ABUNDANCE ESTIMATION AND POPULATION DYNAMICS OF THE BLUE CRAB IN THE CHESAPEAKE BAY

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ABUNDANCE ESTIMATION AND POPULATION DYNAMICS OF THE BLUE CRAB IN THE CHESAPEAKE BAY

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SUMMARY

This report to the Chesapeake Bay Stock Assessment Committee details the results of research conducted by the University of Maryland Center for Environmental and Estuarine Studies (UMCEES) between 1 October 1992 and 30 September 1993. The winter dredge survey was conducted from January 7 through March 27 by UMCEES and the Maryland Department of Natural Resources, in conjunction with the Virginia Marine Resources Commission and the Virginia Institute of Marine Science.

Our research during FY 1993 has focused on: 1) optimizing the winter dredge survey for estimating abundance and population characteristics; 2) developing methods for obtaining more accurate estimates of catching-efficiency for the sampling gear; and 3) implementing efficient estimators for density, along with estimators for size/sex composition accounting for the effects of intra-cluster correlation.

The spatial distribution of blue crab is highly patchy across the Chesapeake Bay, but tends to be more homogeneous on a local scale. As a result, the observations of numbers of crabs from neighboring area units are less variable than observations for units with larger spatial separation. In previous years double-tows were taken at each station; the correlation between catches within a station was typically greater than $r = 0.5$. By taking one dredge tow at each station, instead of two, we were able to increase the number of stations sampled per boat-day by more than 30%. Furthermore, the survey stratification scheme was modified; the sediment stratification employed in 1991/92 was not used. As a result, the relative precision of density for the 1992/93 survey was higher (lower $k = cv/\sqrt{n}$) than for the 1991/92 survey even though the survey cost (number of boat days) was reduced by approximately 30%, and the survey area was expanded. The allocation of stations in the various strata was conducted so that data analysis was simplified. At the same time, the survey design had near-optimum properties in terms of obtaining precise estimates of abundance and sex/size composition at minimum cost.

Average number of crabs caught per area-unit swept during the winter dredge survey provides an estimate of the relative density for the blue crab population. Results suggest that blue crab abundance (for all size categories combined) in 1992/93 has increased by approximately 50 % from the previous year. The population is highly segregated by size and sex, with a large proportion of the mature females in Virginia waters. This population structure compares with results from previous studies, providing further evidence that females are significantly more vulnerable than males during the winter dredge fishery which only takes place in Virginia waters.

Estimates of proportions of crabs in different size/sex categories by strata are based on the ratio estimator; stratified estimates for the entire population are based on the combined ratio estimator. The binomial or multinomial distributions, which are based on the assumption that individual crabs are sampled randomly, can severely underestimate the variance of proportion-estimates. This is due to between station variability in density, combined with intra-haul correlation with respect to size and sex of individual crabs.

A new method for estimating gear-efficiency is proposed, yielding more realistic estimates which are also consistent between years. Our estimated catchability coefficients indicate that the standard Virginia crab dredge employed in the winter surveys on average catch less than 15% of the total number of crabs in the area swept by the dredge. Thus, the absolute density of crabs is nearly 7 times greater than the survey indices of density (average catch per 1000m^2). In comparison, the method used in previous studies resulted in a catchability estimate of 26 %. Survey estimates of absolute abundance of the winter population of blue crabs for 1990/91-1992/93 are provided, along with estimates of number of crabs landed in the commercial hard-crab fishery. Sources of errors in these estimates are discussed.

1. INTRODUCTION

The blue crab (*Callinectes sapidus*) in the Chesapeake Bay has supported a significant fishery since the early 1880's. Reported catch from the Maryland-Virginia fishery for 1880 was approximately 4 million pounds (Tang, 1983; Knotts, 1988). Fishing effort and catch levels increased rapidly in subsequent years, as result of increased consumer demand and improved technology. Estimated total landings (baywide) of hard and softshell crabs peaked at 97 million pounds in 1966 (Knotts, 1988). During the 1980's the average harvest of hardshell crab from Maryland's commercial fishery is estimated at approximately 45 million pounds. Historic catch data reveal fairly wide fluctuations in catch levels over the last century due, in part, to natural changes in recruitment related to environmental conditions such as temperature and salinity. However, there has been a declining trend in reported commercial landings of hardshell crabs in Maryland during recent years, dropping to approximately 31 million pounds in 1992. This decline has led to concern about causal factors, including pollution and over-fishing.

In order to maximize long term landings from the blue crab fishery, it is important to determine how the population is affected by harvesting. Accurate estimates of population abundance, and size/sex composition over time, together with estimates of precision, is crucial for effective management. In addition, reliable estimates of total landings, including recreational catches, are important. Models for assessing the impact of pollution and other environmental effects (e.g., temperature, salinity) on stock size over time also require precise estimates of population abundance and composition.

Since 1987, the National Oceanographic and Atmospheric Administration (NOAA) has sponsored a program to estimate key statistics for the blue crab population in the Chesapeake Bay, through a grant to the Chesapeake Bay Stock Assessment Committee (CBSAC). During the first year of the study, a comprehensive program of data collection on-board commercial fishing vessels was developed by the University of Maryland Center for Estuarine and Environmental Studies (UMCEES), in cooperation with the Maryland

Department of Natural resources (MDNR). These data have provided information on catch rates, size-distribution, and ratios of males to females in the commercial harvest. Since 1988, statistics have also been collected from commercial crab dealers.

Catch per unit fishing effort (CPUE), e.g., catch per day for each gear type in the entire fishing fleet averaged over a month (or an entire fishing season), is often used to monitor monthly (or yearly) changes in the abundance of a fish stock. Increases or decreases in stock abundance should result in similar changes in measures of CPUE, assuming that they reflect the true population size. However, estimates of fish stock abundance based solely on commercial catch data may be extremely inaccurate. For example, if the population is concentrated in a few areas of high density, that are successfully located by the fishermen, then high CPUE may be sustained regardless of a more general stock decline. Furthermore, due to the patchy distribution of marine populations, it is not reasonable to assume that catches at locations chosen by fishermen are representative for the entire Bay. Thus, estimates of the precision of CPUE abundance indices can generally not be obtained.

In 1987, direct observations were made of commercial operations for 60 crabbers participating in the pot, scrape and trotline fisheries (Rothschild et al. 1988). In this study it was observed that CPUE increased or remained stable as the season progressed, for all gear types. This was also observed in the estimates of commercial harvest by month (see, also, Cronin 1982). This phenomena, not commonly observed in fisheries, could be explained if the availability of legal sized crabs increased as the season progressed, perhaps the result of growth and/or immigration (see Rothschild et al. 1988). The catching efficiency might also increase during the season, from increased skill by crabbers in locating high density areas.

In 1988, a fishery-independent survey and tagging study was conducted by UMCEES in order to provide information on growth, mortality, and migration patterns. The utility of crab dredges for sampling the blue crab population during the winter months was evaluated.

From November through March blue crabs are largely inactive, and bury themselves in the bottom sediment (Van Engel 1958). They are, therefore, less likely to escape the dredge by swimming. Also at this time, fishing activity is at a minimum; only crabs in the Virginia mainstream are harvested during winter. During the summer months blue crabs are active swimmers, and easily caught by otter trawls. However, it may be difficult to obtain representative samples across the Bay during summer, due to obstructions from fishing gears (crab pots and trotlines) placed throughout the Bay.

A pilot winter dredge survey was conducted by UMCEES from December 1988 through March 1989. This survey has since evolved to a multi-institutional sampling program conducted annually throughout the entire Chesapeake Bay during the coldest winter months (see Rothschild et al. 1991; 1992). The field work is conducted by UMCEES, MDNR and VIMS, through dredging contracts with local watermen. These dredge surveys provide abundance estimates for the winter population of blue crab, along with estimates of population composition by size and sex. Presently, there is no technique available for obtaining accurate information on the age of individual blue crabs. Standard tagging techniques, for example, fail as a result of molting. However, distinctive modes in the size frequency distributions may be used as a proxy for age classes. For effective management it is equally important to estimate numbers of crabs being harvested, with respect to their size, sex, and age distributions. Only then, can the relationship between levels of abundance and harvest, within a predictive framework, be determined (Vølstad and Patrick, 1993). The winter dredge survey for 1992/93 was conducted between January 7 and March 27.

2. SURVEY DESIGN AND PLANNING

Observations from the winter dredge surveys conducted in the Chesapeake Bay are used to estimate abundance, size/sex composition, and to quantify the dynamics of the blue crab population. Due to survey errors, there may be discrepancies between these estimates and the "true" status of the population. Survey errors result from: 1) *sampling errors* related to the survey design employed in selecting a subset of the target population; and 2) *non-*

sampling errors encompassing all other factors that contribute to the survey error (see Lessler and Kalsbeek 1992). Small sampling errors result in high precision; i.e. each observation is close to the average over repeated samples (see Jessen 1978). The second type of error is often referred to as bias. Accuracy is a measure of closeness of survey estimates to the targeted population value (Jessen 1978), and is often measured by the means square error: MSE = bias^2 + variance.

A carefully designed survey yields more representative samples and, therefore, reduces sampling errors. Realistic estimates of precision, or the magnitude of sampling errors, can generally be obtained by employing probability sampling, i.e. selecting each sampling unit from the frame with known probability (see, e.g., Særndal at al. 1992). The frame is the list (or population) of units to which the probability sampling scheme is applied (see Kish 1965). The population of sampling units may differ from the target population of the investigation. In marine surveys the sampling unit is typically a fixed volume or unit of area swept by a standard tow (see Pennington and Vølstad 1994a). As result, it is generally not feasible to sample individuals randomly from the target population. The frame from which sample units are selected consists of a list of area units, or a collection of geographic coordinates, covering every possible sampling location in the survey area. This sampling method is often referred to as area sampling (see Jessen 1978, p. 171).

Although no comprehensive theory exists for assessing the impact of non-sampling errors (Lessler and Kalsbeek 1992), bias in survey results may be substantially reduced by careful planning. Two apparent sources of bias in the winter dredge survey for blue crab are: 1) failure to cover the entire distribution area of the target population; and 2) low catching efficiency of the sampling gear. A comprehensive coverage of the survey area should minimize errors from source number (1). The bias resulting from source number (2) can, in part, be corrected for by obtaining accurate estimates of gear efficiency.

Size selectivity of the sampling gear is another source of non-sampling errors, particularly critical in estimating the absolute number of recruits (size class 0). The standard Virginia sampling dredge has an inner lining of 12 mm mesh size; crabs less than 15 mm are retained only sporadically. For larger crabs ($\geq$ 15 mm), it is reasonable to assume that the catchability is constant across different size/sex classes during the winter months, since behavioral effects are negligible during cold winter months. Furthermore, if catchability is constant overtime, such bias would not effect estimates of changes in abundance. In contrast, inadequate sampling in some years of shallow ($\leq$ 5 ft) or deep ($\geq$ 40 ft) areas of the Bay is likely to bias the estimates of yearly changes in abundance. An additional complicating factor is that the direction and magnitude of such bias may change between years, resulting in increased errors in estimates of abundance changes. The comprehensive coverage in 1992/93 provides insights on the magnitude of errors which can result from using such incomplete sampling frames.

