Abstract.—A winter dredge survey of blue crab (*Callinectes sapidus* Rathbun) is conducted annually in Chesapeake Bay as a key element of a long-term, bay-wide population dynamics study. Removal experiments are performed routinely as part of this stratified random survey of the blue crab population. We present a method for estimating the catching efficiency of the standard Virginia crab dredge used in the winter survey. Data from 88 experiments conducted between November 1992 and March 1995 were analyzed; up to 10 removals were completed in each experiment. Two models were used to estimate catching efficiency for each experiment: 1) the Leslie model, and 2) a log-linear model in which it is assumed that a fixed proportion of crabs is removed in each sweep of the experimental area, allowing for an error term ε. We estimated the catchability coefficient ($\bar{q}$) as a weighted mean of the point estimates from each experiment; its standard error was estimated with the jackknife method. The average catchability coefficients across years were 0.16 (SE=0.01) for model 1, and 0.15 (SE=0.02) for model 2. There were no significant differences in yearly estimates of dredge efficiency for the period investigated in our study. We show how the estimated catching efficiency can be used to calibrate catch per unit of effort in a dredge survey. The precision of estimates of absolute abundance could be improved significantly by increasing the precision of the estimates of catchability. Similar improvements of estimates of absolute abundance are expected for analogous dredging surveys of slow-moving or sedentary benthic species buried in the sediment, such as scallops and clams.

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A method for estimating dredge catching efficiency for blue crabs, *Callinectes sapidus*, in Chesapeake Bay

Jon H. Vølstad
Versar, Inc.
9200 Rumsey Road
Columbia, Maryland 21045
E-mail address: Volstadjon@versar.com

Alexei F. Sharov
Maryland Department of Natural Resources
Tawes State Office Building B-2
580 Taylor Avenue
Annapolis, Maryland 21401

Glenn Davis
Brenda Davis
Maryland Department of Natural Resources
301 Marine Academy Drive
Stevensville, Maryland 21666

Stratified random dredge surveys have been conducted in Chesapeake Bay yearly since 1989 during the coldest winter months to estimate abundance and other key statistics for the blue crab (*Callinectes sapidus* Rathbun). The survey design implemented during the winter of 1992–1993 became the standard. Three geographic strata were sampled every year thereafter: upper bay and rivers (61% of the total area), middle bay (27% of the total area), and lower bay (12% of the total area). The number of randomly selected stations in each stratum was proportional to the area of the stratum. The strata were designed to encompass major areas of habitat and to account for differences in spatial distribution of crabs by size and sex. Details of the design of the Chesapeake Bay blue crab winter survey, its characteristics, and history can be found in Vølstad et al.[1] and Rothschild and Sharov.[2] Survey results indicated that the distribution of blue crabs is highly patchy, and the coefficient of variation (CV) of average crab density is usually large. Nevertheless, catch per unit of effort (CPUE) from the annual dredge surveys generally provides accurate estimates of relative abundance because of efficient stratification and large sample sizes.

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[1] Vølstad, J. H., B. J. Rothschild, and T. Maurer. 1994. Abundance estimation and population dynamics of the blue crab in the Chesapeake Bay. Ref. No. UMCEES [CBL] 94-014. Final report to the Maryland Department of Natural Resources, the Chesapeake Bay Stock Assessment Committee, and the National Oceanic and Atmospheric Administration (NOAA). Chesapeake Biological Laboratory, P.O. Box 38, Solomons, MD 21236.

[2] Rothschild, B. J., and A. F. Sharov. 1997. Abundance estimation and population dynamics of the blue crab in the Chesapeake Bay. Final report to the Maryland Department of Natural Resources and Chesapeake Bay Stock Assessment Committee. Center for Marine Science and Technology, University of Massachusetts, North Dartmouth, MA 02747-2300.

Accurate estimates of absolute abundance and population characteristics over time provide a means of ensuring a sustainable harvest of the Chesapeake Bay blue crab stock. CPUE must be adjusted for the dredge catching efficiency to estimate absolute abundance from the survey data. Catching efficiency (i.e. the fraction of crabs present in the path of the dredge that is captured) can be estimated from removal experiments (e.g. Seber, 1973; Ricker, 1975; Hilborn and Walters, 1992). In such experiments, a closed population is sampled repeatedly over a relatively short time. An estimate of the catching efficiency is typically based on the slope of a linear regression of CPUE on cumulative catch (Leslie and Davis 1939), or on log-transformed CPUE and cumulative effort (Delury, 1947). It is assumed that no emigration, immigration, or natural mortality occurs during the experiment and that all animals caught are not returned to the population (Otis et al., 1978; Schnute, 1983).

During the summer months, blue crabs are active swimmers; therefore, an otter trawl is more effective for sampling. Estimates of absolute abundance, however, are difficult to obtain during the summer. First, trawling at random locations may be difficult because of the presence of crab pots and trotlines throughout Chesapeake Bay. Second, the catching efficiency of trawls is difficult to estimate because it is affected by the swimming behavior of blue crabs. The key assumption for estimating catching efficiency of a closed population is likely to be violated in depletion experiments conducted with an otter trawl in small geographic areas because of migration.

