Abundance Estimation of the Chesapeake Bay Blue Crab, *Callinectes sapidus*

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This study is to estimate abundance of the Chesapeake Bay blue crab stock. Using 823 dredge tows which were conducted during the 1991 winter survey, blue crab abundance was estimated on the basis of newly developed methods which account for unequal dredge tow distances, size- and sex-specific heterogeneous overwintering spatial distributions, wintertime exploitation, the time period of quasi-hibernation, and dredge capture efficiency. The estimate of total abundance before correction by gear efficiency was 131.8 million crabs (95% C.I.=118.2 million crabs to 145.4 million crabs). Dredge capture efficiency was estimated to be 0.474. Thus, the estimate of total abundance was calculated as 278.1 million crabs after correction by the efficiency factor.

Key words: abundance, Chesapeake Bay, blue crab, dredge tow, gear efficiency

Introduction

The blue crab (*Callinectes sapidus*) is an important component of the Chesapeake Bay. The species currently constitutes one of the Bay's most productive and economically important living resources. The total commercial catch, while exhibiting cyclical variability, has generally increased over the past 60 years, and a significant recreational catch is also taken. It is not known whether the factors causing variability in blue crab production are stock-related or environmentally-driven. Despite the high exploitation of the blue crab stock in this region, relevant scientific knowledge concerning population dynamics is virtually lacking making it difficult to develop proper management policy. This has been true for some time in the Chesapeake Bay. The lack of information and an impression that fishing effort is increasing raises concern as to whether the present utilization of the resource is sustainable, optimal, or in fact might lead to eventual stock collapse.

Effective stock management depends on a clear understanding of blue crab population dynamics and the stock response to exploitation. However, the scientific information base derived from the blue crab fishery has lacked sufficient accuracy and precision to accomplish this objective. Blue crab data base problems stem from several causes. Because of large scale migrations during the warm months, blue crabs are distributed heterogeneously by size and sex throughout the Chesapeake Bay (Churchill, 1919; Van Engel, 1958). Commercial crabbers land and sell their catch at hundreds to thousands of locations throughout the bay, complicating monitoring of blue crab landings. The recreational fishery is mostly unquantified. This heterogeneous spatial distribution of both blue crabs and their fisheries has thus limited sufficient spatial coverage in both fishery dependent and independent sampling surveys.

Fishery independent surveys have the potential to circumvent all the aforementioned catch data problems. However, previous surveys in the Chesapeake

Bay have been hindered because they have employed fishing gears which are ineffective in capturing all population size groups. In addition, they have habitually sampled with insufficient spatial resolution relative to the stock distribution. The statistical programs designed to assess the stock have not utilized certain properties of the stock's dynamics in an efficient manner. Blue crabs quasi-hibernate in the bottom sediments of the Chesapeake Bay during winter months. This behavior facilitates sampling because during this period crabs are not harvested in Maryland and only in the Virginia mainstem, and movement is very limited. Sampling during winter therefore provides a "snapshot" of the static, sedentary population prior to extensive exploitation from all sources (i. e., both commercial and recreational). Despite the apparent benefits of conducting such a population-wide sampling program during the winter, only one small-scale study (Schaffner and Diaz, 1988) has taken advantage of blue crabs' quasi-hibernation behavior. In the study of Schaffner and Diaz (1988), the research area covered was limited to the southern part of the distribution area. Considering the seasonal migratory behavior of crabs, it is recognized that this kind of study should be carried out for the whole distribution area.

The objectives of this paper are to estimate blue crab abundance for the whole distribution area, which is one of the most important parameters to develop efficient monitoring techniques for providing appropriate management advice.

Materials and Methods

Sampling Surveys

Two survey vessels were used for the 1991 winter dredge survey. Sampling gears were identical standard "Virginia crab dredges" (width 1.83 m) lined with hexagonal chicken wire mesh (12.7 mm). At each sampling site, a timed one-minute tow at a constant speed of 3 nautical miles per hour was performed. LORAN coordinates were recorded at tow start and end points. Survey area covered by each one-minute tow was calculated by computing the least linear distance traversed and multiplying this quantity by the dredge width. Each captured crab was sexed and measured for carapace width (cw), and maturity condition was determined. At each sampling site, water depth was measured and the bottom physical parameters such as, salinity, water temperature, sediment composition and dissolved oxygen were recorded.

Sampling was conducted from December 1990 to March 1991 in the entire Chesapeake Bay mainstem and major tributaries (Fig. 1). Survey vessels were unable to sample depths less than 1.5 m (5ft).