2.1. Use of historic data in survey design

Studies by Van Engel (1958), Lippson (1971), and Sulkin (1973), for example, provide information on the geographic distribution of blue crabs and their depth range during winter. Commercial harvest data from the Virginia fishery in the Bay provide additional information. However, previous studies are generally not obtained by random sampling, and only covers part of the entire distribution area for the blue crab. Since the present winter survey's inception, as more detailed information has become available, the survey has been modified to provide more comprehensive coverage of the blue crab population. A summary of sampling effort, stratification schemes and areas surveyed during 1988/89 through 1991/92 is given in Rothschild et al. (1992). The area surveyed has increased yearly. Since 1990/91 areas of the Bay with depths greater than 40 ft have been sampled; shallow waters ($\leq$ 5 ft) have also been sampled since 1991/92. Whereas only limited sampling, on an ad hoc basis, had been conducted in these deeper and shallow waters during earlier years.

Planning/design for the 1992/93 survey was based primarily on data from the two preceding years. These were stratified random surveys, conducted with comprehensive coverage. If we assume the survey area include the entire target population, and constant catchability, then estimates of (relative) population mean density, and its variance for each strata, are unbiased if stations within each strata are randomly allocated. The efficiency of these past surveys may be assessed by estimating the (relative) precision ($k = cv/\sqrt{n}$) of the stratified mean catch per m^2 for the survey design used, and then comparing this estimate with: 1) expected precision from a design with sampling allocation proportional to strata size; and 2) expected precision from optimum allocation. If one stratum has twice the area of another, sample allocation proportional to strata areas results in twice as many stations being allocated to the larger. For optimum allocation, often referred to as Neyman allocation (see, e.g., Cochran 1977), the number of stations in stratum h (n_h) is chosen proportional to the standard deviation times the stratum area ($n_h \propto S_h A_h$). Neyman allocation yields the maximum precision (minimum standard errors) obtainable when the total sample size is fixed. In 1990/91 and 1991/92, two tows were taken at each location. Since station locations were chosen at random, the analyses are based on the average of the two tows at each station. In effect, two 1 minute tows at a station is analogous to using a larger sampling unit (i.e. 2 minute tows) at each station.

In previous surveys, the number of stations sampled in each stratum was not selected proportional to strata areas; some strata were sampled more intensely than others. Since the probability of a station being selected varied significantly among strata, the total number of stations can **not** be assumed to form a simple random sample from the entire survey area. Therefore, the resulting relative precision of estimates for the design actually used in the blue crab survey can not be compared with expected values for a simple random sampling scheme. However, a crude comparison might be based on simulation studies. For example, a resampling scheme taking into account the actual survey design could simulate a situation where each station had the same probability of being selected (i.e. random sampling). Although such simulations may provide some insights, we do not expect that estimates based on random sampling would differ much from proportional allocation.

Our evaluation of survey designs is based on the sampling stations taken as part of the standard stratified random winter survey. For example, the additional stations sampled by VIMS to monitor the winter dredge fishery in Virginia waters were not analyzed, since their inclusion probabilities were not known. Tables 1 and 2 provide estimates of mean catch per area swept, and its standard error, for 1990/91 and 1991/92 surveys, along with expected values from optimum and proportional-to-size allocation schemes. Details on the actual stratification schemes used in past surveys, are given in Rothschild et al. (1992). The s.e.'s of stratified means for the actual designs are similar or slightly lower than the expected s.e.'s from proportional allocation; similar results hold for different size and sex classes.

An allocation scheme proportional to strata size may have advantages over other designs, particularly for marine surveys. The spatial distribution of marine populations is generally influenced by environmental and behavioral factors; such factors are difficult to incorporate in the survey planning phase. Furthermore, the time series of survey data for blue crab is short, thus it becomes difficult to verify if the spatial distribution among years is consistent, or related to key environmental variables. If spatial distribution changes significantly between years, for example as a result of changes in temperature or salinity levels, the estimated variability of crab density in a given strata is also likely to be affected. Hence, allocation of stations made proportional to strata area times the standard deviation of mean catch per tow for the previous year, may yield much lower precision than allocation proportional only to the strata area. In this allocation scheme, relatively fewer stations may be allocated to a stratum if variability was low in previous years. If variability has increased significantly the next year, a low sampling fraction in this stratum may significantly increase the variance in stratified estimates of overall density. Proportional allocation is a safe guard towards such changes in spatial distribution (see Cochran 1977). For many marine populations, the coefficient of variation (cv) is fairly constant between strata. In that case, station allocation proportional to strata area would be near optimal, i.e., the relative precision would be maximized (minimum $k = cv/\sqrt{n}$) for fixed number of stations.

In the 1991/92 survey, the study area was divided into 3 geographic strata, each of which was partitioned into two sub-strata based on sediment type (see Rothschild 1992). Mean catch per tow and its standard deviation for this survey was higher for sandy bottom than for bottom types with higher percentages gravel (> 80%); extra stations were allocated to sub-strata with sandy bottom. This survey design resulted in a relative precision that was only slightly higher (lower $k = cv/\sqrt{n}$) than would be expected for proportional allocation (Table 2). Furthermore, stratification by sediment type may introduce non-sampling errors since the bottom type in every part of the Bay is not known prior to dredge sampling. For example, if the sediment type observed during the survey at some locations actually differs from the information in the data base, this must be taken into account in the estimation procedure. The weight assigned to each observation must be determined from the selection probability for each unit, and not on the probability attached to units with the sediment type being observed in the sample (see Særndal et al. 1992). If stratification by sediment is based on the sediment type actually observed in the survey, the resulting estimates will be biased. The simplicity and self-weighing feature of proportional allocation reduces such error, and probably justifies a small increase in variance (see also Cochran, 1977, p. 103). Furthermore, if the correlation between observed sediment type and abundance is high for a particular survey, this auxiliary information might be used to increase precision by using a regression estimator or a post-stratification procedure (see Særndal et al. 1992).

2.2. Determination of sample size

An important aspect of the planning of a survey is to determine the sample size, so that ineffectual or over-expensive surveys can be avoided. Sample size directly effects the precision of survey estimates, i.e., sampling error, but does not effect the magnitude of bias resulting from other sources such as inadequate coverage of the population. The following discussion refers to sampling errors that can be controlled through sampling design. In order to obtain an estimate of average density ($\bar{y}$) with acceptable confidence limits, the number of stations, n, needs to be determined so that

$$\mathrm{Var}(\bar{y}) \leq \Theta^2.$$

If we chose Θ = (acceptable 95% confidence-interval half-width)/1.96, say, then $n \geq S^2/\Theta^2$ would yield a satisfactory estimate of mean density. This requirement involves S^2, the population variance which is generally unknown. Estimates of S^2 may be obtained from pilot surveys, or comparable studies from other areas. The above formulation is based on the assumption that we are primarily interested in absolute precision. For marine populations, the variance is generally related to the mean density. For high population abundance, achievement of a fixed and low standard error of mean catch per tow is likely to be overly expensive. In many circumstances, relative precision ($k = cv/\sqrt{n}$) may be a more relevant consideration. In that case, we require that $k \leq \Theta$, or $n \geq cv^2/\Theta^2$ for suitable Θ. The between stations variance in number of crabs per area swept can be approximated by

$$S^2 = \bar{y} + b\bar{y}^2,$$

where $\bar{y}$ is average number of crabs per area swept. Hence, the coefficient of variation,

$$cv = 1/\bar{y} + b,$$

is fairly constant for average levels of density, and has asymptotic value b for high density. For such reason, the relative precision ($k = cv/\sqrt{n}$) is less sensitive than the standard error to changes in population abundance. Note that k simply is the percentage of standard error relative to the mean.

In many marine surveys, the number of stations that can be sampled is limited by available resources. Due to high variability in density for most marine populations, and high cost associated with conducting sampling surveys, the precision of the resulting estimates of density and other population characteristics may be lower than required for effective fisheries management. Hence, the issue is usually 1) to maximize precision (k) at a fixed cost, or 2) minimize cost for a fixed level of precision (see Pennington and Vølstad 1991; 1994a).

2.3. Selecting number of tows at a station

Measurements of density and other characteristics for marine populations are generally highly variable between locations, but tend to be relatively more homogeneous on a local scale. If so, it may be inefficient to take more than one dredge tow at each location. By reducing the time at a station, the number of locations sampled can be increased, resulting in more precise estimates of density and other population parameters (Pennington and Vølstad 1991; 1994a; 1994b).

The effect of local homogeneity on the efficiency of various survey designs for estimating density can be evaluated as follows: Suppose that m non-overlapping tows of fixed duration are taken at each of n_m locations chosen randomly in an area. For fixed survey cost, the number of stations that can be sampled depends on the time spent at each station and, hence, on number of replicate tows (m) at a station. Let y_i denote the number of animals caught in the j'th tow at the i'th station. The average of the y_{ij}'s is

$$\bar{y}_{..} = \sum \sum y_{ij}/n_m m, \tag{1}$$

and the variance of (1) can be estimated by

$$V(\bar{y}_{..}) = (S^2/n_m m)[1 + (m\text{-}1)\rho], \tag{2}$$

where ρ, the intra-class correlation coefficient, is a measure of within station homogeneity for y_{ij} (see, e.g, Cochran, 1977; Jessen, 1978; Särndal et al., 1992). An expression for ρ is

$$\rho = 1 - (S^2_W/S^2)$$

where S^2_W is the (weighted) average of the within-station variances of y_{ij}, and S^2 is the overall variance (see Særndal et al., 1992, p 130). In the following, we will refer to ρ as the homogeneity coefficient. A positive ρ means that observations from replicate tows at a station tend to be more similar than observations from tows that are taken further apart, i.e. the spatial distribution of animals is locally homogeneous. It follows from equation (2) that the mean catch per tow from n_1 single-tow stations would be more efficient for estimating the population density than the mean from n_m stations with m replicate tows if

$$n_1 \geq n_m m/[1+(m-1)\rho]. \tag{3}$$

An evaluation of historic winter dredge surveys reveal that catches from double-tows at each station are more similar than catches from tows that are taken further apart. For example, for the winter dredge surveys in Virginia waters the average homogeneity coefficient, $\bar{\rho} = .6$ (Marcel Montane, College of Williams and Mary, VIMS, pers. comm.). The estimate for the Maryland part of the Bay is similar, varying from .5 - .7 between years. For ρ=.6, 125 independent tows would achieve approximately the same precision as 200 tows from 100 randomly selected stations.

In Pennington and Vølstad (1994a,b) it is demonstrated that the variance of estimates of population characteristics such as age-length distributions is greatly inflated in the presence of intra-cluster correlation for size and age.

2.4. Design of the 1992/93 winter dredge survey

The standard dredge survey for blue crab in the Chesapeake Bay during the winter of 1992/93 was conducted in a stratified random design, with 3 geographic strata: 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay (see Rothschild et al. 1992). A map of the survey area and geographic strata is in Figure 1. In Figure 2 is a map of the effort allocation between UMCEES, MDNR and VIMS. In the Maryland waters, dredging were conducted in waters deeper than 3 ft. In Virginia waters the minimum depth for dredging was 5 ft; a suction sampling technique was employed in waters with depths less than 4 ft. The total area sampled by the dredge was approximately 11,000 km^2. The selection of sampling locations was conducted in two steps. Firstly, 939 stations were allocated within the entire survey area, in a stratified random design with number of stations in each geographic stratum proportional to the stratum area. These stations simplify analytical studies based on the survey data, since they can be treated as a random sample over the entire survey area (see Skinner et al. 1989).

