $< 34\text{‰}$) comprising the central and western bay (Figure 5, strata 1–4), an area influenced by freshwater discharges along the coastline from an extensive network of drainage canals. During discharge events, salinities in the vicinity of canal mouths can fluctuate by 25‰ within 1–2 h (Serafy et al. 1997). Juvenile pink shrimp were found in significantly higher densities (Kruskal-Wallis test, $p < 0.001$) in the variable, lower-salinity region compared with the stable, high-salinity region (Figure 4c). The same pattern was observed for subadults (Kruskal-Wallis test, $p < 0.01$), although the difference in density between the two salinity regimes was less dramatic than for juveniles (Figure 4c).

Poststratification Analysis

We further explored relationships between pink shrimp density and habitat using poststratification analysis. This technique reanalyzes sampling data for stratification schemes differing from the one actually implemented. We evaluated five alternatives to the original nine-strata sampling design: simple random sampling; three StRS designs, each based on a single habitat variable (bottom substrate, depth, and salinity); and a composite habitat StRS design incorporating all three habitat variables. The composite habitat design comprised five strata (Figure 5) and was constructed as follows: (1) the sampling domain was separated into high-salinity and low-salinity regions following Figure 4c; (2) the low-salinity region was divided into three substrate types (Figure 4a); and (3) the seagrass substrate was further divided into two depth categories (Figure 4b). A limitation of poststratification analysis is that estimates of $\text{var}[\bar{D}_{st}]$ (equation 6) are not technically valid for data collected under a different stratification regime (Gavaris and Smith 1987; Smith 1991). This is in contrast to estimates of $\text{var}[\bar{D}_{ran}]$ (equation 11). We thus use poststratification as a comparative analysis tool and not as a reestimation methodology.

Poststratification results for the pilot surveys are presented in Table 4. Stratified random designs based on the single habitat variables of substrate, depth, or salinity were similar in performance to SRS as measured by the CV and relative efficiency in almost all cases; however, these designs were