A stratified random sampling design was adopted to estimate population abundance of crabs, and a total of 823 dredge tows were made from the twenty five geographical strata based on analyses of data obtained from earlier pilot surveys which were conducted by the Chesapeake Biological Laboratory of the University of Maryland System in 1989~1990. They used survey design results of the analysis between benthic sediment composition and over-wintering crab abundance, which indicate that both geographical region and bottom sediment composition were major factors determining over-wintering blue crab spatial distribution.

Abundance Estimation

To estimate overwintering habitat area for each stratum for blue crabs in the Chesapeake Bay, stratum surface area A_h was determined from navigational charts using an electronic planimeter and coordinate digitizing system (Numonics Corp., Lansdale, PA).

Each stratified random sampling stratum h includes a weighting factor W_h defined as

$$W_h = \frac{N_h}{N} \quad (1)$$

where N_h is the total possible stratum samples and

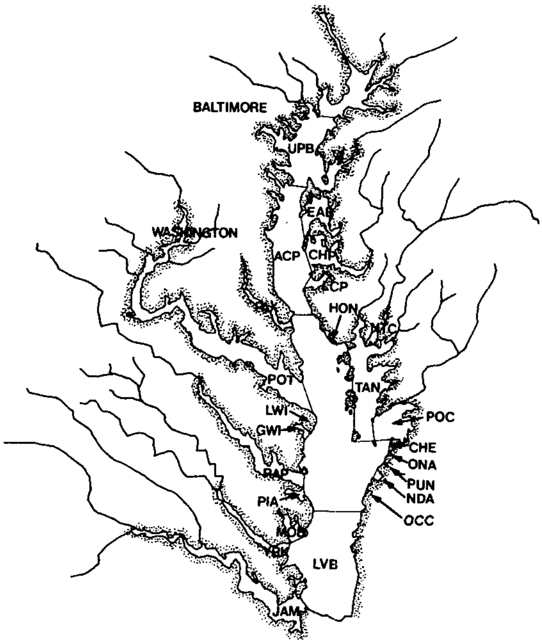

Fig. 1. Map of the Chesapeake Bay illustrating the locations of the 25 winter dredge survey sampling strata. Stratum area codes are as follows:

UPB (Upper Bay); ACP (Above Cove Point)
BCP (Below Cove Point); LVB (Lower Bay)
EAB (Eastern Bay); CHP (Choptank River)
LCP (Little Choptank River)
HON (Honga River); NTC (Nanticoke River)
TAN (Tangier Sound); PAX (Patuxent River)
POT (Potomac River); PCO (Pocomoke Sound)
CHE (Chessconessex Creek)
ONA (Onancock Creek)
PUN (Pungoteague Creek)
NDA (Nandua Creek)
OCC (Occohannock Creek)
LWI (Little Wicomico River)
GWI (Great Wicomico River)
RAP (Rappahannock River)
PIA (Piankatank River); MOB (Mobjack Bay)
YRK (York River); JAM (James River)

N is the total possible samples for all strata combined. N_h can be computed by dividing the stratum area by the stratum average tow area ($\overline{T}_h$). Calculation of stratum mean abundance of crabs per unit area per tow was based on the consideration of mean density of crabs $\overline{D}_h$ in a stratum, computed as the ratio of the mean number of crabs over mean tow area

$$\overline{D}_h = \frac{\overline{C}_h}{\overline{T}_h} = \frac{\dfrac{\sum_j C_{jh}}{n_h}}{\dfrac{\sum_j T_{jh}}{n_h}} = \frac{\sum_j C_{jh}}{\sum_j T_{jh}} \qquad (2)$$

$\overline{D}_h$ is a ratio estimator (Cochran, 1977); its variance is calculated by

$$S^2_{\overline{D}_h} = \frac{\left(1-\frac{n_h}{N_h}\right)}{n_h \overline{T}^2_h} S^2_{D^*_h}, \qquad (3)$$

$$S^2_{D^*_h} = (S^2_{C_h} + \overline{D}^2_h S^2_{T_h} - 2\overline{D}_h S_{CT_h}),$$

where $S^2_{C_h}$ and $S^2_{T_h}$ are the respective variances, and S_{CT_h} the covariance of C_h and T_h. The population mean density is calculated by

$$\overline{D}. = \frac{\sum_h W_h \overline{C}_h}{\sum_h W_h \overline{T}_h} \qquad (4)$$

The variance of $\overline{D}.$ is

$$S^2_{\overline{D}.} = \sum_h \frac{\left(1-\frac{n_h}{N_h}\right)}{n_h \overline{T}.^2} S^2_{D^*}, \qquad (5)$$

$$S^2_{D^*} = (S^2_{C_h} + \overline{D}.^2 S^2_{T_h} - 2\overline{D}. S_{CT_h}).$$