Dredging in shallow ($<$ 5 ft) and deep ($\geq$ 40 ft) waters has been limited in previous years. Hence, it was decided to conduct additional studies in these waters in order to gain more knowledge on abundance and size/sex composition by depth. For this study, strata 1 and 2 where further divided into three sub-strata according to the following depth intervals: A) less than 5 ft; B) greater or equal to 5 ft and less than 40 ft, and C) greater or equal to 40 ft. Stratum 3 was divided into two depth intervals; B and C. In the shallow waters (A) a total of 38 extra stations were allocated; and 110 extra stations were allocated in the deeper waters (C). Highly accurate information on depth topography of the survey area are obtained from NOAA, the National Geological Survey, and from previous dredge surveys. A bathymetric contour map is presented in Rothschild et al. (1992); sample location and abundance levels are mapped in Vølstad and Patrick (1993).

Total survey effort for the entire Chesapeake Bay was 126 boat-days, including 20 days used for gear efficiency experiments. With the exception for some experimental studies for assessing gear saturation effects, one dredge tow of 1 minute duration was taken at each location. Standard towing speed was approximately 3 knots. A standard sampling unit is defined as the area swept (in m^2) by a standard tow. The towing distance was determined by the Loran C navigation system. The 1087 stations sampled altogether can be analyzed as a stratified design with 3 main (geographic) strata, each of which is divided into sub-strata according to depth. Within each stratum, extra stations in shallow and deep waters were approximately randomly selected within depth boundaries in the computerized map of the Bay. A limited number of stations falling outside the boundary, as a result of inaccuracy in the map, were not sampled. For simplicity, the weighing factors for the 8 strata were based on the fractions of the proportionally allocated stations falling in each depth interval.

Shallow areas (3-5 ft) in strata 1 and 2 were sampled using a modified oyster dredge (1.05 m wide); a standard Virginia crab dredge (1.83 m wide) was used for sampling in waters with depths $\geq$ 5 ft (see Rothschild et al. 1991; 1992). Stations were randomly allocated within each stratum and depth-interval. In Maryland waters, double-tows were taken at 77 randomly selected stations; one tow of 0.5 min and one tow of 1 min duration in random order (selected by flipping a coin). These experimental tows were conducted in order to evaluate possible gear-saturation effects on the CPUE.

Sampling stations were selected the following way: Using a computerized map of Chesapeake Bay, the survey area was divided into 15 by 15 sec rectangular units. The list of units constitute the sampling frame from which samples are selected. Units were randomly selected within each stratum (and sub-stratum), and x-y coordinates (in seconds) for the site to be dredged within a 15 by 15 sec unit was randomly selected. Strictly speaking, this selection procedure may cause a slight bias in the estimates of average catch per tow. Since the area of each 15 by 15 sec rectangle decreases with increasing latitude, locations further north will have a slightly increased probability of being selected. However, the maximum difference in area of the rectangles across the survey region is less than 3%, and hence we consider this bias to be negligible.

2.5. A model for survey cost

At each station it takes on average a certain time, c_1, to conduct one haul of fixed duration. If time for other studies at a station, such as collecting environmental data, is t_s, the total time at a station with m replicate tows is $c_1 m + t_s$. If n stations are selected randomly in a survey region, and a cruise track of approximately minimum length is chosen, then the total travel time between stations will be approximately proportional to $\sqrt{n}$ (see, e.g., Cochran 1977, pp. 96, 244; Pennington and Vølstad 1991). Let total survey cost, C, be the effective time for sampling, measured as the time elapsed (in minutes) between the first and last tow.

For a random survey with fixed cost, C, the number of stations, n_m, that can be sampled if m tows of fixed duration are taken at each location, is approximately determined by

$$C = (c_1 m + t_s) n_m + c_2 \sqrt{n_m},$$

or

$$n_m = [\{(c_2 + 4(c_1 m + t_s)C)^{1/2} - c_2\}/2(c_1 m + t_s)]^2, \tag{4}$$

where c_2 is a constant which depends on the survey area and the cruising speed between stations (see also Cochran 1977, p244; Pennington and Vølstad 1991). If the survey design is a grid of equally spaced stations, then the travel time will also be approximately proportional to $\sqrt{n}$ (Hansen, Hurwitz, and Madow 1953, p. 273), and formula (4) will hold.

It is apparent from equations (2), (3) and (4) that more than one tow at a station is inefficient if: time associated with each tow, c_1, is relatively large; the travel time parameter, c_2, is relatively small as a result, e.g., of a small survey area; and if the similarity between observations from replicates at a station, as measured by the homogeneity coefficient ρ, is high.

2.6. Computer software for station selection

A system for allocation of stations in the winter dredge survey has been developed. The system is written in IDL ("Interactive Data Language"), and presently runs on a work-station. IDL can also be installed and run on PC's. Graphical software for mapping and exploratory data analysis has been completed. The present implementation is a command-line version that requires familiarity with IDL. The next stage of the development of the system will be an implementation using a graphical user interface. Under the current budget and program plan the implementation in a user friendly configuration could not be funded. The current implementation provides the following functionality:

1. Generates and displays a gridded map of Chesapeake Bay at any desired resolution, in latitude-longitude co-ordinates. Universal Transverse Mercator (UTM) and other co-ordinates are partially implemented. Typical gridding is 15 sec by 15 sec as used in the 1992/93 survey. Gridding by 10X10 or 7.5X7.5 sec is straight forward.

2. A data-base and overlay of all Bay partitions used through the survey development. Partitions from this collection can be interactively selected and overlaid on the map of the Bay. New partitions can be interactively drawn and subsequently stored in a file. With a full partitioning of the Bay selected, a random or stratified random sampling design can be interactively generated using arbitrary effort allocation.

3. Physical features, including depth, sediment and salinity, can be used interactively to generate strata. Currently depth is fully implemented. Data-bases of historical salinity observations along with sediment measurements are on-line, and can be implemented. These features can be used to generate sub-strata within existing geographical strata, or entirely feature based strata.

4. Bottom areas for strata (e.g., for use in the stratified mean estimator) are automatically calculated.

5. Cursor interrogation is fully implemented for position, depth, and area of the strata.

6. User interactively selects strata weights and total effort, and the stratified random station allocation is automatically. The program also generates a map of station positions, along with a hard-copy report of co-ordinates, depth, sediment and historical average salinity.

3. ESTIMATION THEORY

Mean catch per area swept from randomly selected locations provides an (unbiased) estimate of the relative abundance of blue crab in the survey area. Nevertheless, this abundance index is likely to be substantially lower than the true density of the population since the dredge catches only a small fraction of crabs in the area swept. However, estimates of catching efficiency of the sampling gear (q) from depletion experiments may be used to correct such bias. For simplicity, we omit the correction factors for catchability in the following estimators for density. It is generally assumed that the catchability is constant for all crabs with carapace width greater than or equal to 15 mm. Note that a significance level of 5% is used in all statistical tests in this study.

3.1. Stratified mean density and its variance

Suppose independent samples of size n_h are taken within each of L strata indexed by $h = 1,2,...,L$. We attach an extra suffix so that $y_{h,1}, y_{h,2}, y_{h,2}, ..., y_{h,nh}$ are the observations (e.g.

number of crabs per area swept) for the n_h samples from stratum h, the population values for which are $Y_{h,1}$, $Y_{h,2}$, $Y_{h,3}$, ..., $Y_{h,Nh}$. The overall ("true") population mean per unit is

$$\bar{Y}=\sum_{h=1}^{L}\left(\frac{N_h}{N}\right)\bar{Y}_h \tag{5}$$

which is a weighted mean of stratum means. Similarly in the sample

$$\bar{y}=\sum_{h=1}^{L}\left(\frac{n_h}{n}\right)\bar{y}_h \tag{6}$$

An estimator of $\bar{Y}$ is provided by

$$\bar{y}_{st} = \Sigma W_h \bar{y}_h \tag{7}$$

where for stratum h, $W_h = N_h/N$ is the proportion of the survey area in the stratum. In the case of proportional allocation, i.e. with equal sampling fraction in all strata, the sample is self-weighing and

$$\bar{y}_{st} = \bar{y}.$$

An estimator for the variance of (7) is

$$Var(\bar{y}_{st}) = \Sigma W_h^2(1-f_h)s_h^2/n_h \tag{8}$$

where $f_h = n_h/N_h$ is the sampling fraction, and $s_h^2 = \sum(y_{hj} - \bar{y}_h)^2/(n_h-1)$ is the sample variance in the h'th stratum (for details, see, e.g., Cochran 1977). In marine surveys the sampling fraction is generally very small, and, hence, can safely be ignored.

The above estimators are unbiased with respect to the survey design and, hence, do not depend on any assumptions about the target population itself (see, e.g., Thompson 1992). If the same population is sampled repeatedly, using identical survey design, the survey estimates may be higher or lower than the "true" values. However, the mean of estimates for all possible samples equals the true population values. In the statistical literature, estimators with this important property are often referred to as design-unbiased.

3.2. The delta estimator

Data on number of crabs caught per tow (or area swept) from the winter dredge surveys typically contain a large proportion of zero-values. The distribution of catch-per-tow is generally highly skewed, and as a result the ordinary sampling estimates of the mean and its variance may not be efficient, especially for small sample sizes. It may be assumed that the fraction of the samples with zero-catch provide an estimate of the fraction of the Bay with unsuitable habitat for overwintering. The delta method (Pennington 1983), which in effect is a post-stratification scheme, separates the zero-values and the positive catches in the estimation procedure. For simplicity, the strata indexes have been omitted in the equations to follow. Let $x = x_1, x_2, x_2, ..., x_m$ be the vector of observations from the m samples with positive catches in stratum h. If the $\log_e$-transformed values of x follow a normal distribution, and the variance of $\ln(x)$ is large, then an estimate of the population mean (i.e. the mean of $Y_{h,1}$, $Y_{h,2}$, $Y_{h,2}$, ..., $Y_{h,Nh}$) based on the delta-distribution may be considerably more efficient than the ordinary sample mean (Pennington 1983). Unbiased estimates of the mean and its variance from the delta-distribution is given by (Pennington 1983)

$$(a) \qquad \bar{y}_\Delta = \begin{cases} (m/n)\exp(\bar{z})G_m(s^2/2), & m > 1 \\ x_1/n, & m = 1 \\ 0, & m = 0 \end{cases} \tag{9}$$

and

$$Var(\bar{y}_\Delta) = \begin{cases} (m/n)\exp(2\bar{z})\left\{(m/n)G_m^2(s^2/2) - [(m-2)/(n-1)]G_m[s^2(m-2)/(m-1)]\right\}, & m > 1 \\ (x_1/n)^2, & m = 1 \\ 0, & m = 0 \end{cases} \tag{10}$$

where $\bar{z}$ and s^2 are the sample mean and sample variance, respectively, of the log of the x's and

$$G_n(t) = 1 + \frac{n-1}{n}t + \sum_{j=2}^{\infty} \frac{(n-1)^{2j-1}}{n^j(n+1)(n+3)\ldots(n+2j-3)} x \frac{t^j}{j!}.$$

3.3. Estimation of proportions

In order to characterize the size and sex composition of the population, the proportions (p) of crabs falling in 3 size groups, by sex, are estimated. The size categories (carapace width, CW) are as follows: group 0: CW $<$ 50 mm; group I: 50 $\leq$ CW $<$ 120 mm; and group II: CW $\geq$ 120 mm (see Rothschild et al. 1992). It is believed that size group 0, I and II approximately correspond to 0, 1 and 2+ year old crabs, respectively. Due to the size selectivity of the standard sampling gear, number of crabs in size category 0 is biased: crabs less than 15 mm are caught only sporadic.