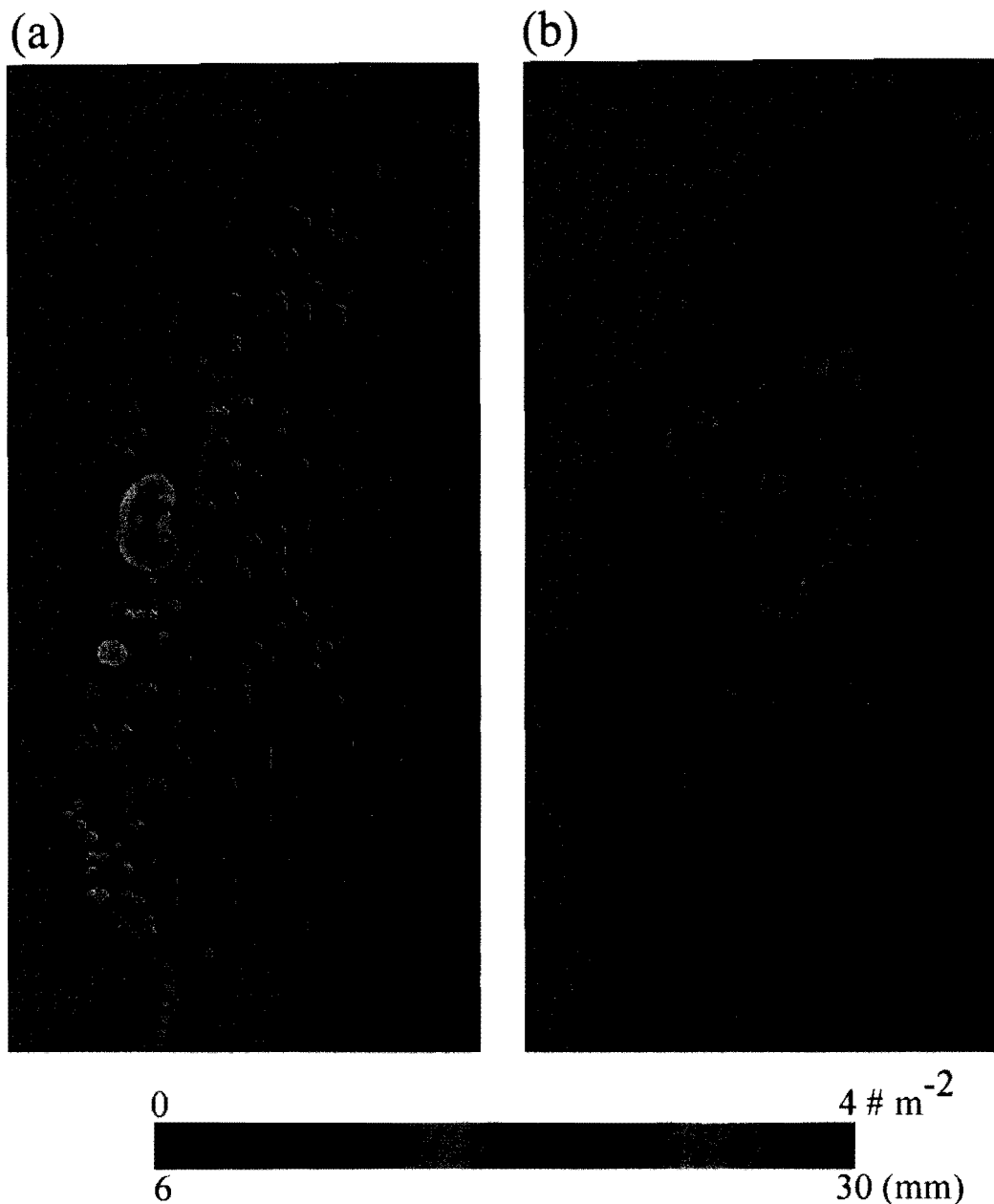


FIGURE 3.—Contour maps of pink shrimp (a) average density and (b) average carapace length for late fall 1996. Yellow dots in panel (a) indicate trawl station locations ($n = 151$).

generally more cost-effective (i.e., lower n^*) than SRS in most seasons. The two StRS designs that used all three habitat variables (Figures 1 and 5) were generally more efficient and cost-effective than SRS and StRS designs based on a single habitat variable. The five-strata habitat design in particular performed consistently well in all sampling

seasons and was less complex than the original nine-strata design.

Surveys in Late Summer and Late Fall 1997

We implemented the new five-strata composite habitat design (Figure 5) for surveys carried out in late summer and late fall 1997. The procedure

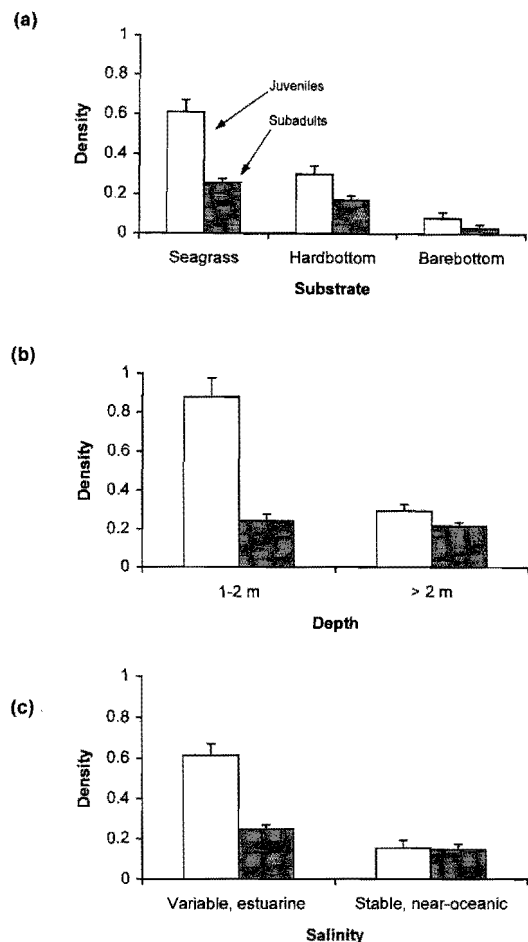


FIGURE 4.—Late fall 1996 juvenile (open bars) and subadult (shaded bars) pink shrimp mean density (animals/m²) and standard error for different (a) bottom substrate, (b) depth, and (c) salinity categories.

for allocating trawl stations among strata was also revised; survey results from the same season in the previous year were used in equation (7) to compute n_h (Table 5) rather than survey results from the preceding season. Average pink shrimp density in Biscayne Bay exhibited a fourfold increase between late summer and late fall 1997 (Table 6). This density increase occurred within each stratum and was accompanied by increases in stratum-specific variance (Figure 6). Juvenile shrimp made up 94% of the population in late summer and 86% in late fall 1997 (Table 6). The summer-to-fall increase in density in 1997 was similar to that observed in 1996. Late summer 1997 average density was only one-half the density level for late summer 1996; however, the proportion of juveniles during this season was essentially the

same in both years. In late fall, average shrimp density was similar in 1996 and 1997, but the proportion of subadult shrimp was only 14% in 1997 compared with 30% in 1996.