Blue crab abundance, P, within each stratum h is computed for the estimator as

$$P_h = \overline{D}_h A_h, \qquad (6)$$

with variance

$$S^2_{P_h} = \frac{N^2_h\left(1-\frac{n_h}{N_h}\right)}{n_h} S^2_{D^*_h}. \qquad (7)$$

Total population abundance, P., is calculated by summing the stratum abundance estimates of Eq(6)

$$P. = \sum_h P_h. \qquad (8)$$

The variance of Eq(8) is computed in the same manner by summing the stratum variances of P_h.

Four pilot gear efficiency experiments were conducted in March and April of 1991. The Leslie's method was used for estimating catchability (efficiency) and population size (Leslie and Davis, 1939). Leslie's model is

$$C_{ij}=qN_0-q\sum_{i}C_{i-1}, \tag{9}$$

where N_0 is the initial population size present in the sampling area at the start of the experiment, and C_i is the total crabs captured during run i, $\sum_j C_{ij}$. N_0 and q were estimated by linear regression.

A given experimental area was repeatedly sampled until all crabs were assumed captured. The following sampling protocol was employed:

(i) A given area was marked off by four anchored buoys. This area contained 7 dredge "tracks" of either 50 m or 100 m lengths.

(ii) The outside tracks were sampled first, followed by the interior tracks in random order. Successive tows were in opposite directions.

(iii) The pattern of step (ii) was repeated until 3 consecutive tows yielded zero crabs.

A "run", one complete areal coverge (i. e., 7 dredge tows), as a unit of effort was defined. Catch per unit of effort (CPUE) was measured as the number of crabs in the tow of the ith experimental run, C_{ij}. Zhang et al.(1993) give a more complete description of the dredge capture efficiency method.

Evaluation of the Employed Method

For evaluating the efficiency of a stratification scheme on the basis of geography and sediment types, winter survey data were analyzed by various geographical stratification schemes.

The relative efficiency was estimated, which is expressed as the coefficient of variation (CV) ratio of simple random sampling over that obtained from another sampling design. Thus, designs that produce a low CV will have higher relative efficiency than those that produce a high CV. In addition to relative efficiency, the required sample size for a desired variance (V) was used as another criterion for efficiency, computed as

$$n^*=\frac{\left(\sum_h W_h S_{D^*h}\right)^2}{V+(1/N)\sum_h W_h S^2_{D^*h}}, \tag{10}$$

where V is desired varinace (Cochran, 1977).

The relationship between bottom sediment composition and crab abundance was analyzed. Analysis of variance was conducted for comparing mean crab density among various combinations of geographical regions and sediment types.

Several combinations of strata were examined to find the best survey stratification designs in terms of precision, required sample size, and cost-effectiveness. Areas of each stratum were calculated from sediment contour maps based on the sediment database and estimated population abundance, variance, and optimal sample size for each stratification design by the method of Rothschild et al.(1991). Coefficients of variation (CV) of the estimates were used instead of variances for comparing relative efficiencies of each design, because higher estimates of abundance generally have larger variances.

We also examined whether the "double-tow" sampling scheme is superior in terms of cost-effectiveness to one having more stations with only one tow. Under the assumption that the time and cost of the number of stations with one tow is 25% larger than that of station with two tows, if the optimal sample size of "one-tow" sampling is less than 3799 (=3039×1.25), then, we decide that a one-tow sampling scheme is better than a double-tow scheme.

The optimal sample size was estimated by the most conservative "composite" method, which chooses the maximum number of samples from all values estimated for each stratum as discussed in Rothschild et al. (1991).