Since crabs are caught in clusters, statistical methods based on the assumption that samples of individuals are independent, identically distributed (IID), such as the binomial or multinomial distributions for estimating proportions, are not valid (see Brier 1980; Fay 1985; Roland Thomas and Rao 1987; Skinner et al. 1989). The sampling unit in the blue crab survey is the individual tow, and not the individual crab (see Pennington and Vølstad 1994a). Hence, a ratio estimator is used for estimating the proportion of blue crabs within a specific size or sex group (see Cochran 1977).

Assume that in each of L strata (indexed by h = 1, 2, 3, ..., L), n_h stations are randomly chosen, and $y_{i,h}$ crabs are caught at the i^{th} station ($y_{i,h}$ can equal 0). Let $a_{i,h}$ be the number of crabs at the i^{th} station in stratum h falling in class C (e.g. females of age-group II), and let $p_{i,h}=a_{i,h}/y_{i,h}$. A sample estimate of the proportion, p_h, falling in class C in the population in stratum h (Cochran 1977, p.66) is

$$p_h = \frac{\sum_{i=1}^{n_h} a_{i,h}}{\sum_{i=1}^{n_h} y_{i,h}} \tag{11}$$

and an estimate of the variance of p_h is

$$Var(p_h)=\frac{\Sigma a_{i,h}^{\ 2}-2p_h\Sigma a_{i,h}y_{i,h}+p_h^2\Sigma y_{i,h}^{\ 2}}{n_h\bar{y}^2(n_h-1)} \qquad (12)$$

where summation is over all stations (n_h) in stratum h.

The ratio estimator is slightly biased, but the bias is small for large sample sizes. For sample sizes of, say, less than 30 a jackknife estimator would be more efficient (see, Efron and Gong 1983; Wu and Deng 1983; Pennington and Vølstad 1994a). For estimating the proportion falling in class C in the entire population (i.e. in all strata), the areal stratification of dredge stations needs to be taken into account. In order to take into account the areal stratification, we use the combined ratio estimator (Cochran 1977) to estimate proportions of the overall population (p_{st}) in class C.

Or

$$p_{st}=\frac{\Sigma w_h a_h}{\Sigma w_h y_h} \qquad (13)$$

where for the h^{th} stratum w_h is the proportion of the survey area in the stratum, a_h is the total number of crabs in class C caught in the stratum, and y_h is the total number of crabs (all classes) caught in the stratum. The variance of p_{st} is estimated by jackknifing (Særndal et al. 1992, p440).

3.4. Depletion estimates of gear efficiency

For management purposes estimates of the total harvestable stock size is important, especially for short-lived species. Average catch per square meter from the winter survey provides an estimate of the relative density of blue crabs over the survey area. If catchability is constant between years, estimates of changes in stock size in the survey area would be unbiased. However, in order to obtain absolute estimates of the stock size it is necessary to know the catchability of the dredge (q), i.e. what percentage of the crabs existing in the area covered by a dredge tow is actually caught, on average. Depletion experiments may provide reliable estimates of catchability for a closed population, i.e. with no new crabs coming in to the area, and no loss of crabs due to natural mortality or emigration. The general concept of such gear-efficiency experiments is to measure the effect of removal of crabs from the study area on the catch per unit effort (see Hilborn and Walters 1992).

Gear efficiency may vary between years, areas and vessels. In order to obtain a more reliable time series for monitoring changes in the abundance of blue crab, catchability coefficients estimated from depletion experiments could possibly be used to correct for spatial and temporal changes in catchability. The spatial distribution of blue crabs is typically highly patchy, and a few tows with high catches may dominate the estimated average number of crabs per m^2. Hence, it is particularly important to have accurate estimates of catchability for areas with high density of crabs.

From December through March, blue crabs are largely inactive, buried in the bottom sediments. Hence, they are less likely to escape the dredge by swimming. Orth and van Montfrans (1987) reported negligible catches from bottom trawls during winter, supporting the hypothesis that crabs are buried in the substrate (see also Rothschild et al. 1991). Also, fishery activity is at a minimum; only crabs in the Virginia mainstem are harvested during winter. Since each depletion experiment is conducted over a short time period (2-4 hours), it is reasonable to assume that the population in the study area is closed for immigration or migration.

3.4.1. Experimental design

In Maryland waters with depth ≥ 5 ft, an area of approximately 100 m by 5.5 m were covered 10 times ($i=10$) by dredging (for details, see Rothschild et al. 1992, Appendix A). For the experiments conducted by VIMS, the area was 100 m by 9 m. Each coverage of the area consisted of 3 (UMCEES) or 5 (VIMS) parallel non-overlapping dredge tows conducted within an area marked by buoys. A maximum of 10 coverage of the area was completed for each experiment. In shallow waters (depth < 5 ft), UMCEES conducted two gear efficiency studies within an area of 100 m by 3.2 m.

3.4.2. Models for estimating catchability

Two models are used for estimating the dredge efficiency (q). Model 1 is a standard Leslie model (Leslie and Davis 1939):

$$y_i = q[P_0 - K_{i-1}] = qP_0 - qK_{i-1} \qquad \textbf{(14)}$$

where y_i is the catch in the i'th coverage, and K_{i-1} is cumulative catch taken prior to each coverage. P_0 is the initial population in the area, prior to the fishing experiment. The catchability coefficient q is simply the slope of the regression-line estimated from Model 1. In this model the basic assumption is that the depletion of the population by each dredge coverage is measured without error. An implication this assumption is that if the i'th coverage in a particular depletion experiment has zero catch, then the cumulative catch provide an absolute measure of the initial population P_0. However, some crabs may in fact remain in the experimental area although zero are caught in an individual coverage by the dredge, resulting in an under-estimate of P_0 and an over-estimate of catch efficiency (q).

A different technique (Model 2) may be used for estimating the dredge efficiency: For each coverage (i) of the experimental area, we can assume that a proportion q of the true population in the area are removed. Hence, the catch (y_1) in the 1st coverage is q multiplied by P_0, the initial population, and for the i'th coverage, we have:

$$y_i = q(1-q)^{i-1}P_0e^{\epsilon}$$

which is linear on the log-scale:

$$\log y_i = \log(q) + \log P_0 + \{\log(1-q)\}(i-1) + \epsilon. \qquad \textbf{(15)}$$

In the following, eq. 15 is referred to as Model 2. A simple regression of log y_i against (i-1) provide estimates of the slope, $\log(1-q)$, and the catchability coefficient (q) is obtained by a re-transformation. In this model, it is (perhaps more realistically) assumed that a proportion (estimated with an error ϵ) of the population is removed in each coverage.

If catchability is related to the number of crabs in the path of the dredge, then estimates of q from experimental areas with high abundance of crabs should have more weight than estimates from areas with low abundance. An estimator for the overall correction factor to employ for the dredge survey is

$$\bar{q} = \Sigma c_i q_i / C \qquad \textbf{(16)}$$

where c_i is the total number of crabs caught in the i'th experiment, q_i is the corresponding estimated gear efficiency, and C is total number of crabs caught in the n experiments. Since the number of experiments (n) is small, the jackknife estimate of the average gear efficiency and its standard error is used (Cochran 1977; Efron and Gong 1983). The jackknife estimator for standard error is

$$\sigma = \{[(n-1)/n]\Sigma(\mu_{(i)} - \mu_{(.)})^2\}^{1/2} \qquad \textbf{(17)}$$

where

$$\mu_{(i)} = \sum_{i \neq j} c_i \bar{x} / (C - c_j)$$

is the weighted mean catchability deleting the *n*th experiment and

$$\mu_{(\cdot)} = \sum \mu_{(i)} / n$$

is the jackknife estimate of $\bar{q}$ for the *n* experiments.

4. THE 1992/93 DREDGE SURVEY: RESULTS AND CONCLUSIONS

4.1. Estimates of cost-efficiency.

Onboard one survey vessel contracted by UMCEES in 1992/93, data were collected daily on: 1) total survey cost, i.e., time elapsed (in minutes) between first and last station, *C*; 2) number of stations sampled, *n*; and 3) average time to conduct a tow, c_1. Results for the 18 day survey period are in Table 3. The time required per station to collect sediment samples, t_s, is approximately 1 minute. A total of 388 stations were sampled, averaging 21.6 stations per day. An estimated 287 stations could be sampled if double-tows were taken at each station, an average of 16 stations per day. This compares favorably with 1991/92 survey results from the same area, when an average of 16.5 double-tow station were sampled per day using the same vessel and crew.

During the 1992/93 survey, 964 stations with single-tows were sampled in waters $\geq$ 5 ft. The precision ($k = cv/\sqrt{n}$) of this survey's stratified mean catch per 1000 m^2 swept is $k = .09$. In the 1990/91 survey, 823 stations were sampled in 25 strata using double-tows; this resulted in a precision of $k = .07$ for estimated stratified mean density. In the 1991/92 survey, 1266 stations with double-tows were sampled in 6 strata, resulting in a precision of $k = .13$. Survey cost in 1992/93, measured in number of boat-days, was lowered more than 30% from 1991/92. Furthermore, the survey area was increased more than 20 % relative to previous years.

4.2. Estimates of relative abundance and population characteristics

The average numbers of crabs caught per 1000m^2 swept (all size and sex groups combined) by geographic strata and depth intervals are in Table 4. Estimates of relative abundance for intermediate depths (5-40 ft) is significantly higher than for deeper waters ($\geq$ 40 ft). Tables 5 and 6 present relative abundance estimates for size classes 0 and I+II, respectively. Estimated relative abundance for any of these size classes does not significantly differ between the three depth intervals. These results suggest that abundance in shallow and deep waters is substantial. Therefore, surveys not covering these depths will result in biased estimates of abundance.

On average, the delta estimator provides more precise estimates of relative abundance than the usual mean, or stratified mean estimator. However, due to relatively low variability in $\log_e$ transformed non-zero values ($x = x_1, x_2, x_2, ..., x_m$), the estimator of mean density, based on the Δ-estimator, is only slightly more efficient than the ordinary sample mean. In contrast, if the variance of $\ln x$ is high, the delta estimator could be substantially more efficient (see Pennington 1983). Nevertheless, the delta-estimator is recommended since the resulting estimates generally are more precise, at no extra cost. Although the distribution of catch-per-tow is highly skewed, the ordinary sample mean would have a fairly normal distribution for large sample sizes, according to the central limit theory.

Proportions of the population in size categories 0, I and II, for males (M) and females (F), are in Table 7. These results provide further evidence that the size and sex composition of blue crab is highly variable across the Bay, with a significant part of the mature female population (F2) in Virginia waters (see also Van Engel 1958, 1962). Such indications of areal stratification by size and sex is important for effective management of the blue crab fishery. For example, the female population may be particularly vulnerable to the winter dredge fishery in Virginia waters (Stratum 3). However, the ratio of males to females in the total population does not significantly differ from 1:1 for any of the three size classes.