Blue crabs in Chesapeake Bay are largely inactive and bury themselves in the bottom sediment from November through March (Van Engel, 1958); thus, they are less likely to escape the dredge by swimming. Orth and van Montfrans (1987) reported negligible catches in bottom trawls during winter, further supporting the premise that crabs are buried in the substrate. Blue crabs captured in removal experiments showed little signs of mobility when brought aboard the vessel. We, therefore, believe that the assumption of a closed population is fairly well met during the short time span of each experiment in winter. Also, fishing activity is at a minimum during winter; only crabs in the Virginia mainstem of the bay are harvested.

We report on the catching efficiency of the sampling dredge estimated from multiple removal experiments in the blue crab survey. We demonstrate that catchability estimates from a single or a few removal experiments will not be reliable for the entire bay. We show how the estimated catchability can be used to calibrate the relative estimate of abundance from the survey.

Material and methods

Removal experiments

Maryland Department of Natural Resources (MDNR), Chesapeake Biological Laboratory (CBL), and Virginia Institute of Marine Science (VIMS) conducted 88 removal experiments between November 1992 and March 1995 using the standard 1.83-m wide Virginia sampling dredge. The dredge was lined with either 12.7-mm hexagonal chicken wire or nylon mesh and is assumed to have "knife edged" selectivity for crabs with a carapace width (CW) of at least 15 mm (Sulkin and Miller, 1975).

Depletion experiments generally were conducted at locations that represent the variations in depth and sediment type typical of Chesapeake Bay (Fig. 1), taking into account up-to-date survey data. It is impractical to select sites for depletion experiments randomly because blue crabs have a patchy distribution, and the annual baywide dredge survey generally has a large number of zero catches. Because of cost considerations, removal experiments were conducted each year at a random subset of survey stations with positive catches.

Removal experiments were conducted within an area of approximately 100 m by 5.5 m in Maryland waters and 100 m by 9 m in Virginia waters. In both cases experimental areas were marked with buoys. Each removal from the experimental area (coverage) consisted of three (CBL and MDNR) or five (VIMS) parallel, nonoverlapping dredge tows conducted back and forth (Fig. 2) at a standard towing speed of 3 knots. A maximum of 10 removals was completed for each depletion experiment. The unit of effort was one coverage (i.e. the combined 3 or 5 hauls required to sweep the experimental area), and catch was recorded as the total number of crabs caught per coverage.

Estimating catchability

Hirst (1994) formulated the following standard assumptions for the removal method: 1) there is no immigration to or emigration from the enclosed area during the removal experiments; 2) each animal has an equal probability of being caught; 3) each removal is equally efficient (i.e. the probability of capture for each animal is constant from one removal to the next). The first of these assumptions is reasonable because crabs are largely inactive during winter, and each depletion experiment is conducted over a short time (2 to 4 hours). The latter two assumptions may be less likely to be true because crabs generally are clustered in distribution. In marine surveys the sampling unit is typically a fixed volume, or a unit