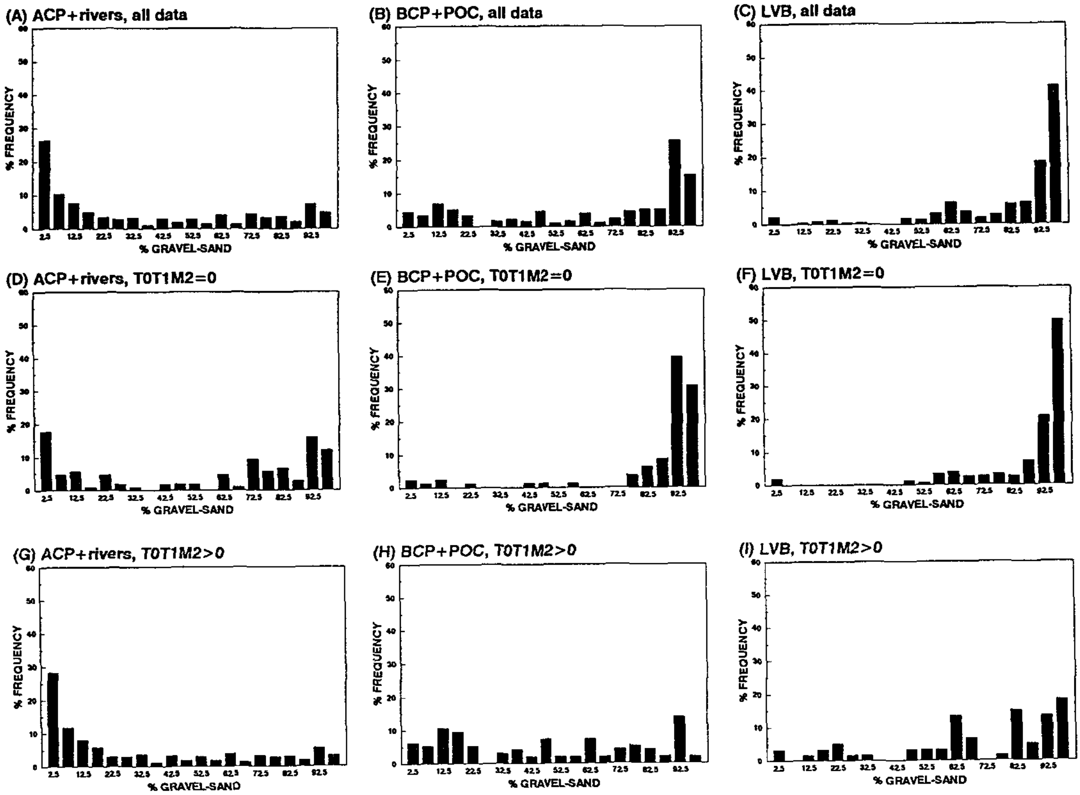

Fig. 2. Frequency (%) histograms of the % gravel-sand bottom compostion for differing levels of crab abundance (C_j≡ average catch of j-th station) of T0T1M2 size- and sex-group combination (T0 ≡ crabs <50 mm cw, T1≡ crabs $\geq$ 50 mm cw and <120 mm cw, and M2≡ male crabs $\geq$ 120 mm cw): (A) all stations, above Cove Point mainstem and rivers, (B) all stations, below Cove Point mainstem and Pocomoke Sound, (C) all stations, lower bay mainstem, (D) $C_j=0$, above Cove Point mainstem and rivers, (E) $C_j=0$, below Cove Point mainstem and Pocomoke Sound, (F) $C_j=0$, lower bay mainstem, (G) $C_j>0$, above Cove Point mainstem and rivers, (H) $C_j>0$, below Cove Point mainstem and Pocomoke Sound, and (I) $C_j>0$, lower bay mainstem.

Results

Analyses and Evaluation of Sampling Design

Based on the earlier surveys, the benthic sediment patterns were indentified by geographical region: upper bay mainstem and rivers were almost muddy; middle bay mainstem exhibited a mixtures of muddy and sandy sediments; and the lower bay mainstem was mainly sandy. It was found that mature female crabs were predominantly more abundant than any other size or sex groups in the lower bay mainstem, while in the other regions all size and sex groups were distributed together.

Further information on the relationship between sediment type and crab distribution were obtained. The lack of habitat preference was confirmed for male and immature female crabs in any portion of the bay (Fig. 2). Rothschild et al.(1991) showed crabs preferably distribute in muddy bottom areas based on survey data from Virginia protion of the bay. However, mature females had less preference for particular sediment types than other size and sex groups, especially in the lower bay mainstem (Fig. 3). According to the analysis of variance for comparing mean crab density among various combinations of geographical regions and sediment types, there were no signi-