Since proportions (p) by sex and size vary significantly between strata, one expects stratified estimates (p_{st}) for the entire Chesapeake Bay, based on the combined ratio estimator (eq. 13), to be more precise than estimates from a simple random sample. Nonetheless, ratio estimates (eq. 11) of proportions of the population in different size and sex classes, based on the 854 "random stations", are as precise as estimates from the combined ratio estimator (Tables 7 and 8). Variances of the ratio estimates are based on eq. 12, and variances of the combined ratio estimates are based on jackknifing of eq. 13. One explanation for the relatively low efficiency of the combined ratio estimator, is that the total number of crabs (y_h) by strata is unknown, and therefore has to be estimated. The uncertainty of these estimates counteracts the gain from areal stratification.

Estimates of the number of crabs in size class 0 (CW < 50 mm) is negatively biased as result of size selectivity of the dredge. To reduce such bias, we have also estimated proportions by size and sex for size groups I and II (CW $\geq$ 50 mm); results are in Table 8. It is estimated that the population of crabs in size categories I and II consist of 45 % females. However, the ratio of males to females does not differ significantly from 1:1. If comparisons are made between different size and sex classes, it should be noted that variances for different classes are correlated, due to intra-haul correlation by size and sex (Table 9). Size frequency distributions by depth for each strata are in Figures 3-5. We have not tested for significant differences in these frequency distributions. Since crabs are sampled in clusters, and the intra-cluster correlation for size is relatively high, the chi-squared or Kolmogorov-Smirnof tests for differences in size frequencies are likely to yield extremely erroneous results (see Skinner et al. 1989). Resulting from such intra-cluster correlation, the s.e.'s of proportions in various size classes by sex, based on the ratio or combined ratio estimators, are significantly higher than the (erroneous) estimates based on binomial or multinomial distributions. The multinomial distribution typically yields estimates of proportions by size and sex with s.e.'s that are only half the size of the ratio estimates (Pennington and Vølstad 1994b).

4.3. Estimates of gear efficiency

Table 10 presents estimates of gear-efficiency for the standard Virginia crab dredge, for 12 depletion experiments conducted by UMCEES, and 4 experiments conducted by VIMS, during 1992/93. The average catchability coefficient, and its standard error, is estimated to be $\bar{q}$ = 0.14 (s.e.=.03) using Model 1 (eq. 14), while Model 2 (eq. 15) yields $\bar{q}$ = 0.15 (s.e.=.04). Four similar experiments conducted by VIMS yielded $\bar{q}$ = 0.20 (s.e.=.02) and $\bar{q}$ = .19 (s.e.=.02) using the same models, respectively. Based on 28 depletion experiments conducted by UMCEES during 1991/92, the estimates of average q and its s.e. (weighted by the cumulative catch in each experiment) is 0.13 (s.e.=.06) based on Model 1, and 0.13 (s.e.=.07) based on Model 2 (Table 11). The s.e.'s are based on jackknifing of eq. 17; the q's from individual experiments are assumed to be independent. In comparison, the method used by Rothschild et al. (1992) resulted in a gear efficiency, q = .26 for the 1991/92 experiments.

Higher gear-efficiency for the Virginia experiments, although not significantly different from the UMCEES estimates, could be a result of the experimental design. In several of these experiments only 5 coverage were completed, while 10 coverage have generally been completed in the Maryland experiments. The slopes of the regressions from eqs. 14 and 15 provide estimates of gear efficiency. Estimates of the slopes for Models 1 and 2 are likely to be more accurate if the independent variables (i.e. cumulative catch, K_i;

or coverage, *i*) have a wider range. For example, estimates of gear efficiency based on only the first 5 out of the 10 coverage completed in the Maryland experiments were generally higher than estimates based on all 10 coverage. This indicates that fewer coverage can result in a negative bias for depletion estimates of gear efficiency. Differences in gear efficiency may also result from vessels (and area) effects. Based on experiments conducted by two vessels in Maryland waters, we could not detect significant differences in catchability. A randomized block experiment, involving all 3 vessels, would be an efficient design for testing such differences in catchability.

Two efficiency experiments conducted by MDNR and UMCEES to estimate catchability of the modified oyster dredge used to sample shallow waters, yielded a negative estimate of catchability. This could result from factors such as: 1) navigation errors; 2) unfavorable bottom conditions; 3) strong currents; or 4) crab behavior.

We recognize that the number of crabs removed by dredging (y_i), and the "true" abundance (P_0) in the experimental area is estimated from the same data, i.e. they are not independent (eqs. 14 and 15). For such reasons, estimates of q, and its s.e., for individual experiments must be interpreted carefully. Ideally, an independent measure of abundance would be available after each coverage of an area by the dredge. However, to our knowledge there is presently no available method for obtaining such independent estimates for depths greater than 5 feet.

For shallow waters (< 5 ft), the suction sampling method used by VIMS could possibly be used to obtain independent estimates of abundance in the experimental area between each coverage by the dredge. An effort was made by UMCEES and VIMS to combine suction sampling and dredging in the same experimental area. However, these experiments were not successful due to logistic constraints. Suction sampling is generally limited to depths less than 4 ft. Dredging is limited to depths greater or equal to 3 ft. This narrow overlap, combined with tidal affects, made it very difficult to conduct efficient studies using both sampling methods.

Gear-saturation effects

For soft sediments, the dredge may be saturated before a one minute tow is completed. If so, the catch per minute (or area swept) would be expected to decrease for longer tow durations. To investigate such gear-saturation effects, double-tows were taken at 77 randomly selected stations in the Maryland part of the Bay. One tow of 1 minute duration, and one tow of 30 seconds duration were taken in random order at each station. Average catch per minute for the half-minute tows was 3.671 (s.e. = .799), compared to 2.342 (s.e. = .738) for the 1 min tows. The higher CPUE for half-minute tows, although not significant, may also be explained if the dredge is towed along the bottom for some time after the start of haul back. Such a delay would have a relatively larger effect on shorter tows.

4.4. Estimates of absolute abundance.

Absolute abundance of blue crabs in the winter population (N_s) are estimated by adjusting survey estimates of relative abundance (e.g., average catch per 1000m^2 swept) for gear efficiency (q), and then extrapolating for the entire survey area. The total survey area with depth $\geq$ 5 ft is approximately 10,000 km^2, and we have assumed that gear-efficiency, q = .15. Number of crabs landed, N_c, is based on the assumption that the average weight of an individual crab in the landings is 150g. Table 12 presents survey estimates of the absolute number of crabs (all size classes) for the winters of 1990/91 - 1992/93, along with estimates of the commercial landings of hardshell crabs during the following fishing season. Due to size selectivity of the dredge, survey estimates of the exploitable population (Table 12) in effect are for crabs with CW $\geq$ 15 mm. In Table 13 are survey estimates of crabs in size classes I and II, i.e. crabs with CW $\geq$ 50 mm.

If only crabs with CW $\geq$ 50 mm in winter can grow into legal size for harvest during the following fishing season, then estimates of (commercial) exploitation rate (last column in Table 13) seem unreasonably high. This is underscored by the fact that catches of peelers and softshell crabs, along with recreational harvest, are not included in the landings estimates. Hence, the total number of crabs harvested may be significantly higher than the estimates in Tables 12 and 13. In addition, the exploitable population estimated during winter is reduced by natural mortality before, and during, the fishing season. The survey could, also, under-estimate the harvestable population if: 1) the catchability estimates are too high; or 2) a substantial fraction of the population is outside the survey area, and migrates into the area as the season progresses. In order to obtain accurate estimates of the exploitation rate, these potential sources of error require further investigation. In particular, we recommend that gear-efficiency studies be conducted as part of any future dredge surveys.

Due to a lack of accurate methods for ageing blue crabs, little is understood about their actual growth rates in the wild. If, in fact, a significant fraction of blue crabs in size category 0 (CW $\leq$ 50 mm) in winter actually do grow into legal size by the following fishing season, then survey estimates of absolute abundance in size groups I and II could substantially under-estimate the harvestable population. If this is the case, survey estimates of the exploitable stock, based on size groups 0, I and II, would be more accurate (Table 12). These estimates of the rate of exploitation seem more realistic, and more stable between years. This hypothesis is further supported by the stable, or increasing, catch rates commonly observed in the commercial fishery as the season progresses.

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TABLE 1. Average numbers of crabs (all size classes) caught per $1000m^2$ swept ($\bar{y}$), by strata (L) for the 1990/91 winter survey for blue crab in the Chesapeake Bay. The actual standard error of the mean is s.e.(1); s.e.(2) and s.e.(3) are the expected standard errors for allocation proportional to strata areas and for Neyman allocation, respectively. The actual number of stations by strata is n_h; n_2 is proportional to area, and n_3 is proportional to SDxArea (Neyman allocation). Two tows were taken at each station; the estimates are based on the averages for the two tows at each station. The strata boundaries are defined in Rothschild et al. (1992). Strata areas are in km^2.

L	Area	$\bar{y}$	s.e.(1)	n_h	s.e.(2)	n_2	s.e.(3)	n_3
BCP	2420.7	8.27	1.31	92	.78	259	.96	170
CHE	2.1	95.09	15.94	6	27.61	2	27.61	2
CHP	181.0	29.88	4.66	23	5.13	19	4.76	22
EAB	142.3	14.06	2.51	71	5.46	15	5.13	17
FBY	2.6	54.79	8.96	11	21.01	2	21.01	2
GWI	17.1	22.17	4.73	16	13.38	2	13.38	2
HON	29.1	98.34	24.47	17	58.25	3	25.22	16
JAM	91.0	12.95	3.29	35	6.48	9	6.48	9
LCP	38.1	37.95	7.93	19	17.28	4	13.06	7
LVB	1364.9	7.37	1.39	53	.84	144	1.16	76
LWI	2.1	119.45	24.81	7	46.42	2	46.42	2
ACP	890.1	7.30	1.71	45	1.18	95	1.52	57
MOB	91.0	19.66	2.65	55	6.55	9	6.21	10
NDA	5.1	31.40	15.10	3	18.49	2	18.49	2
NTC	27.1	54.09	8.70	10	15.88	3	13.76	4
OCC	1.7	10.74	4.00	8	8.00	2	8.00	2
ONA	2.7	40.17	6.33	4	8.95	2	8.95	2
PIA	29.8	36.46	5.06	33	16.78	3	14.53	4
POC	158.1	8.63	1.78	81	4.05	16	4.28	14
POT	767.4	12.70	3.02	16	1.33	82	1.69	51
PAX	82.6	17.23	5.23	21	8.47	8	7.23	11
RAP	208.7	12.75	5.96	38	7.83	22	5.67	42
TNG	430.3	42.33	3.93	56	4.34	46	3.52	70
UBY	613.9	20.71	7.50	70	7.78	65	4.28	215
YRK	92.4	17.26	5.45	33	9.90	10	7.83	16
All	7691.9	13.38	.91	823	.86	826	.67	825

TABLE 2. Average catch in numbers of crabs per $1000m^2$ ($\bar{y}$) by strata for the 1991/92 winter survey for blue crab in the Chesapeake Bay. Geographic strata (L): 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay. The actual standard error of the means is s.e.(1); s.e.(2) and s.e.(3) are the expected standard errors for allocation proportional to strata areas and for Neyman allocation, respectively. The actual number of stations by strata is n_h; n_2 is proportional to area, and n_3 is proportional to Sdxarea (Neyman allocation). Two tows were taken at each station. Area is in km^2. Sediment is in percent gravel. In the last row is the stratified mean and s.e.'s of the different allocation schemes.