The five-strata sampling design achieved CVs of 8.2% and 10.5% in summer and fall 1997, respectively, and was consistently more efficient than SRS in both seasons (Table 6). In comparison with the nine-strata design used in 1996, however, performance results for the five-strata design were somewhat mixed. The number of sampling stations increased by approximately 60% in late summer 1997 over the previous summer; accordingly, coefficient of variation declined and relative efficiency increased. Sample size was 20% lower in late fall 1997 compared with late fall 1996, with the reverse effect on CV and relative efficiency. Comparing values of n^* , the sample size needed to achieve a target CV, between seasons and years provides a measure for assessing the relative variability of the sampled population in addition to the cost-effectiveness of a particular sampling design. From equations (12), (13), and (3), it can be seen that the combination of higher stratum variances (or standard deviations s_h) and lower stratum means ($\bar{D}_h$) will produce higher n^* values, and vice versa. For the late summer season, n^* values computed at the point value $CV[\bar{D}_{st}] = 5\%$ were comparable between 1996 and 1997 (Table 6). The predicted relationship between CV and n^* over a range of values, computed from equation (12), is shown in Figure 7. The plotted point (n , CV) actually achieved in the late summer 1997 survey (Figure 7, open diamond) was quite close to the value predicted from the late summer 1996 survey (Figure 7, dashed line). This suggests that relative variability of pink shrimp density in late summer was similar in both years. In late fall, however, relative variability appeared to be much higher in 1997 than in 1996 (Table 6; Figure 7).

Population Abundance for 1996 and 1997

The temporal dynamics of pink shrimp population abundance (P) in Biscayne Bay for survey years 1996 and 1997 are illustrated in Figure 8. Our estimates of total shrimp abundance ranged from 58 million in late summer 1997 to 291 million in late fall 1996. While the range of P was quite dramatic, seasonal fluctuations exhibited a consistent pattern. Abundance was generally low in late summer and rose to peak levels in late fall, which was followed by a steady decline through winter and spring.