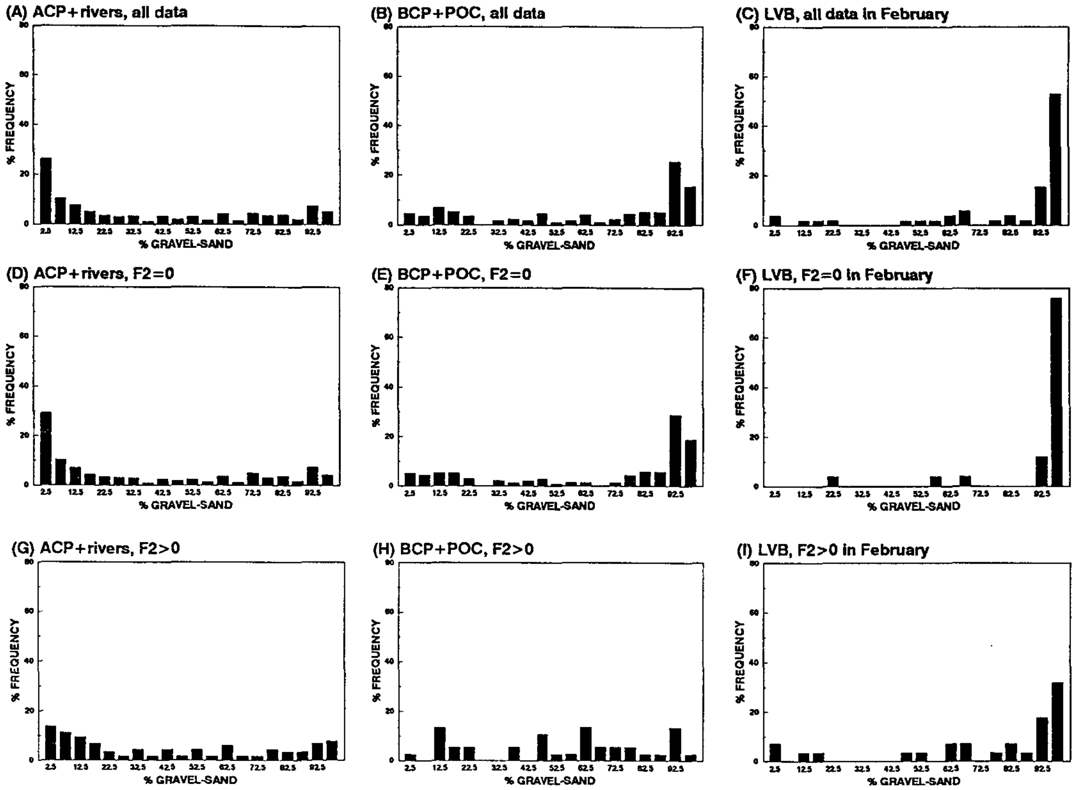

Fig. 3. Frequency (%) histograms of the % gravel-sand bottom compositon for differing levels of crab abundance (C_j≡average catch of j-th station) of mature female crabs (F2) : (A) all stations, above Cove Point mainstem and rivers, (B) all stations, below Cove Point mainstem and Pocomoke Sound, (C) all stations sampled in February, lower bay mainstem, (D) $C_j=0$, above Cove Point mainstem and rivers, (E) $C_j=0$ below Cove Point mainstem and Pocomoke Sound, (F) $C_j=0$ in February, lower bay mainstem, (G) $C_j>0$, above Cove Point mainstem and rivers, (H) $C_j>0$, below Cove Point mainstem and Pocomoke Sound, and (I) $C_j>0$ in February, lower bay mainstem.

ficant differences in the density of mature females amongst sediment types. Eventually, the analysis finally led to unique stratifications for mature females and other crabs in which the crab density in each stratum were significantly different from any other strata (Table 1).

The calculated areas of each stratum are summarized in Table 2. All designs provided similar estimates of population abundance, but the 6-strata design produced the closest abundance estimate to that of the simple random design. The relative efficiencies based on CV were similar for all designs with the range of 110~112%, which indicated improvements with stratification. According to criterion for the 10% detection level, the 6-strata design yielded the smallest optimal sample size.

Based on the examination to test whether the "double-tow" sampling scheme is superior to having more stations with only one tow, as shown in Table 3, both cases of tow 1 and tow 2 produced sample sizes greater than 3799. Therefore, the 6-strata design with double-tow sampling was determined to be the best design and that scheme was used for the next winter dredge survey. Table 4 shows estimated sampling strata and design parameters for the next winter dredge survey. According to the estimation of the op-

Table 1. **The stratification for (A) T0T1M2 size- and sex-group combination (T0≡crabs <50 mm cw, T1≡crabs ≥50 mm cw and <120mm cw, and M2≡male crabs ≥120 mm cw) and for (B) mature female crabs (F2) in which the crab density of each stratum was significantly different from any other strata in analysis of variance and SNK test (α=0.05)**

(A)

Geography	% Gravel-Sand	# Sample	Mean Density	S.E.
Mainstem (above Cove Point) and all rivers	0~ 80	488	0.0270	0.00142
	80~100	107	0.0160	0.00304
Mainstem (below Cove Point) and Pocomoke Sound	0~ 80	144	0.0084	0.00262
	80~100	245	0.0013	0.00201