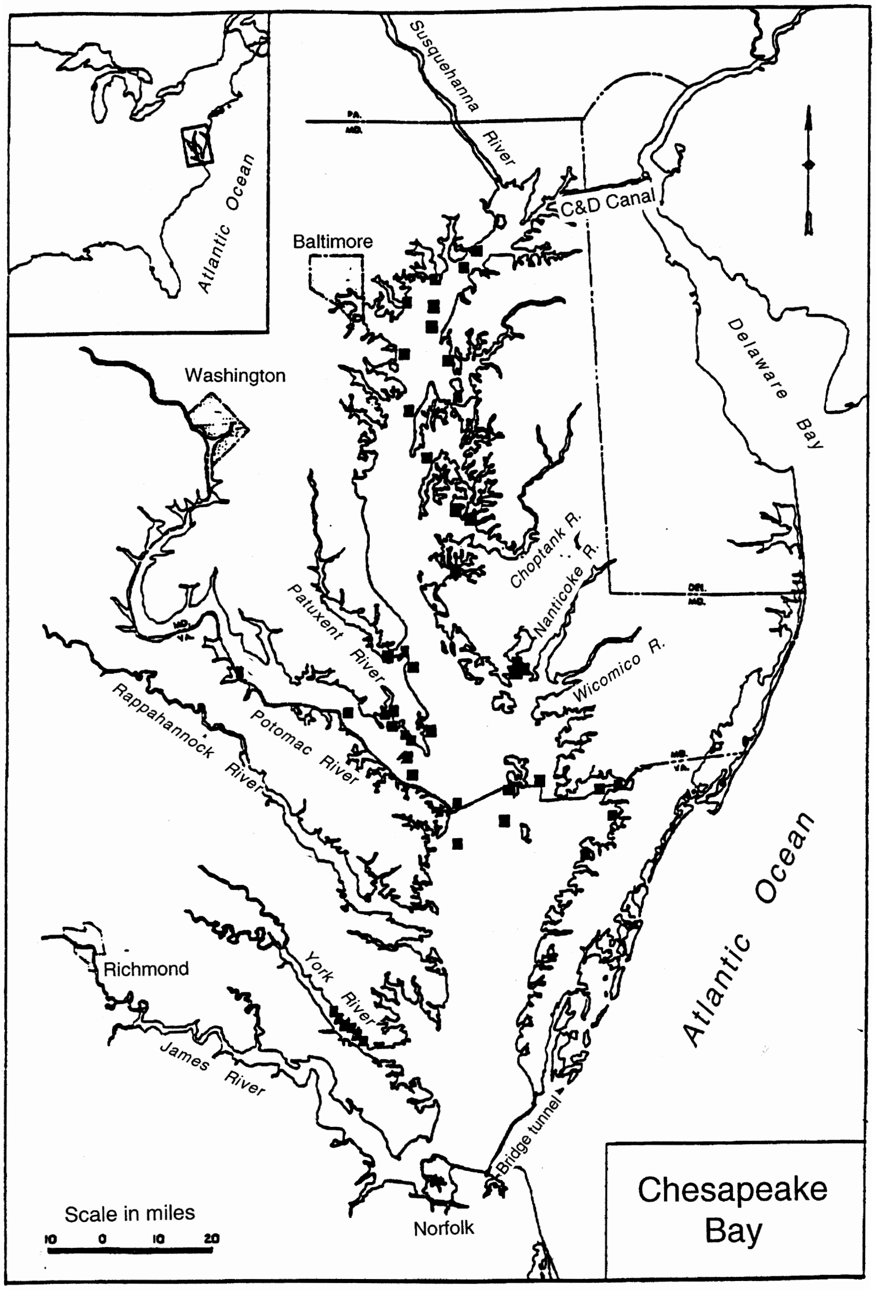

Figure 1

Map of Chesapeake Bay with positions of the dredge efficiency experiments conducted between November 1992 and March 1995.

of area swept by a standard tow (see Pennington and Vølstad, 1994). As a result, sampling individuals randomly from the target population generally is not feasible. The possible dependence of animal capture probability on environmental conditions, or on the characteristics of individual animals, such as body size, is another important practical problem.

In our study we assumed that each crab has an equal probability of being caught by the dredge within each experimental area. The catching efficiency of the dredge, however, may vary significantly between experimental sites because of different bottom topography and sediment types. The possible effect of body size on catching efficiency was evaluated by comparing mean carapace width and size-frequency distributions between removals. Assume, for example, that large crabs have a higher probability of capture than small crabs. In this case the mean cara-

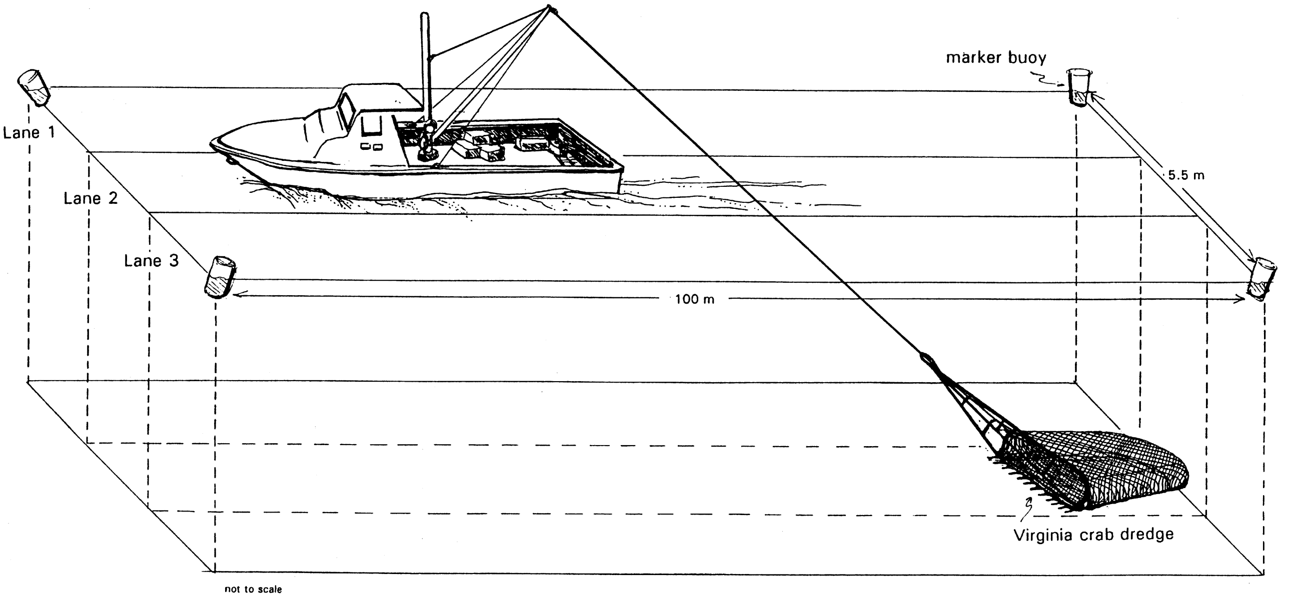

Figure 2

Schematic diagram of a standard removal experiment conducted in Maryland waters. Each removal from the area (coverage) consisted of three parallel tows conducted back and forth at a speed of 3 knots. A maximum of ten removals was completed for each experiment.

pace width of crabs in the first removals would, on average, be larger than in the final removals.

We used two models to estimate the dredge efficiency for each experiment. Model 1 is a standard Leslie model (Leslie and Davis, 1939)

$$y_i = q[P_0 - K_{i-1}] = qP_0 - qK_{i-1}, \tag{1}$$

where y_i = the catch from the ith removal; and
K_{i-1} = cumulative catch taken before each removal;
P_0 = the initial population in the area before the depletion experiment.

The catchability coefficient q = the slope of the linear regression estimated from Equation 1. The basic assumption of this model is that the number of crabs in each removal and the unit of effort is measured without error. An implication of using model 1 is that if the ith removal in a particular depletion experiment is zero, then the cumulative catch provides an absolute measure of the initial population P_0. Some crabs, however, may remain in the experimental area, even though no crabs are caught in an individual removal. This results in an underestimate of P_0 and an overestimate of q for this site.