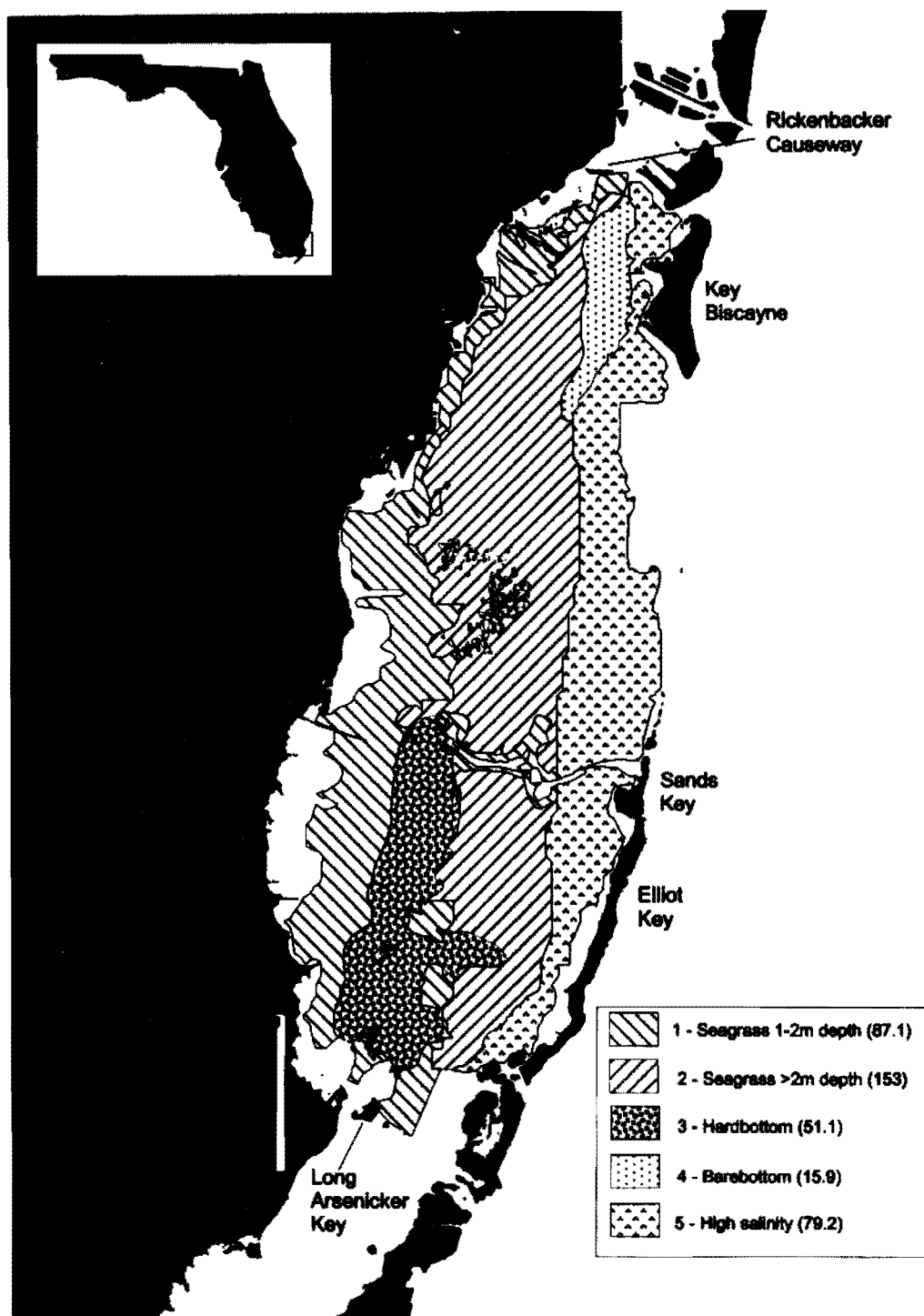


FIGURE 5.—Map of Biscayne Bay illustrating the five-strata composite habitat sampling design implemented for the late summer 1997 and late fall 1997 surveys. Stratum areas in km^2 are given in parentheses.

TABLE 4.—Poststratification analysis results for pilot sampling surveys conducted in spring 1996, late summer 1996, late fall 1996, and late winter 1997. Symbols and units are defined in Table 1. Values of n^* (equation 12) were computed for a target coefficient of variation of 5%.

Design	Number of strata	$\bar{D}_{st}$	$CV[\bar{D}_{st}]$	ξ	n^*
Spring 1996 ($n = 118$)					
Simple random	1	0.268	10.5	100	516
Actual StRS	9	0.269	9.4	124	322
Substrate	3	0.268	10.0	109	418
Depth	2	0.263	10.4	105	511
Salinity	2	0.277	9.9	105	379
Composite habitat	5	0.272	9.0	132	277
Late summer 1996 ($n = 93$)					
Simple random	1	0.271	14.6	100	794
Actual StRS	9	0.289	14.3	93	387
Substrate	3	0.313	14.7	75	527
Depth	2	0.236	12.3	185	563
Salinity	2	0.302	13.6	93	512
Composite habitat	5	0.285	12.8	118	333
Late fall 1996 ($n = 151$)					
Simple random	1	0.751	7.9	100	378
Actual StRS	9	0.758	5.8	183	159
Substrate	3	0.757	7.5	109	301
Depth	2	0.759	7.3	114	273
Salinity	2	0.746	7.5	112	323
Composite habitat	5	0.749	6.0	178	172
Late winter 1997 ($n = 125$)					
Simple random	1	0.560	6.9	100	239
Actual StRS	9	0.475	6.7	147	199
Substrate	3	0.531	7.0	109	234
Depth	2	0.558	6.7	107	193
Salinity	2	0.523	7.4	100	272
Composite habitat	5	0.492	6.4	150	158