L	Sed.	Area	$\bar{y}$	s.e.(1)	n_h	s.e.(2)	n_2	s.e.(3)	n_3
1	0-80	804	9.98	1.70	47	1.05	123	1.50	60
	80-100	873	3.12	.88	33	.44	133	.96	28
2	0-80	1469	5.80	.59	235	.60	224	.98	85
	80-100	1331	2.42	.52	102	.37	203	.78	44
3	0-80	3258	9.25	1.83	723	2.21	499	1.54	1025
	80-100	553	3.72	.59	126	.72	84	1.38	23
All	All	8288	6.60	.76	1266	.88	1266	.67	1266

Table 3. Daily observations of the cost associated with dredge sampling conducted by Chesapeake Biological Laboratory during the 1992/93 winter survey for blue crabs in Maryland. The last two columns contain the actual number of single-tow stations and the predicted number of stations (from eq. 4) to be had if double-tows were taken at each location.

C	c_1	c_2	n_1	n_2
408	2.0	68.6	24	20.1
292	4.0	50.2	17	12.6
295	4.5	58.3	14	10.6
488	4.5	63.1	28	20.3
390	4.0	53.0	25	18.2
349	4.5	44.3	24	16.8
170	4.0	29.1	13	9.1
370	4.0	47.1	26	18.6
415	4.0	97.1	13	10.7
530	3.5	98.4	20	16.4
365	3.5	85.0	13	10.8
295	4.0	43.6	20	14.4
280	3.0	33.1	27	19.3
316	3.5	37.4	27	19.1
50	3.0	13.4	5	3.5
482	3.5	54.9	35	25.6
567	3.0	70.5	36	27.8
290	4.5	42.6	19	13.4

Table 4. Average number (all size classes) of crabs caught per 1000 m^2 in the 1992/93 winter dredge survey for Blue crab in the Chesapeake Bay. Stations are randomly selected within each geographic strata (L) and depth interval. Geographic strata (L): 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay. The strata weights are $w_h = n_h/\Sigma n_h$; and $k = cv/\sqrt{n}$ is a measure of relative precision.

		Sample statistics					Delta-estimates			
L	Depth	$\bar{y}$	S.E.	k	n_h	n	$\bar{y}_\Delta$	S.E.	k	m
1.	<5	4.33	1.32	.39	77	105	4.01	1.02	.26	23
	[5-40)	14.97	1.59	.11	379	379	15.03	1.69	.11	181
	40+	10.09	1.41	.14	65	94	10.11	1.48	.14	56
2.	<5	23.10	10.19	.44	8	18	22.59	10.49	.46	10
	[5-40)	5.40	2.23	.41	175	175	4.67	1.51	.32	25
	40+	5.34	0.60	.11	95	157	5.29	0.60	.11	78
3.	[5-40)	3.93	.83	.21	113	113	3.74	.70	.19	36
	40+	5.30	.99	.19	27	46	5.27	1.00	.19	25
L	Depth	$\bar{y}_{st}$	S.E.	k_{st}	n_i	n	$\bar{y}_{st}$	S.E.	k_{st}	
1&2	<5	6.10	1.53	.25	85	123	5.76	1.35	.23	33
All	[5,40)	10.59	1.09	.10	667	667	10.40	1.05	.10	242
All	40+	6.99	.59	.08	187	297	6.97	.62	.09	159
All	≥5	9.80	.86	.09	854	964	9.65	.83	.09	401

Table 5. Average number of crabs in size group 0 caught per 1000 m^2 in the 1992/93 winter dredge survey for Blue crab in the Chesapeake Bay. Stations are randomly selected within each geographic strata and depth interval. Geographic strata (L): 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay. The strata weights are $w_h = n_h/\Sigma n_h$; and $k = cv/\sqrt{n}$ is a measure of relative precision.

		Sample statistics					Delta-estimates			
L	Depth	$\bar{y}$	S.E.	k	n_h	n	$\bar{y}_\Delta$	S.E.	k	m
1.	<5	1.66	.54	.34	77	105	1.54	.47	.31	14
	[5-40)	6.40	.84	.13	379	379	6.33	.86	.14	105
	40+	6.49	1.10	.17	65	94	6.23	.95	.15	48
2.	<5	15.37	8.74	.57	8	18	14.97	9.05	.60	6
	[5-40)	3.28	1.59	.49	175	175	2.83	1.15	.41	16
	40+	1.57	0.34	.22	95	157	1.57	0.35	.22	24
3.	[5-40)	.45	.23	.52	113	113	.44	.23	.51	5
	40+	0			27	46	0			25
L	Depth	$\bar{y}_{st}$	S.E.	k_{st}	n_i	n	$\bar{y}_{st}$	S.E.	k_{st}	
1&2	<5	2.90	.96	.33	85	123	2.80	.95	.34	20
All	[5,40)	4.57	.64	.14	667	667	4.41	.58	.13	126
All	40+	2.88	.39	.09	187	297	2.80	.35	.09	72
All	≥5	4.24	.50	.12	854	964	4.10	.46	.11	198

Table 6. Average number of crabs in size groups I+ caught per 1000 m^2 in the 1992/93 winter dredge survey for Blue crab in the Chesapeake Bay. Stations are randomly selected within each geographic strata (*L*) and depth interval. Geographic strata (*L*): 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay. The strata weights are $w_h = n_h/\Sigma n_h$; and $k = cv/\sqrt{n}$ is a measure of relative precision.

		Sample statistics					Delta-estimates			
L	Depth	$\bar{y}$	S.E.	k	n_h	n	$\bar{y}_\Delta$	S.E.	k	m
1.	<5	2.73	1.20	.44	77	105	2.38	.82	.34	15
	[5-40)	8.57	1.29	.15	379	379	7.79	.96	.12	134
	40+	3.60	.84	.23	65	94	3.56	.82	.23	24
2.	<5	7.73	2.72	.35	8	18	7.60	2.64	.35	9
	[5-40)	2.13	.82	.38	175	175	1.87	.61	.33	19
	40+	3.77	.45	.12	95	157	3.71	.43	.11	68
3.	[5-40)	3.48	.64	.22	113	113	3.34	.64	.19	33
	40+	5.30	1.00	.19	27	46	5.27	1.00	.19	25
L	Depth	$\bar{y}_{st}$	S.E.	k_{st}	n_i	n	$\bar{y}_{st}$	S.E.	k_{st}	
1&2	<5	3.20	1.12	.35	85	123	2.87	.77	.27	24
All	[5,40)	6.02	.77	.13	667	667	5.48	.58	.11	186
All	40+	3.93	.40	.10	187	297	3.88	.39	.10	117
All	≥5	5.56	.61	.11	884	964	5.13	.46	.09	303

TABLE 7. The proportion of the blue crab population in distinctive sex and size groups by strata (L) for 1992/93. The estimates of p_h and its standard error for each class is based on the ratio estimator (eqs. 11 and 12). Geographic strata (L): 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay. The overall population estimates for areas with depth ≥ 5 ft are based on the combined ratio estimator (eq.13). The s.e. is estimated by jackknifing. In the last row is estimates from 854 stations selected proportional to strata area (depth ≥ 5 ft.), treated as a random sample.

			M0		M1		M2		F0		F1		F2	
L	D	n	p	s.e.	p	s.e.	p	s.e.	p	s.e.	p	s.e.	p	s.e.
1	< 5	105	.31	.10	.51	.10	.02	.02	.11	.05	.04	.03	.00	.00
	5-40	379	.21	.03	.22	.02	.16	.03	.20	.03	.16	.02	.05	.01
	40+	94	.28	.04	.09	.02	.10	.04	.38	.06	.06	.02	.09	.03
2	< 5	18	.48	.06	.24	.09	.00	.00	.21	.05	.07	.04	.00	.00
	5-40	175	.23	.06	.13	.07	.07	.04	.40	.10	.08	.02	.11	.07
	40+	157	.10	.03	.07	.10	.10	.03	.20	.04	.11	.03	.43	.05
3	5-40	113	.09	.04	.07	.01	.01	.01	.04	.01	.01	.01	.78	.09
	40+	46	.00	.00	.04	.02	.02	.02	.00	.00	.00	.00	.94	.03
All	≥ 5	964	.20	.02	.18	.02	.13	.02	.23	.02	.13	.02	.13	.01
All	≥ 5 RS	854	.20	.02	.18	.02	.14	.02	.22	.02	.13	.02	.14	.02

TABLE 8. The proportion of the blue crab population in distinctive sex and size groups by strata (L) for 1992/93, relative to total number of crabs of size class I+. Geographic strata (L): 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay. The estimates of p_h and its standard error for each class is based on the ratio estimator (eqs. 11 and 12). The overall population estimates for areas with depth ≥ 5 ft are based on the combined ratio estimator (eq.13). The s.e. is estimated by jackknifing. In the last row is estimates from the 854 stations selected proportional to strata area, treated as a random sample.

			M1+M2		M1		M2		F1+F2		F1		F2	
L	D	n	p	s.e.	p	s.e.	p	s.e.	p	s.e.	p	s.e.	p	s.e.
1	< 5	105	.92	.04	.88	.05	.04	.02	.08	.04	.08	.03	.00	.00
	5-40	379	.65	.03	.38	.03	.27	.03	.35	.03	.27	.02	.08	.01
	40+	94	.57	.08	.27	.07	.30	.04	.43	.08	.18	.02	.25	.06
2	< 5	18	.77	.12	.77	.12	.00	.00	.23	.12	.23	.04	.00	.00
	5-40	175	.52	.11	.34	.11	.18	.04	.48	.11	.20	.02	.28	.15
	40+	157	.24	.04	.09	.04	.14	.03	.76	.05	.15	.03	.61	.05
3	5-40	113	.19	.04	.08	.04	.01	.01	.90	.04	.01	.01	.89	.05
	40+	46	.06	.03	.04	.03	.02	.02	.94	.03	.00	.00	.94	.03
All	≥ 5	964	.20	.02	.31	.02	.23	.02	.22	.02	.22	.02	.24	.02
All	≥ 5 RS	854	.20	.02	.18	.02	.14	.02	.22	.02	.13	.02	.14	.02
All		1027	.56	.02	.34	.02	.22	.02	.44	.02	.22	.02	.22	.01
All	RS	942	.55	.03	.32	.03	.22	.02	.45	.03	.22	.02	.23	.03

TABLE 9. Sample correlations between number of crabs per tow of males and females falling in size groups 0, I and II. Estimates are from 942 stations allocated proportional to strata areas.

	F0	F1	F2	M0	M1	M2
F0	1.00					
F1	.14	1.00				
F2	-.03	.12	1.00			
M0	.61	.10	-.03	1.00		
M1	.22	.56	.06	.23	1.00	
M2	.02	.53	.17	.02	.52	1.00

TABLE 10. Estimates of dredge efficiency (q) from depletion experiments carried out by UMCEES and VIMS in 1992/93, using the standard deep-water dredge. Estimates for Model 1 is based on eq. (14), and for Model 2 on eq. 15. For the UMCEES experiments, the jackknife estimates of average q and s.e., weighted by the cumulative catch in each experiment, is 0.14 (s.e.=.03) and 0.15 (s.e.=.04) from the two models, respectively (eqs. 16 and 17). For the VIMS experiments (in the last four rows), the weighted average q for the two models is .20 (s.e.=.02) and .19 (s.e.=.02).