(B)

Geography	# Sample	Mean Density	S.E.
Mainstem (above Cove Point) and all rivers	488	0.0270	0.00142
Mainstem (Cove Point to Wolftrap) and Pocomoke Sound	144	0.0084	0.00262
Mainstem (below Wolftrap)	245	0.0013	0.00201

timal sample size by the most conservative "composite" method, besides the mature female group (F2) and the combination of other size and sex groups (T0 T1M2) used as the standard for the stratification, the distributions of female crabs ≥50 mm carapace width (cw) and <120 mm cw (F1), recruit groups (M0≡ male crabs <50 mm cw, F0≡female crabs <50 mm cw, and T0≡total crabs <50 mm cw), and the combination of crabs ≥50 mm cw and <120 mm cw and male crabs ≥120 mm cw (T1M2) were considered to be different (Table 1). A total of 3,039 samples needed to be taken baywide according to the composite estimate. Using an optimum allocation scheme, the proportion of the sample size for each stratum to the total sample size was used for the allocation of 1,500 samples given the time and fiscal resource constraints for the next winter survey (Table 4).

Estimates of Density and Abundance

Table 5 shows the estimates of abundance from 1991 winter survey data using the 6-strata design (not corrected by gear efficiency). The estimate of total abundance was 131.8 million crabs with the standard error (SE) of 6.94 million crabs, which yielded 95% confidence intervals of 118.2 million to 145.4 million crabs. A total of 64% of the blue crab population was distributed in the above Cove Point mainstem and rivers with 0~80% gravel-sand bottom although the area covered by the strata was only 39% of total area. Crab density in 0~80% gravel-sand bottom was higher than the density in 80~100% gravel-sand bottom. The density in above Cove Point mainstem and rivers was highest whereas the density in below Cove Point mainstem and Pocomoke Sound was the lowest.

Table 6 shows density estimates by age group by strata. The density of size group 0 (<50 mm cw) was much higher in above Cove Point mainstem and rivers than other strata. Size group I (≥50 mm cw and <120 mm cw) exhibited somewhat higher densities in above Cove Point mainstem and rivers compared to those in the other strata. However, size group II crabs (≥120 mm cw) appeared to have highest density in the lower bay mainstem with 0~80% gravel-sand bottom. Mature female crabs considerably dominated in their density in below Cove Point mainstem and Pocomoke Sound with 80~100% gravelsand bottom and the lower bay mainstem.

Density estimates were based on the assumption that dredges are efficient sampling gears; however, the dredge is probably less than 100% efficient. According to the experiments to test whether dredge efficiency caused underestimation of average crab den-

Table 2. Effect of various stratified random sampling designs on blue crab population abundance estimates for the 1991 winter dredge survey: (A) description of stratification designs; (B) 1991 survey results

(A)

Stratification	Description
Simple Random	Simple Random
3-strata	(1) mainstem (above Cove Point) and all rivers; (2) mainstem (below Cove Point) and Pocomoke Sound, 0~80% gravel-sand; (3) mainstem (below Cove Point) and Pocomoke Sound, 80~100% gravel-sand
4-strata A	(1) mainstem (above Cove Point) and all rivers, 0~80% gravel-sand; (2) mainstem (below Cove Point) and all rivers, 80~100% gravel-sand; (3) mainstem (below Cove Point) and Pocomoke Sound, 0~80%, gravel-sand; (4) mainstem (below Cove Point) and Pocomoke Sound, 80~100% gravel-sand
4-strata B	(1) mainstem (below Cove Point) and all rivers; (2) mainstem (Cove Point to Wolftrap) and Pocomoke Sound, 0~80% gravel-sand; (3) mainstem (Cove Point to Wolftrap) and Pocomoke Sound, 80~100% gravel-sand; (4) mainstem (below Wolftrap)
5-strata	(1) mainstem (above Cove Point) and all rivers, 0~80% gravel-sand; (2) mainstem (above Cove Point) and all rivers, 80~100% gravel-sand; (3) mainstem (Cove Point to Wolftrap) and Pocomoke Sound, 80~100% gravel-sand; (4) mainstem (below Wolftrap)
6-strata	(1) mainstem (above Cove Point) and all rivers, 0~80% gravel-sand; (2) mainstem (above Cove Point) and all rivers, 80~100% gravel-sand; (3) mainstem (Cove Point to Wolftrap) and Pocomoke Sound, 0~80% gravel-sand; (4) mainstem (Cove Point to Wolftrap) and Pocomoke Sound, 80~100% gravel-sand; (5) mainstem (below Wolftrap), 0~80% gravel-sand; (6) mainstem (below Wolftrap), 80~100% gravel-sand