Discussion

Spatial and Temporal Dynamics

Abundance of juvenile pink shrimp (6–17 mm CL) in Biscayne Bay increases twofold to fourfold between late summer and late fall (Figure 8). This dramatic summer-to-fall increase occurs just after the peak midsummer period of postlarval immigration (Figure 8, dotted horizontal line) that is known to occur in nearby Florida Bay (Allen et

al. 1980). At summer temperatures, pink shrimp are estimated to grow from 2 mm CL, size at postlarval settlement (Costello et al. 1986), to 6 mm CL, size at first capture in the roller frame trawl, in 4–6 weeks (Teinsongrasmee 1965). Taking account of the delay between postlarval settlement and capture in our sampling gear, the June–August season of peak postlarval influx in Florida Bay seems to apply also in Biscayne Bay. Our estimates of total shrimp abundance in late fall were comparable in 1996 and 1997 (Figure 8), indicating that the magnitude of recruitment into Biscayne Bay was similar in both years. However, the temporal pattern of pink shrimp recruitment into Biscayne Bay differed somewhat between 1996 and 1997. Higher juvenile abundance in late summer 1996, coupled with a higher proportion of subadults in late fall 1996, suggest that peak postlarval immigration occurred earlier in 1996 than in 1997 (Figure 8). This interannual variation in recruitment timing is in accordance with the 3-year study of Allen et al. (1980), who found that the annual peak in postlarval immigration could vary by several months in Florida Bay.

The spatial abundance pattern of juvenile pink shrimp was essentially the same in all sampling seasons. Densities of juveniles were highest in shallow nearshore seagrass habitats, significantly lower in deeper seagrass areas, and very low in hard-bottom and bare-bottom substrates and in regions of near-oceanic salinity (e.g., Figures 3–5). The affinity of early juvenile pink shrimp for shallow seagrass beds has been documented in Florida Bay (Costello et al. 1986). It is generally accepted that seagrass beds offer favorable food and shelter conditions for juvenile pink shrimp compared with other bottom substrates (Thayer et al. 1979; Penn 1984), but this hypothesis remains to be tested in a rigorous manner. The low abundance of juveniles in the high-salinity region in eastern Biscayne Bay is perhaps related to the transport mechanism of immigrating postlarvae.

TABLE 5.—Stratum mean tow area, $\bar{T}_h$, weighting factor, w_h , and percent sample allocation for surveys conducted in late summer 1997 and late fall 1997. Stratum numbers correspond to the map shown in Figure 5.

Stratum	Late summer 1997 ($n = 151$)			Late fall 1997 ($n = 120$)		
	$\bar{T}_h$ (SE)	w_h	%	$\bar{T}_h$ (SE)	w_h	%
1	614.8 (3.3)	0.225	46.4	618.2 (4.3)	0.224	34.2
2	609.9 (3.2)	0.398	29.8	619.5 (3.5)	0.392	38.3
3	635.5 (7.7)	0.128	5.3	598.9 (5.6)	0.136	7.5
4	578.0 (17.9)	0.044	2.0	592.6 (24.2)	0.043	2.5
5	611.2 (4.0)	0.205	16.5	612.3 (5.5)	0.205	17.5

TABLE 6.—Comparison of results of five-strata sampling for the late summer 1997 and late fall 1997 surveys with results for nine-strata surveys conducted in late summer 1996 and late fall 1996. Symbols and units are defined in Table 1. Values of n^* were computed for a target coefficient of variation of 5%.

Survey	Number of strata	n	$\bar{D}_{st}$	Juveniles (%)	$CV[\bar{D}_{st}]$	ζ	n^*
Late summer 1996	9	93	0.289	94.9	14.3	94	387
Late summer 1997	5	151	0.151	94.4	8.2	119	322
Late fall 1996	9	151	0.758	69.8	5.8	183	159
Late fall 1997	5	120	0.671	85.8	10.5	124	467

Laboratory experiments by Hughes (1969) found that postlarvae can detect minute changes in salinity, an ability they probably use to move via shoreward tidal currents from high-salinity oceanic regions to lower-salinity nearshore areas within coastal bays.

Our results show that as pink shrimp grow larger, they extend their range into the deeper seagrass habitat located in the central bay (Figures 3–5). This notable shift in spatial distribution occurs at about 18 mm CL, the reported size at the onset of sexual maturity (Eldred et al. 1961). Subadults reach their annual peak in abundance between late fall and spring (Figure 8). The substantial drop in total shrimp abundance from winter through spring coincides with the peak season of subadult emigration (Figure 8, solid horizontal line) to offshore spawning grounds (Eldred et al. 1961; Costello and Allen 1970). During this period, subadults are found in moderate densities in the high-salinity stratum in the eastern bay (Figures 3–5), indicating that this region may serve as a staging ground for emigrating shrimp.