Model 1			Numb. of		Model 2		
q	s.e.	R^2	crabs	Inst.	q	R^2	DF
.13	.04	.58	88	CBL	.10	.38	9
.06	.03	.30	327	-	.06	.31	9
.07	.05	.18	67	-	.08	.22	9
.13	.05	.39	19	-	.11	.39	8
.14	.05	.51	121	-	.18	.56	9
.01	.03	.02	88	-	.01	.04	9
.10	.04	.42	180	-	.09	.37	9
.22	.05	.66	223	-	.32	.73	9
.30	.08	.65	73	-	.19	.36	9
.30	.03	.91	102	-	.27	.77	9
.12	.04	.55	106	-	.17	.62	9
.79	.04	.99	5	-	.55	.99	2
.24	.05	.88	139	VIMS	.22	.85	4
.19	.15	.34	68	-	.24	.19	4
.17	.06	.71	129	-	.17	.55	4
.18	.05	.63	163	-	.16	.44	9

Table 11. Estimates of dredge efficiency (q) from depletion experiments carried out by UMCEES and MDNR in 1991/92, using the standard deep-water dredge. The jackknife estimates of average q and s.e., weighted by the cumulative catch in each experiment, is 0.13 (s.e.=.06) and 0.13 (s.e.=.07) from the two models, respectively. Estimates for Model 1 is based on eq. 14, and for Model 2 on eq. 15.

Model 1			numb. of	Model 2		
q	s.e.	R^2	crabs	q	R^2	DF
-0.14	.07	.48	518	-0.20	.61	5
.03	.06	.09	106	.02	.05	4
.22	.03	.93	235	.25	.90	5
.01	.05	.00	128	.00	.00	5
.13	.02	.89	180	.14	.87	6
.66	.10	.96	76	.68	.82	3
.29	.04	.93	175	.38	.88	5
.45	.06	.94	76	.33	.38	5
.32	.03	.96	73	.27	.93	5
.04	.09	.05	54	.04	.03	5
.15	.03	.84	79	.15	.85	5
.36	.04	.94	29	.30	.60	5
.32	.09	.78	137	.21	.38	5
.69	.09	.98	7	.59	.98	2
.42	.13	.83	19	.52	.85	3
.14	.10	.32	159	.15	.14	5
-.03	.11	.02	175	-.04	.04	5
.30	.13	.58	123	.47	.71	5
.59	.07	.97	15	.55	.98	3
.27	.06	.84	38	.33	.74	5
.26	.09	.67	36	.24	.45	5
.12	.06	.49	107	.17	.54	5
.28	.06	.83	129	.26	.53	5
-.11	.06	.55	318	-.11	.51	4
.38	.09	.85	36	.48	.88	4
.41	.12	.80	64	.53	.75	6
.32	.33	.33	25	.44	.42	3
.36	.09	.18	48	.26	.47	5
.03	.13	.01	45	.00	.00	5

Table 12. Survey estimates of the abundance of crabs (all size classes) in Chesapeake Bay (depth ≥ 5 ft.) during winter, along with estimates of commercial landings of hardshell crabs the following fishing season. The survey indices, $\bar{y}$, are average number caught per 1000m^2 swept. Survey estimates of absolute number of crabs (N_s) in the winter population are based on the assumptions that; 1) total area is 10,000 km^2, and 2) gear-efficiency, q = .15. Number of crabs landed, N_c, is based on the assumption that the average weight of an individual crab in the landings is 150g. Estimates of total number of crabs are in millions; landings are in million pounds. In the last column are total landings as percentage of the available population (not corrected for natural mortality).

	Survey estimates			Maryland landings		Virginia landings		MD+VA
Year	$\bar{y}$	N_s	.e.	Weight	$N_{c,MD}$	Weight	$N_{c,VA}$	$N_{c,tot}/N_s$
1991	13.4	893.3	60.7	48.0	144.0	43.5	130.5	.31
1992	6.6	440.0	50.7	31.4	94.2	23.3	69.9	.37
1993	9.8	653.3	57.3	51.0	153.0	NA	NA	⋗ .23

Table 13. Survey estimates of the abundance of crabs (size groups I+) in Chesapeake Bay (depth ≥ 5 ft.) during winter, along with estimates of commercial landings of hardshell crabs the following fishing season. The survey indices, $\bar{y}$, are average number caught per 1000m^2 swept. Survey estimates of absolute number of crabs (N_s) in the winter population are based on the assumptions that; 1) total area is 10,000 km^2, and 2) gear-efficiency, q = .15. Number of crabs landed, N_c, is based on the assumption that the average weight of an individual crab in the landings is 150g. Estimates of total number of crabs are in millions; landings are in million pounds. In the last column are total landings as percentage of the available population (not corrected for natural mortality).

	Survey estimates			Maryland landings		Virginia landings		MD+VA
Year	$\bar{y}$	N_s	.e.	Weight	$N_{c,MD}$	Weight	$N_{c,VI}$	$N_{c,tot}/N_s$
1991	4.5	300.0	NA	48.0	144.0	43.5	130.5	.92
1992	4.9	327.7	NA	31.4	94.2	23.3	69.9	.50
1993	5.5	366.7	40.7	51.0	153.0	NA	NA	⋗ .42

FIGURES

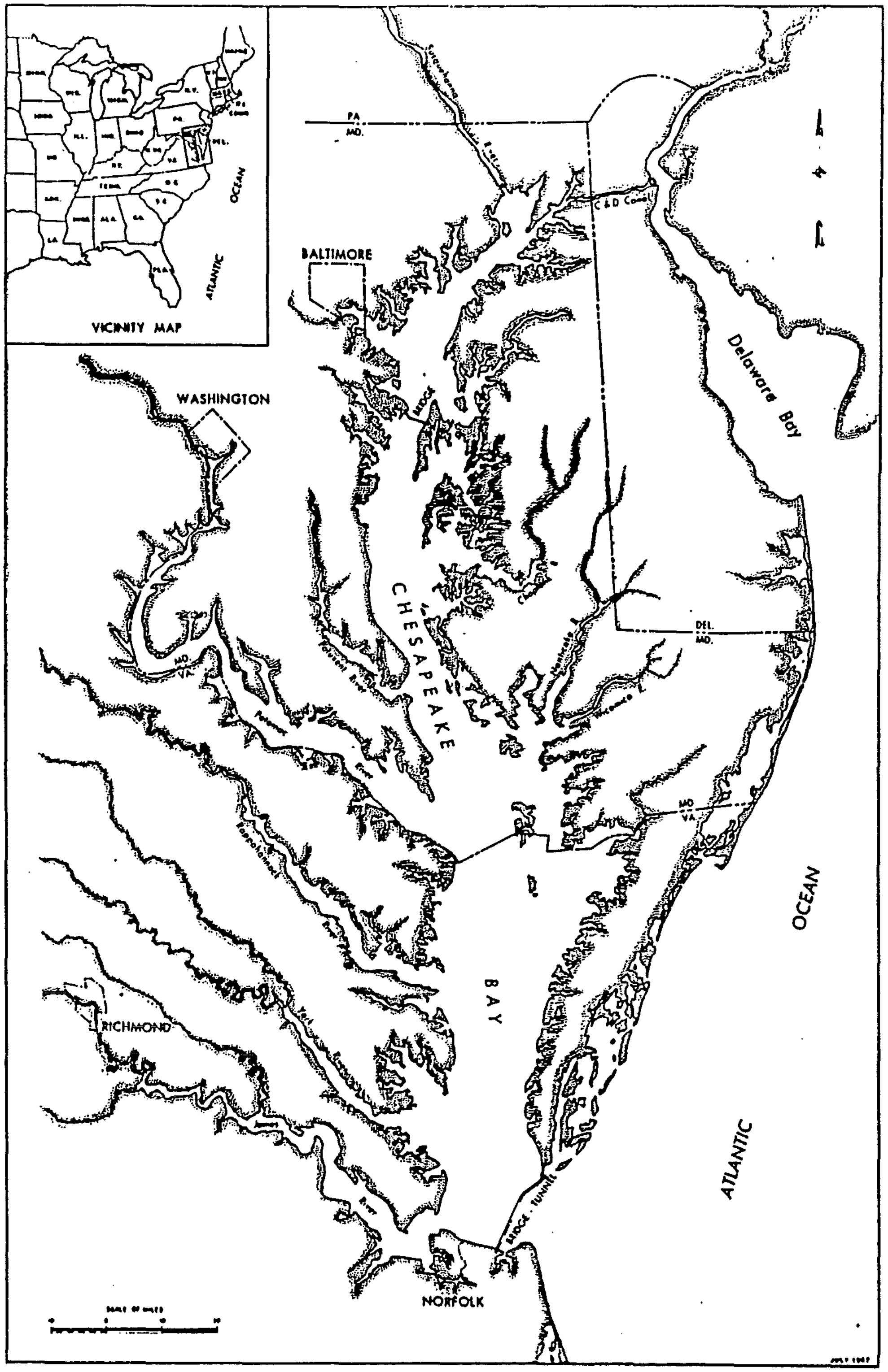

Figure 1. Map of the Chesapeake Bay and its tributaries.