A different technique may be used to estimate dredge efficiency. For each coverage (i) of the experimental area, we can assume that a fixed proportion (q) of the true population in the area is removed; therefore, the catch (y_1) in the first coverage is q multiplied by P_0, the initial population. For the ith coverage, we have

$$y_i = q(1-q)^{i-1}P_0\varepsilon$$

and

$$\ln(y_i) = \ln(q) + \ln(P_0) + [\ln(1-q)](i-1) + \ln(\varepsilon). \tag{2}$$

In this model, it is assumed (perhaps more realistically) that the fraction of the population removed for each unit of effort is estimated with an error ε. A simple regression of $\ln y_i$ against (i–1) provides an estimate of the slope, ln(1–q). An estimate of the expected value of the catchability coefficient (q) is obtained after a retransformation, following the method of Finney (1941; see also Johnson et al., 1994, p. 221). The variance of the slope estimate in model 2 is taken into account in the estimation of (1–q), and hence q. An approximation for estimating q for a single experiment is

$$\hat{q} = 1 - \exp\left(\hat{\beta} + s_{\hat{\beta}}^2/2\right)$$

where $\hat{\beta}$ = an estimate of the slope in Equation 2, with variance $S_{\hat{\beta}}^2$ (Gilbert 1987).

Characteristically, blue crabs have a patchy distribution, and the estimated CPUE from the dredge survey is driven by relatively few large catches. To estimate a mean catchability coefficient that is applicable to the entire survey area, estimates of catchability from each removal experiment were weighted by the abundance in the experimental area. An estimator for the overall catchability coefficient to use for calibrating CPUE in the dredge survey is

$$\overline{q} = \sum \frac{c_i q_i}{C},$$

where c_i = the total number of crabs caught in the ith experiment;
q_i = the corresponding estimated gear efficiency; and
C = total number of crabs caught in the n experiments.

Because n is small within each year, the jackknife estimate of average gear efficiency and its standard error were used (Cochran, 1977; Efron and Gong, 1983). The jackknife estimator of standard error is

$$\hat{\sigma} = \left\{ \left[(n-1)/n \right] \sum (\theta_{(i)} - \theta_{(.)})^2 \right\}^{\frac{1}{2}},$$

where

$$\theta_{(i)} = \sum_{i \neq j} \frac{c_i q_i}{(C - c_j)}$$

is the weighted mean catchability deleting the nth experiment and

$$\theta_{(\bullet)} = \sum \frac{\theta_{(i)}}{n}$$

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

For model 2 we also estimated the weighted mean and variance of the slopes from all n experiments. An estimate of q was obtained after retransformation with the method of Finney (1941); the standard error was estimated by jackknifing (Tukey, 1958; Manly, 1997).

In the annual winter dredge survey, a one-minute tow is standard. For soft sediments, the dredge may be saturated before the tow is completed. A randomized block experiment was conducted during the winter of 1992–1993 to investigate such gear-saturation effects on CPUE. Double tows were made at 77 randomly selected stations in the Maryland part of the bay. One tow of one-minute duration and one tow of 30-seconds duration were taken in random order at each station.

During the winter of 1994–1995, the chicken wire liner of the dredge was replaced with nylon mesh because the latter proved to be easier to operate and repair. To investigate any effect of the new liner on the catchability coefficient estimate, we conducted 9 removal experiments using a dredge with a chicken wire liner and 10 experiments using a dredge with a nylon liner.

Using the estimated catchability to calibrate CPUE

If r is the true blue crab density (number of crabs per m^2) in Chesapeake Bay at the time of the winter survey, and if we have an approximately unbiased estimate of the overall catching efficiency q that is uncorrelated with CPUE, an estimator for blue crab density is then

$$\hat{r} = CPUE / \hat{q},$$

where CPUE = the estimated mean number of crabs caught per m^2 swept.

A baywide estimate of the population total τ is

$$\hat{\tau} = A\hat{r},$$

where A = the area of blue crab habitat in Chesapeake Bay, which we estimated using geographic information system (GIS) to be approximately 11,000 km^2.

Using Taylor series approximations, we estimated the variance of $\hat{\tau}$ (Thompson, 1992, p 168) as

$$\mathrm{var}(\hat{\tau}) = \frac{A^2}{\hat{q}^2} \left[\hat{\mathrm{var}}(\overline{y}) + \frac{(1-\hat{q})}{\hat{q}} \overline{y} + \frac{\overline{y}^2}{\hat{q}^2} \hat{\mathrm{var}}(\hat{q}) \right],$$

where $\overline{y}$ = the estimated CPUE.

The relative precision of $\hat{\tau}$ is $k = \sqrt{\mathrm{var}(\hat{\tau})} / \hat{\tau}$. The variance of estimated catching efficiency thus adds to the variance of absolute abundance estimates.

If sampling fractions differ between strata, the absolute abundance can be estimated separately for each stratum. Here, $\hat{q}$, CPUE, and hence $\hat{\tau}$ can be estimated by stratum, by using the same approach as above. The size of each stratum must also be known. If the sampling in each stratum is independent, the variance in the combined estimate of absolute abundance is additive. This approach would also be appropriate if the density of depletion experiments was higher for some strata than for others.