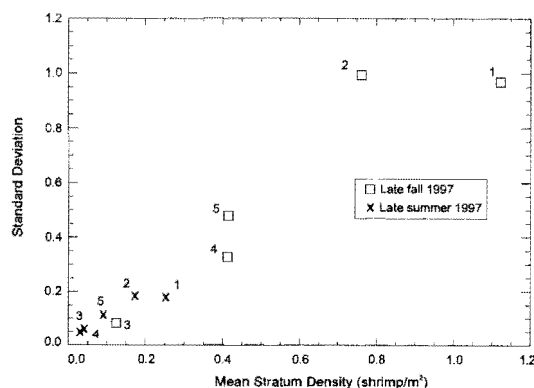


FIGURE 6.—Plots of stratum standard deviation s_h against mean density $\bar{D}_h$ for sampling surveys conducted in late summer 1997 (crosses) and late fall 1997 (open squares). Values are labeled with stratum numbers corresponding to the map in Figure 5.

Stratification and Allocation

The efficiency of a SRS abundance survey is directly linked to how the sampling domain is stratified and how samples are allocated among strata (Gavaris and Smith 1987). Our habitat-based stratification schemes (Figures 1, 5) effectively partitioned Biscayne Bay into distinct spatial regions with respect to pink shrimp density and variance (Figures 2, 6). The habitat variables bottom substrate, depth, and salinity, which formed the basis of both the five-strata and nine-strata designs, each demonstrated a significant relationship with pink shrimp density (Figure 4). Poststratification results (Table 4) suggest that delineating sampling strata with “composites” of these habitat variables was more efficient and cost-effective than constructing strata from any single habitat variable. Poststratification analysis (Table 4) also indicated that little or no improvement in design performance is achieved by employing a nine-strata

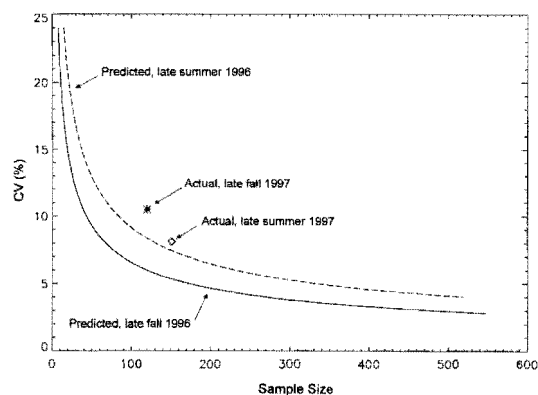


FIGURE 7.—Relationship between coefficient of variation of mean density, $CV[\bar{D}_{st}]$, and predicted sample size n^* estimated using equation (12) from survey results for late summer 1996 (dashed line) and late fall 1996 (solid line). Also shown are actual CV and sample size n point values obtained for surveys conducted in late summer 1997 (open diamond) and late fall 1997 (cross).

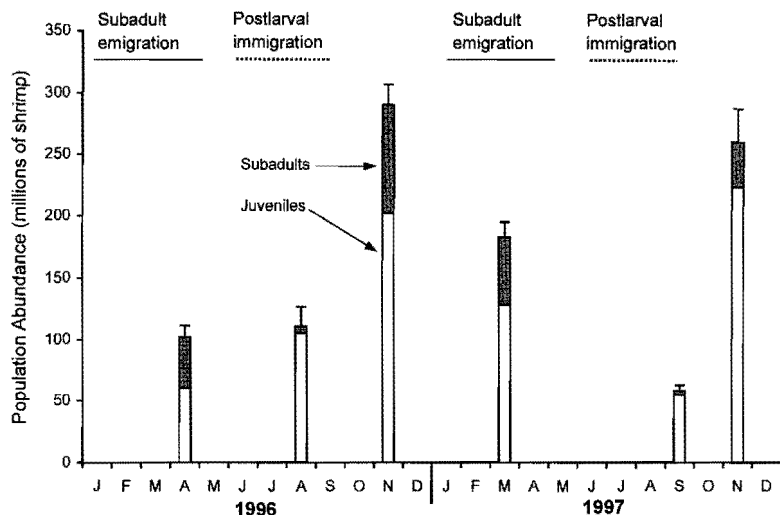


FIGURE 8.—Survey point estimates of pink shrimp total population abundance and standard error in Biscayne Bay for 1996 and 1997. Open portions of histograms denote juveniles; shaded portions denote subadults. Reported peak seasons for postlarval immigration (Allen et al. 1980) and subadult emigration (Eldred et al. 1961; Costello and Allen 1970) in Florida coastal bays are also indicated.