(B)

Stratification	Population Abundance (10^6)	Population Standard Error (10^6)	Population Variance (10^{12})	Coefficient of Variation (CV)	Relative Efficiency	Optimal Sample Size
Simple Random	163.104	9.4686	89.6552	5.81%	100.0%	3992
3-strata	128.468	6.6181	43.7990	5.15%	112.7%	3749
4-strata A	130.710	6.8721	47.2251	5.26%	110.4%	3706
4-strata B	125.458	6.5411	42.7860	5.21%	111.3%	3492
5-strata	129.565	6.6907	44.7650	5.16%	112.4%	3084
6-strata	131.808	6.9420	48.1910	5.27%	110.2%	3039

Table 3. Comparison between 'double-tow' and 'single-tow' sampling scheme on blue crab population abundance estimates for the 1991 winter dredge survey

Data Type	Population Abundance (10^6)	Population Standard Error (10^6)	Population Variance (10^{12})	Coefficient of Variation (CV)	# Sample	Optimal Sample Size
Double Tow	131.808	6.9420	48.1914	5.27%	823	3039
Tow 1	135.380	8.2830	68.6081	6.12%	823	4320
Tow 2	129.719	7.4990	56.2350	5.78%	809	4020

Table 4. Optimal sampling allocation (10% detection level) and practical allocations by size group and sex for the next winter survey. The "composite" column lists the maximum sample number for each stratum

Stratum	Area (km^2)	M0	F0	T0	F1	F2	T1M2	T0T1M2	Composite	Practical
ACP+rivers, 0~80% gravel-sand	3257.46	919	701	729	1855	250	1667	675	1855	915
ACP+rivers, 80~100% gravel-sand	553.42	121	91	96	144	29	123	65	144	70
BCP+POC, 0~80% gravel-sand	1468.75	170	149	137	299	373	190	91	373	185
BCP+POC, 80~100% gravel-sand	1330.64	127	70	88	91	150	42	49	150	75
LVB, 0~80% gravel-sand	803.84	38	10	21	43	305	35	13	305	150
LVB, 80~100% gravel-sand	873.43	6	0	21	84	212	24	8	212	105
Total									3039	1500

Table 5. Stratum density (crabs/m^2) and population abundance estimates (in millions) for the 6-strata design for the 1991 winter dredge survey (W_h≡ stratum weighting factor)

Stratum	Area (km^2)	n	W_h	Average Density (#/m^2)	S.E. of Density (#/m^2)	Population Abundance (10^6)	S.E. of Abundance (10^6)
ACP+rivers, 0~80% gravel-sand	3257.46	488	0.393	0.0260	0.00178	84.816	5.7919
ACP+rivers, 80~100% gravel-sand	553.42	107	0.067	0.0167	0.00215	9.258	1.1869
BCP+POC, 0~80% gravel-sand	1468.75	85	0.177	0.0128	0.00155	18.812	2.2813
BCP+POC, 80~100% gravel-sand	1330.64	90	0.161	0.0027	0.00083	3.654	1.1031
LVB, 0~80% gravel-sand	803.84	14	0.097	0.0147	0.00299	11.800	2.4000
LVB, 80~100% gravel-sand	873.43	39	0.103	0.0040	0.00118	3.468	1.0271
Total	8287.54	823		0.0128	0.00174	131.808	6.9420

sity, values of q obtained from Leslie's method ranged from 0.446 to 0.953. The average q value of 0.474 was chosen as the best preliminary estimate of dredge capture efficiency. Taking into account of the dredge capture efficiency, the estimate of total abundance for 1991 was 278.1 million crabs.

Discussion

The directional bias of the estimates of abundance is still not clear. It can be deduced from bias in estimates that blue crabs are heterogeneously distributed throughout the Chesapeake Bay during winter. Effi

Table 6. Blue crab density (crabs/m²) estimates and percent females by size group by stratum for the 1991 winter dredge survey