Results

Catching efficiency

Estimates of catching efficiency for the standard Virginia crab dredge from individual depletion experiments conducted during the winters between November 1992 and March 1995 are presented in Tables 1 through 3. There was large variation in catchability estimates among individual experiments (from –0.13 to 0.45); however, the difference among average annual catchability coefficients for the entire survey area was small; $\overline{q}$ varied from 0.13 to 0.18 for model 1 and model 2 (Fig. 3). For both depletion models, an analysis of variance revealed that yearly differences in q are not significant (ANOVA, $P>0.3$; we used a significance level of 5% for all tests in our study). Experiments from all years, therefore, were pooled to estimate an overall catchability coefficient for the dredge survey. The weighted mean catchability coefficients were 0.16 (SE=0.01) for model 1 (Eq. 1), and 0.15 (SE=0.02) for model 2 (Eq. 2). The means and standard errors were estimated by using the jackknife method; catchability coefficients from individual experiments were assumed to be independent. The two methods for estimating a mean catchability coefficient for model 2 produced identical estimates. The difference in estimates from the two models was not significant.

Mean carapace width of crabs in each removal for all years combined, which is plotted in Figure 4, did not show any significant trend (nonparametric Mann-Kendall test (Gilbert, 1987), $n=10$, $P=0.19$). Further, the size-frequency distributions of crabs for individual removals were similar (Fig. 5). These results support our assumption that probability of capture is independent of carapace width.

Our test for gear saturation effects resulted in an average catch per minute of 3.7 (SE=0.8) for the half-minute tows, and of 2.3 (SE=0.7) for the 1-minute tows. The higher CPUE for half-minute tows, although not significant, suggests saturation effects and might be explained by the period of time that the dredge continues to be towed along the bottom after it has begun to be hauled back. Such a delay would affect shorter tows more than longer tows.

For the experiments on the effect of the dredge liner, estimates of mean q for the dredge lined with chicken wire were 0.17 (SE=0.02) based on model 1, and 0.15 (SE=0.03) for model 2. For the nylon liner the estimates were 0.22 (SE=0.03) based on model 1, and 0.21 (SE=0.03) for model 2. Means and standard errors were estimated by using the jackknife method. The results indicated that nylon has a higher catching efficiency, but the difference in catchability between the two liners was not significant (ANOVA, $P>0.54$). Results from all 88 experiments combined showed no significant difference in catching efficiency between liners. The jackknife estimates of mean catchability across years for the

Table 1

Estimates of dredge efficiency ($\hat{q}$) from depletion experiments carried out during the winter of 1992–1993, with coefficients of determination (r^2) and degrees of freedom (df) for the regressions. The jackknife estimates of average $\hat{q}$ for the entire survey area were 0.13 (SE=0.02) for model 1, and 0.13 (SE=0.03) for model 2. CBL = Chesapeake Bay Laboratory; MDNR = Maryland Department of Natural Resources; and VIMS = Virginia Institute of Marine Science.

		Model 1		Model 2		
Institution	Number of crabs	$\hat{q}$	r^2	$\hat{q}$	r^2	df
CBL[1]	88	0.13	0.58	0.10	0.38	9
	327	0.06	0.30	0.06	0.31	9
	67	0.07	0.18	0.08	0.22	9
	23	0.13	0.39	0.06	0.39	8
	121	0.14	0.51	0.18	0.56	9
	89	0.01	0.02	0.01	0.04	9
	180	0.10	0.42	0.09	0.37	9
	223	0.22	0.66	0.32	0.73	9
	59	0.30	0.65	0.38	0.36	9
	102	0.30	0.91	0.27	0.77	9
	267	–0.01	0.00	0.03	0.03	9
	615	0.01	0.12	–0.03	0.17	9
	106	0.12	0.55	0.17	0.62	9
MDNR[1]	368	0.20	0.60	0.20	0.61	5
	137	–0.10	0.15	–0.11	0.14	5
	190	0.14	0.61	0.16	0.66	5
	203	0.23	0.83	0.31	0.85	5
	60	0.08	0.13	0.07	0.09	5
	109	0.17	0.24	0.11	0.11	5
	154	0.13	0.47	0.13	0.30	5
	96	0.11	0.29	0.11	0.29	5
	311	0.14	0.85	0.16	0.85	9
	312	0.22	0.41	0.24	0.48	4
VIMS[2]	139	0.24	0.88	0.22	0.85	4
	74	0.17	0.32	0.20	0.19	4
	129	0.17	0.71	0.16	0.55	4
	193	0.18	0.63	0.17	0.44	9
	132	0.20	0.31	0.20	0.34	4
	161	0.09	0.18	0.09	0.52	4

[1] Chicken wire liner used.

[2] Nylon mesh liner used.

Table 2

Estimates of dredge efficiency ($\hat{q}$) from depletion experiments carried out during the winter of 1993–1994, with coefficients of determination (r^2) and degrees of freedom (df) for the regressions. The jackknife estimates of average $\hat{q}$ for the entire survey area were 0.18 (SE=0.02) for model 1 and 0.18 (SE=0.02) for model 2. CBL = Chesapeake Bay Laboratory; MDNR = Maryland Department of Natural Resources; and VIMS = Virginia Institute of Marine Studies.