ta design (Figure 1) compared with the simpler five-strata design (Figure 5). This finding is supported by Cochran (1977), who showed that minimal gains in efficiency are obtained by dividing a sampling domain into more than five or six strata. As described above, the spatial distribution pattern of pink shrimp in Biscayne Bay is quite similar among seasons. This provides a further simplification for conducting abundance surveys of this population because the same stratification scheme can be employed irrespective of sampling season. In some respects, the five-strata design represents a compromise between sampling exclusively for juvenile or subadult pink shrimp because these two life stages have somewhat different spatial distribution patterns. A survey targeting juveniles would likely be improved by combining the low-density bare-bottom and oceanic-salinity strata, whereas a survey for subadults might be improved by combining the shallow and deep seagrass strata (Figures 4, 5).

The other key component of design performance is sample allocation. Allocating more samples to larger (high- w_h) and more variable (high- s_h) strata through use of equation (7) should result in more precise abundance estimates than by simply allocating samples proportional to stratum size (geographical area) alone (Cochran 1977). In practice, however, the use of equation (7) requires that values of s_h be obtained from a previous survey. For

the case of pink shrimp, stratum mean density ($\bar{D}_h$) and standard deviation (s_h) changed dramatically from season to season (Figure 6); consequently, the choice of which previous survey to use for predicting s_h values for a future survey was not an easy one. Our first approach was to estimate s_h values for a future survey using results from the immediately preceding survey. For example, results from the spring 1996 survey were used to allocate samples for the late summer 1996 survey. During spring, the pink shrimp population consists of a high proportion of subadults in both the deep seagrass region in the central bay (Figure 1, stratum 2) and high-salinity emigration staging grounds in the eastern bay (Figure 1, strata 3, 6, and 9). In contrast, in late summer, the pink shrimp population comprises mostly juveniles that are mainly concentrated in the nearshore shallow seagrass region (Figure 1, stratum 1). The fact that the late summer 1996 survey was less precise ($CV[\bar{D}_{st}] = 14.3\%$) was probably due, in part, to an overallocation of samples to the primary subadult habitats and an underallocation to the primary juvenile habitats.

A second approach we employed was to allocate samples for a future survey based on results from the same season in the preceding year. For example, sample allocations for the late summer 1997 survey were based on s_h values obtained from the survey conducted in late summer 1996. The

resultant improvement in sampling design performance in late summer 1997 compared with late summer 1996 (Table 6) was probably due, in part, to a better match between sample allocation among strata (Table 5) and pink shrimp population characteristics during the late summer season, which is dominated by juveniles. Our "same season of preceding year" allocation approach did not perform as well, however, for the late fall 1997 survey. Samples were allocated based on late fall 1996 survey results. In 1996, subadults made up 30% of the late fall population (Table 6). Accordingly, the majority of samples for 1997 were allocated to the deep seagrass habitat (stratum 2 in Table 5 and Figure 5). As detailed above, recruitment of postlarvae into Biscayne Bay occurred later in 1997 than in 1996. Subadults thus made up only 14% of the population by late fall 1997 (Table 6). The decline in late fall sampling design performance in 1997 compared with 1996 is probably partly attributed to the overallocation of samples to the deep seagrass habitat (stratum 2 in Table 5 and Figure 5) and the underallocation of samples to the nearshore shallow seagrass region (stratum 1 in Table 5 and Figure 5). Support for this conclusion was corroborated by the observation that the CV for late fall 1997 was better predicted from late summer 1996 when juveniles dominated the population versus late fall 1996 (Figure 7).

Our findings support those of Smith and Gavaris (1993) that biologically and statistically sound stratification schemes may not perform as well as expected if samples are not properly allocated among strata. A pragmatic modification of our "same season of different year" allocation method, incorporating suggestions of Smith and Gavaris (1993), is to estimate s_h values for a future survey by averaging results from surveys conducted in the same season over three preceding years. This would tend to smooth variations in seasonal population characteristics caused by interannual fluctuations in recruitment timing. Of course, this approach can only be applied in practice for surveys that have been in operation over multiple years.