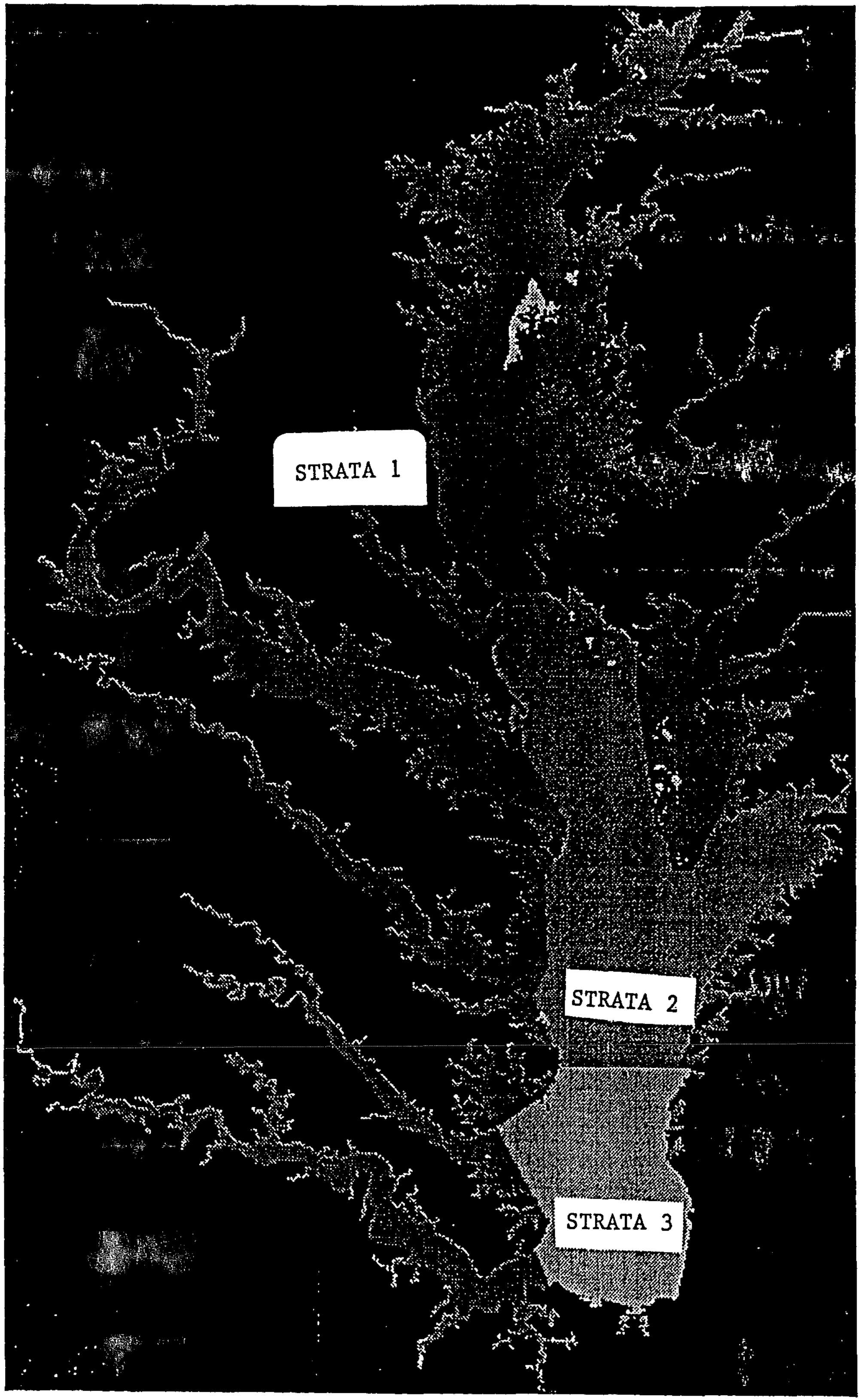

Figure 2. Map showing the 3 geographic strata employed during the 1992/93 winter dredge survey for blue crab in the Chesapeake Bay: 1) Upper Bay and Rivers; 2) Below Cove Point; and 3) Lower Virginia Bay.

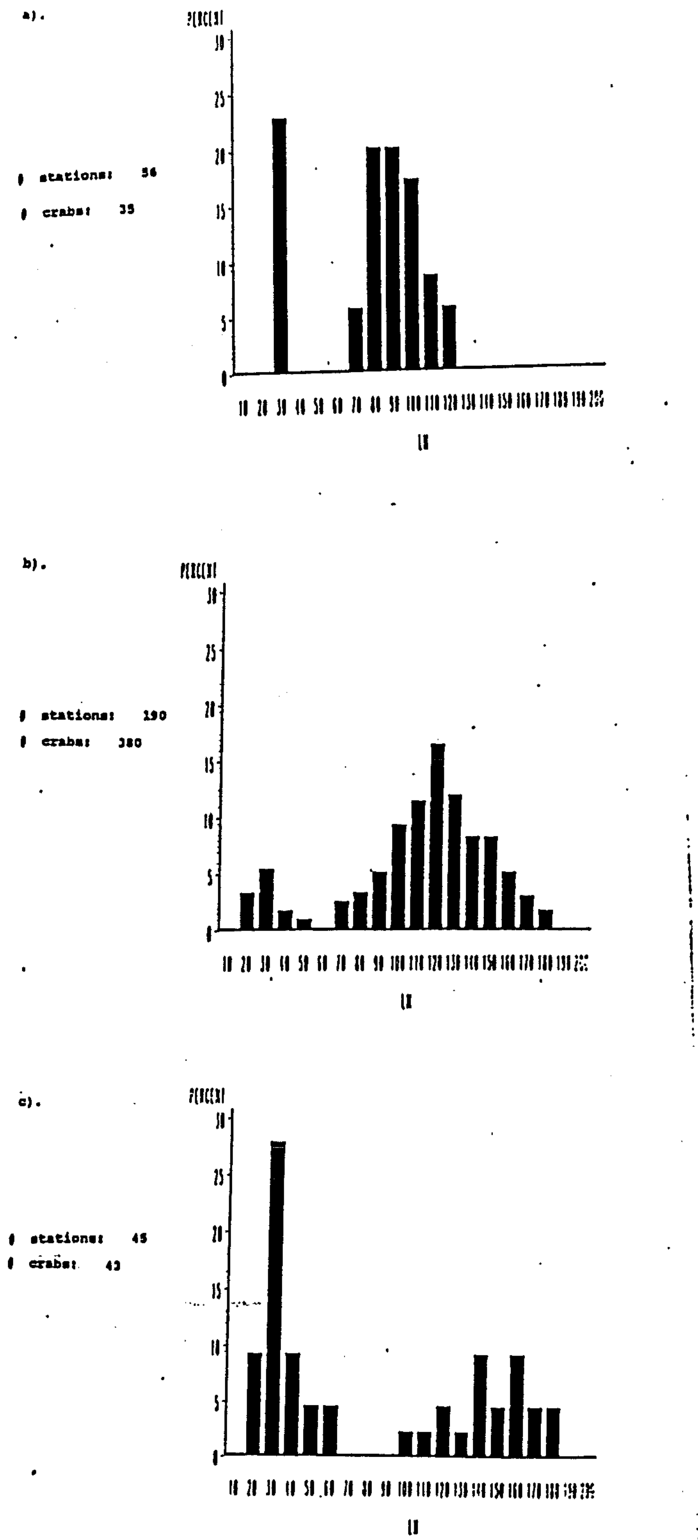

Figure 3. Size frequency of crabs caught in geographic Stratum 1, Upper Bay and Rivers. Substrata: A) depths < 5 ft; B) depths greater or equal to 5 ft and less than 40 ft; C) depth greater or equal to 40 ft.

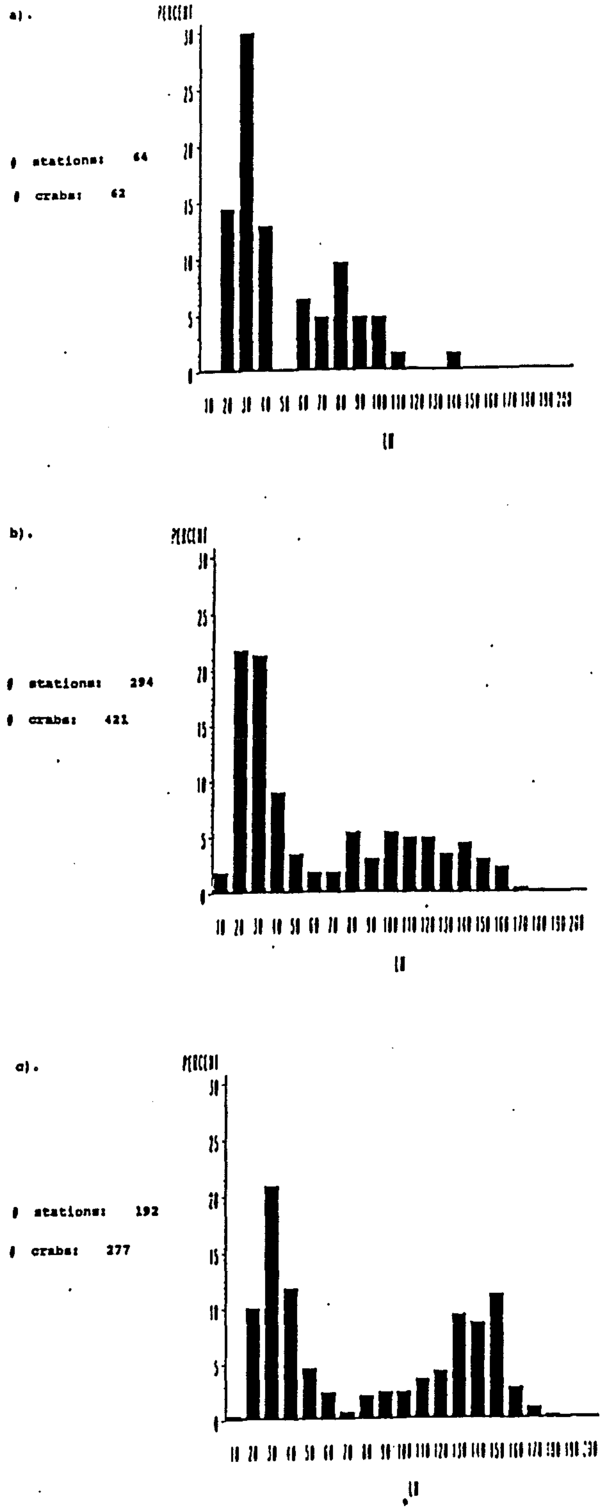

Figure 4. Size frequency of crabs caught in geographic Stratum (2), Below Cove Point. Substrata: A) depths < 5 ft; B) depths greater or equal to 5 ft and less than 40 ft; C) depth greater or equal to 40 ft.

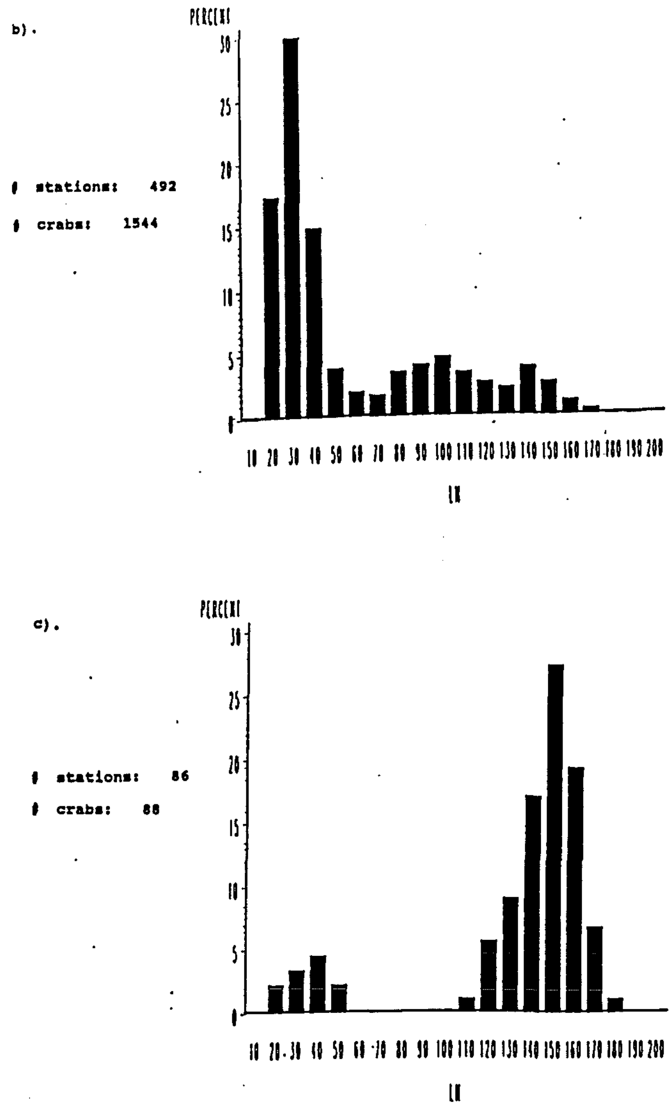

Figure 5. Size frequency of crabs caught in geographic Stratum 3, Lower Virginia Bay; Substrata: B) depths greater or equal to 5 ft and less than 40 ft; C) depth greater or equal to 40 ft. Dredge samples were not taken from depths < 5 ft in Stratum 3.