		Model 1		Model 2		
Institution	Number of crabs	$\hat{q}$	r^2	$\hat{q}$	r^2	df
CBL[1]	100	0.37	0.84	0.24	0.48	5
	118	0.05	0.11	0.05	0.12	5
	78	0.27	0.76	0.30	0.72	5
	55	0.09	0.55	0.10	0.59	5
	83	0.41	0.88	0.35	0.59	4
	11	0.40	0.89	0.23	0.60	3
	52	0.35	0.79	0.34	0.78	5
	34	0.39	0.85	0.43	0.86	5
	20	0.32	0.37	0.36	0.39	3
	92	0.13	0.64	0.13	0.68	5
	321	0.25	0.57	0.38	0.73	5
MDNR[1]	35	0.23	0.60	0.17	0.48	9
	89	0.27	0.65	0.18	0.31	9
	219	0.13	0.38	0.11	0.12	9
	145	0.12	0.64	0.14	0.59	9
	96	0.17	0.44	0.16	0.30	9
	48	0.30	0.81	0.28	0.59	7
VIMS[2]	376	0.22	0.71	0.19	0.73	8
	232	0.34	0.89	0.35	0.77	7
	110	0.13	0.62	0.17	0.41	8
	133	0.02	0.02	–0.04	0.08	8
	188	0.03	0.02	0.04	0.02	8
	244	0.13	0.79	0.14	0.64	8
	174	0.12	0.64	0.14	0.71	8
	346	0.10	0.31	0.14	0.43	8

[1] Chicken wire liner used.

[2] Nylon mesh liner used.

dredge lined with chicken wire were 0.16 (SE=0.02) for model 1, and 0.16 (SE=0.03) for model 2. For the nylon liner, estimates are 0.16 (SE=0.02) for model 1, and 0.13 (SE=0.02) for model 2.

An estimate of absolute abundance

Table 3

Estimates of dredge efficiency ($\hat{q}$) from depletion experiments carried out during the winter 1994–1995, with coefficients of determination (r^2) and degrees of freedom (df) for the regressions. The jackknife estimates of average $\hat{q}$ for the entire survey area were 0.18 (SE=0.02) for model 1 and 0.14 (SE=-0.03) for model 2. CBL = Chesapeake Bay Laboratory; MDNR = Maryland Department of Natural Resources; and VIMS = Virginia Institute of Marine Studies.

		Model 1		Model 2		
Institution	Number of crabs	$\hat{q}$	r^2	$\hat{q}$	r^2	df
CBL[1]	72	0.12	0.49	0.16	0.48	9
	29	0.21	0.34	0.28	0.48	5
	48	0.26	0.55	0.06	0.06	9
	99	0.12	0.42	0.06	0.13	9
	67	0.19	0.57	0.18	0.44	9
	63	0.28	0.84	0.22	0.77	9
	66	0.12	0.48	0.18	0.61	9
	40	0.13	0.39	0.13	0.41	9
	9	0.30	0.70	0.27	0.74	4
CBL[2]	83	0.31	0.96	0.35	0.94	7
	55	0.20	0.69	0.24	0.73	9
	28	0.16	0.26	0.24	0.41	5
	54	0.22	0.77	0.15	0.40	9
	12	0.22	0.60	0.08	0.30	9
	67	0.16	0.46	0.12	0.23	9
	66	0.30	0.84	0.26	0.74	9
	92	0.11	0.64	0.17	0.51	9
	58	0.23	0.68	0.13	0.29	9
	11	0.32	0.60	0.32	0.76	9
MDNR[2]	207	0.16	0.31	0.11	0.16	5
	151	0.22	0.42	0.19	0.48	5
	127	0.26	0.68	0.22	0.50	5
	145	0.22	0.83	0.21	0.69	5
	61	0.38	0.86	0.55	0.86	4
	64	0.45	0.93	0.33	0.64	5
	23	0.36	0.96	0.38	0.94	5
VIMS[2]	113	0.04	0.07	0.07	0.12	5
	114	0.11	0.79	0.11	0.81	5
	139	0.23	0.89	0.18	0.80	5
	121	0.15	0.24	0.13	0.12	5
	185	0.24	0.16	–0.13	0.11	5
	107	0.07	0.35	0.05	0.20	5
	167	0.03	0.03	0.02	0.01	5
	103	0.04	0.05	–0.10	0.19	5

[1] Chicken wire liner used.

[2] Nylon mesh liner used.

A stratified random sample of 1412 stations was taken in the Chesapeake Bay during the winter of 1994–1995 (Rothschild and Sharov[2]). At each station, the standard Virginia crab dredge was towed for 1 minute at 3 knots. The sampling intensity was equal in all three geographic strata. The estimated baywide mean number of crabs (CW ≥15 mm) caught per 1000 m^2 swept was $\bar{y} = 8.53$ (k=0.07). For age group 1+ (CW ≥60 mm) the estimate was $\bar{y} = 3.75$ (k=0.08). With the catchability coefficient $\bar{q} = 0.16$ and standard error 0.01 (from model 1), the absolute abundance estimate for blue crab with CW ≥15 mm was $\hat{\tau}_1$= 5.86×10^8 (k=0.09), and 2.58×10^8 (k=0.10) for crabs with CW≥60 mm. Using $\bar{q}=0.15$ with standard error 0.02 (from model 2), we estimated absolute abundance for crabs with CW ≥15 mm to be $\hat{\tau}_2=6.26\times10^8$ (k=0.15), and 2.75×10^8 (k=0.16) for crabs with CW ≥60 mm. To check plausibility of these estimates, we compared the absolute abundance estimates of the 1+ age group (CW 60 mm) with estimated total landings for 1995. Blue crabs of age 1+ reach harvestable size (127 mm) the following fishing season. The reported total landings in the commercial fishery were 17,820 metric tons (t). Using an average weight per crab of 150 g (Knotts[3]), we estimated the total number of crabs caught to be 1.19×10^8 and the exploitation coefficient (as a ratio of catch in numbers and number of age 1+ crabs) to be about 45%.