Another important aspect of sample allocation is the total number of trawl stations allotted for a particular survey. This is because design performance is linked to overall n , as well as the proportional allocation of n among strata. Increases in n generally result in greater precision (i.e., lower coefficient of variation), as shown in Figure 7. The improved precision and relative efficiency of the late summer 1997 survey compared with the late

summer 1996 survey corresponded to an increase in the number of trawl stations from 93 in 1996 to 151 in 1997 (Table 6). Likewise, the decrease in n for the late fall 1997 survey compared with late fall 1996 was accompanied by a decline in performance (Table 6). In practice, the level of n is usually dictated by the size of the sampling budget. Diagrams relating sample size to survey precision, such as shown in Figure 7, can be useful tools for investigators and budget directors alike in optimizing the use of sampling funds. In our case, approximately 25 stations can be sampled in one nighttime trawl session with one vessel. Tripling sampling effort from two nights ($n = 50$) to six nights ($n = 150$) during late summer is expected to result in a decrease in CV from 13% to 7.5% (Figure 7, solid line). An additional tripling of sampling effort (18 nights, $n = 450$) would further reduce CV to 4.5%. The trade-off between additional cost and gain in precision is probably worthwhile for the first scenario but not for the second. In addition, certain sampling seasons may be inherently more variable than others. Fewer samples are required to achieve the same precision level for a population characteristic of late fall 1996 (Figure 7, solid line), which contained a relatively high proportion of subadult shrimp, than for a population characteristic of late summer 1996 (Figure 7, dashed line), which was dominated by newly recruited juveniles (Table 6).

Stratified Random Sampling and Essential Fish Habitat

Our StRS surveys yielded fairly precise estimates of pink shrimp density (Tables 2, 6) and abundance (Figure 8) with a relatively modest allocation of sampling effort (i.e., five or six nights of trawling per survey). We attribute this achievement to both tactical and strategic aspects of our sampling approach. Important tactical decisions were to employ the services, vessel, and trawling gear of an experienced commercial live-bait shrimper and to keep station tows fairly short in duration (5 min) and more or less constant in distance. At the outset of this study, we made the strategic decision to employ a stratified random sampling design, with strata delineations based on habitat variables related to pink shrimp spatial abundance patterns. We then adopted an iterative sampling and analysis strategy for improving design performance (i.e., achieving greater precision in estimating shrimp abundance while keeping sampling costs low). This iterative process included (1) conducting pilot surveys in different

seasons to obtain information on both the temporal and spatial dynamics of the pink shrimp population, (2) applying supplementary analysis methods (e.g., Figures 3, 4; nonparametric ANOVA tests) to refine our understanding of habitat as it related to juvenile and subadult pink shrimp, and (3) using poststratification analysis to evaluate alternative sampling designs. The result of this iterative process was the five-strata design of Figure 5, which performed well for the late summer and late fall 1997 surveys despite our difficulties in optimally allocating samples among strata.

Although the central focus of our surveys was the estimation of pink shrimp abundance, our study also provided information on the relative importance of different pink shrimp habitats in Biscayne Bay. The general seagrass region in the central and western portions of Biscayne Bay (Figure 5, strata 1 and 2) supported significantly higher shrimp densities than other habitat types (Figures 2, 4, 6). Shallow nearshore seagrass beds (Figure 5, stratum 1) appear to be especially important for newly recruited juveniles (Figure 4). This is perhaps a cause for concern. Of the five pink shrimp habitats we defined (Figure 5), this region is the most susceptible to detrimental anthropogenic impacts because of its proximity to the coastline of the greater Miami urban area.

Our approach to conducting StRS population surveys thus offers a sampling design-based methodology for defining essential fish habitat (EFH), in addition to estimating abundance. We conclude that designing efficient StRS abundance surveys and assessing EFH are mutually dependent endeavors. The basic information on animal density and habitat central to our quantitative understanding of EFH for pink shrimp was obtained by sampling the population according to principles of statistical survey design. At the same time, understanding the relationships between pink shrimp density and habitat greatly aided in the design and performance of our abundance survey.

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