Stratum	Size Group 0		Size Group I		Size Group II		Total	
	Density (S.E)	% Female	Density (S.E)	% Female	Density (S.E)	% Female	Density (S.E)	% Female
ACP+rivers, 0~80% gravel-sand	0.0142 (0.00096)	49.3	0.0078 (0.00099)	32.9	0.0041 (0.00041)	16.4	0.0260 (0.00178)	39.3
ACP+rivers, 80~100% gravel-sand	0.0092 (0.00160)	44.9	0.0036 (0.00062)	37.8	0.0040 (0.00076)	15.9	0.0167 (0.00215)	36.4
BCP+POC, 0~80% gravel-sand	0.0056 (0.00098)	56.7	0.0023 (0.00040)	34.9	0.0049 (0.00010)	57.9	0.0128 (0.00155)	53.2
BCP+POC, 80~100% gravel-sand	0.0015 (0.00067)	41.0	0.0004 (0.00011)	38.9	0.0008 (0.00038)	80.1	0.0027 (0.00083)	52.7
LVB, 0~80% gravel-sand	0.0010 (0.00067)	14.3	0.0006 (0.00034)	25.0	0.0130 (0.00304)	83.9	0.0147 (0.00299)	76.5
LVB, 80~100% gravel-sand	0.0001 (0.00005)	0.0	0.0003 (0.00017)	100.0	0.0037 (0.00108)	89.0	0.0040 (0.00118)	88.6
Total	0.0053 (0.00082)	47.7	0.0025 (0.00044)	35.3	0.0051 (0.00112)	62.4	0.0128 (0.00174)	51.1

cient estimates of population abundance depend upon selecting an appropriate combination of a statistical estimator and survey sampling design. Annual estimates of population abundance are quite different depending on the choice of either simple random or stratified random sampling. Simple random sampling yields a statistically greater estimate of population abundance. Efficient stratification should make abundance estimates more precise than those obtained from simple random sampling (Cochran, 1977). Thus, simple random sampling is not an efficient statistical sampling design.

An efficient stratification scheme designed for the aggregate blue crab population may be inefficient for estimation of specific size, age or sex group abundances. This may partly explain the skewed sex ratios of age group I and II crabs (Table 6). While stratified random sampling appeared to be superior to simple random sampling, it can also be adversely affected in two ways: (1) choosing an incorrect stratification variable, and (2) incorrectly specifying strata. Relative efficiency is useful for comparing variance estimates of different sampling designs (Cochran, 1977).

It can be concluded that crabs appear to be heterogeneously distributed within specific geographical regions. Therefore, stratified random sampling designs based solely on geographical regions are not likely to improve population abundance and variance estimates over those obtained from simple random sampling.

Schaffner and Diaz (1988) state that blue crabs may be distributed preferentially during winter with respect to the composition of sediments. Thus, stratification by bottom sediments may produce a more efficient sampling survey design.

This may indicate growth and/or ontogenetic movement of age group 0 and I crabs. We conjecture that crabs begin to come out of quasi-hibernation sometime in March or April as bay waters become warm. Therefore, we recommend that sampling in the southern Virginia mainstem be conducted in the time-window after the majority of exploitation from the winter dredge fishery has concluded and prior to the time that crabs emerge from quasi-hibernation. The late February through early March period satisfies both of the aforementioned conditions.

By taking advantage of overwintering blue crab population behavior, our strategic approach to blue crab stock assessment is more robust and synoptic than any previous set of methodologies. The results from the winter survey allow us to directly estimate relative and total population abundance, including recruitment, fishable average population size, and the spawning stock biomass. It also allows characterization of blue crab winter spatial distribution by size (age) and sex groupings.

Incorect specification of sampling strata can pro foundly affect estimates of blue crab abundance due to heterogeneous size- and sex-specific overwintering spatial distributions of the stock.

Our estimate of blue crab overwintering habitat area is conservative, based on actual winter sampling observations. The extent of the range of blue crabs in many of the river systems and in the upper bay has not been determined to a high degree of certainty; this applies to the bay mouth region as well. In addition, we have excluded areas shallower than 1.5 m in depth. Studies from the Chesapeake Bay and Texas have demonstrated that high densities of age group 0 blue crabs occupy habitats occurring in depths <1 m (Orth and van Montfrans, 1987; Thomas et al., 1990), even during the winter months (R. Lipcius, VIMS, pers. comm.). This may account for some of the additional bias in estimates of age group 0 abundance.

Dredge capture efficiency has been preliminarily estimated as 0.474; however, this factor is most certainly much lower for crabs ≤ 15 mm cw due to the mesh size utilized in the dredge liner. This would also explain the relatively lower estimates of age group 0 crabs.

In conclusion, improvement in both the efficiency of the winter sampling program and the estimation of the Chesapeake Bay blue crab population requires: (1) determination of the appropriate sampling stratification scheme based on sediment composition and geographical region; (2) allocation of the appropriate level of sampling effort; (3) a comprehensive understanding of dredge capture efficiency; and (4) a more accurate determination of total overwintering habitat area, including an assessment of the shallow water component's contribution.

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Received January, 5, 1995
Accepted September 7, 1995