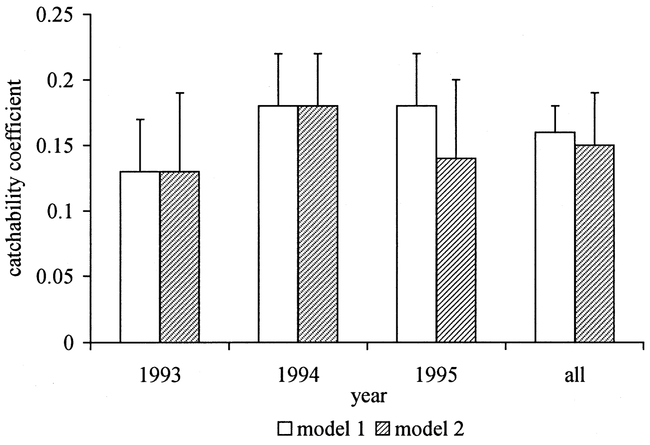

Figure 3

Jackknife estimates of average catchability ($\bar{q}$) by year for model 1 and model 2. The error-bars represent the half width of the confidence intervals.

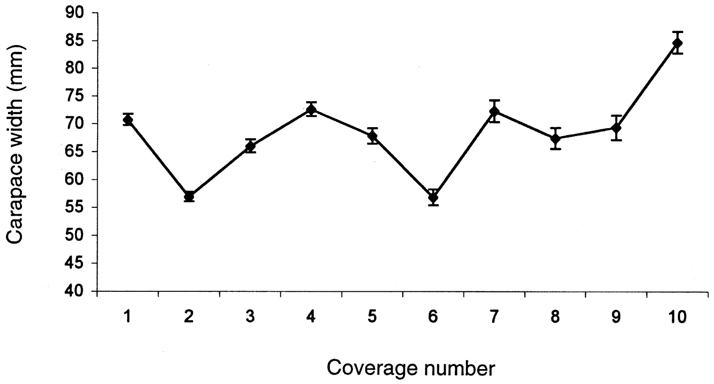

Figure 4

Mean carapace width for blue crabs by coverage in the Maryland depletion experiments. Data from all years are combined.

Exploitation rates can be calculated for males and females separately in similar fashion by using mean CPUE and landings by sex. These rates may be very valuable information because there is an evident disproportion in crab landings by sex; on average more males are landed per year (at least by weight) than females (Rugolo et al., 1998a). For example, 9320 t of males and 7230 t of females were landed in Maryland in 1995. If the average weights of males and females in the catch were similar, the exploitation rate for males would be higher than that for females. However, uncorrected for catchability, the density of age 1+ males (2.31 per 1000 m^2) observed in 1995 was higher than that of age 1+ females (1.44 per 1000 m^2), suggesting that females are being exploited at a higher rate. To obtain precise estimates of sex-specific exploitation rates, data on mean weight of crabs by sex in the harvest are required but are not available.

Discussion

Our method for estimating overall dredge catching efficiency provides consistent estimates over time (Fig. 3). The Leslie model produces the most precise estimate for catching efficiency, but the estimate could be slightly biased upwards if measurement error in effort occurs. In practice, given that the standard unit of effort in the depletion experiments is one complete coverage of the closed area, the three to five tows forming a coverage may partially overlap or extend outside the area because of navigational errors or effects of bottom currents. This measurement error in catch or effort inflates the average catchability coefficient estimates from the Leslie model (Gould et al., 1997). For model 2, the estimate of q for individual experiments depends on the regression slope and its variance and will decrease with increasing variance. The method for estimating q for individual experiments assumes that the distribution of the estimated slope tends toward normality; therefore estimates of based q on model 2 could be biased at low sample sizes, but

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[3] Knotts, K. S. 1989. Preliminary stock assessment of the Chesapeake Bay blue crab population. M.S. thesis, Univ. Maryland, College Park, MD, 206 p.

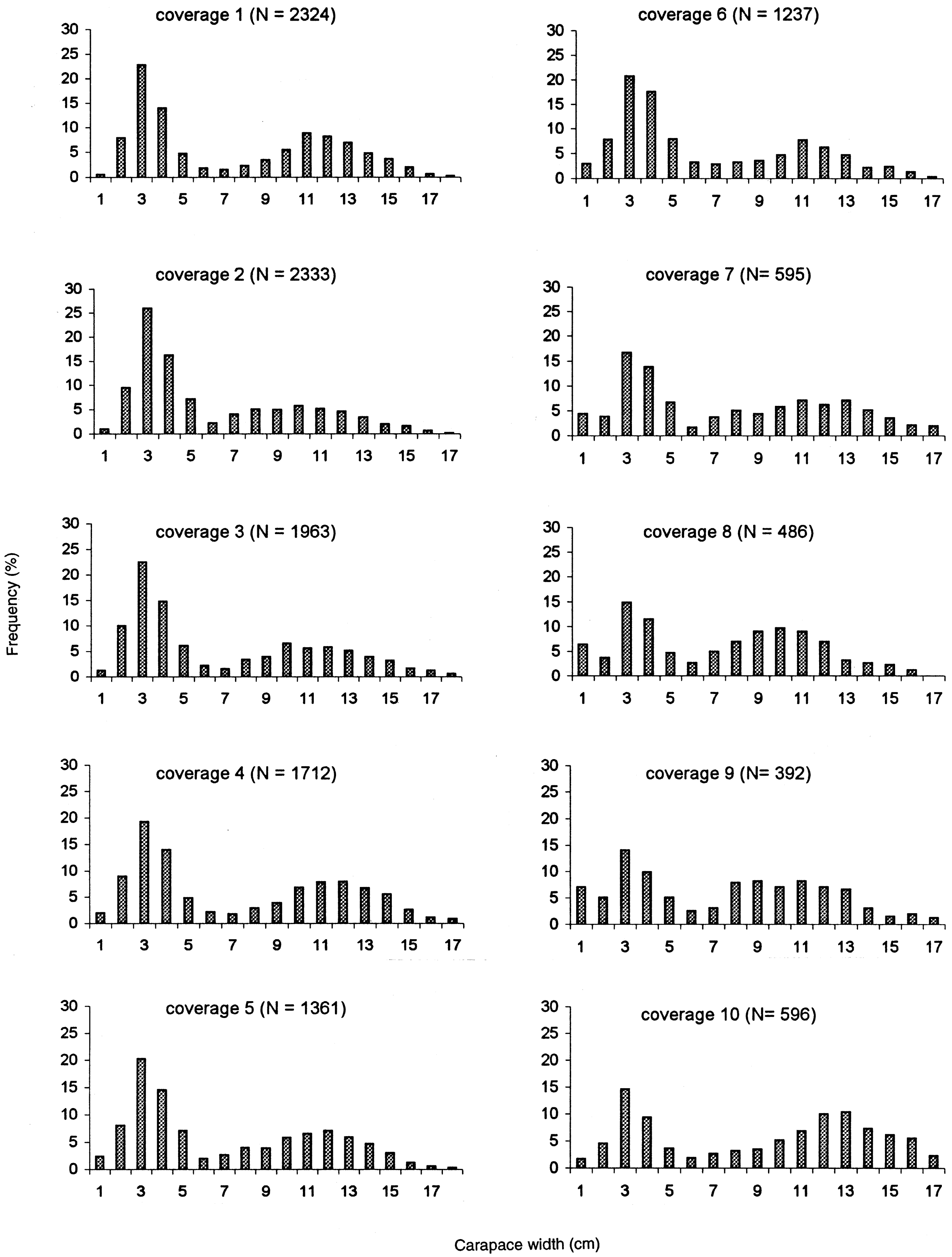

Figure 5

Carapace-width frequency distribution of blue crabs by coverage in Maryland depletion experiments. Data from all years are combined.

the identical estimates of $\overline{q}$ from the two alternative methods indicate that such bias is small.

Obtaining reasonable estimates of catching efficiency from catch-effort techniques requires depleting a substantial proportion (usually more than 30%) of the population (see Gould and Pollock, 1997). Also, estimates of the regression slopes, and hence q, are likely to be more accurate for both models if the independent variables (i.e. cumulative catch, K_i, or coverage, i) have a wider range. For the depletion experiments with ten removals conducted in Maryland waters, estimates of q based on the first five removals were generally higher than estimates of q based on all ten removals. Thus, fewer removals per experiment can bias the estimates of gear efficiency just as vessel effects can. In experiments conducted from two similar vessels in Maryland waters, we did not detect significant differences in catchability between vessels. Environmental factors probably were the principal cause of variability in catchability estimates from different experiments because sediment type, bottom topography, intensity and direction of the current, towing speed, and crab distribution influence dredge performance.

When our overall estimates of catching efficiency are used to adjust CPUE from the baywide winter survey, plausible estimates of absolute abundance of blue crab in the Chesapeake Bay are obtained, resulting in an estimated exploitation rate of about 45% in 1995. The catchability coefficient estimate (q=0.26) presented in Zhang et al. (1993), in contrast, would result in an estimated exploitation rate of 75%. Their method eliminated removal experiments with low coefficients of determination (r^2) for the regressions, or with negative catchability estimates, which could result in a positive bias in the estimated overall catchability.

We have not accounted for landings from the recreational fishery or for natural mortality in our example; therefore the above exploitation rates were probably underestimates. Recreational harvest data are very scarce, but limited surveys conducted by the Maryland Department of Natural Resources in 1983, 1988, and 1990 have indicated that recreational harvest represented approximately 79%, 50%, and 26% of the reported commercial harvest (Rugolo et al. 1998b). The 1990 survey is considered the most reliable of the three. Assuming that the recreational harvest in 1995 represented 26% of the commercial harvest, then the corrected estimate of total blue crab exploitation rate is 56.7%. A bias in the opposite direction would result if the exploitable part of the stock were underestimated because of recruitment during the fishing season.

The results of this study demonstrate that improved estimates of catching efficiency can substantially increase the accuracy of estimates of absolute abundance. In our example based on survey data from the winter 1994–1995, the variance in the absolute abundance estimate for the 1+ age group is driven by the variance in $\hat{q}$. Size of sampling locations in the Chesapeake Bay winter dredge survey for blue crabs have ranged between 877 and 1412 stations per year, and relative precision (k) of the estimated CPUE (i.e. its standard error divided by the mean) has been around 10% for most years. Because of the asymptotic properties of k, it would be prohibitively expensive to significantly increase the precision of absolute abundance estimates by increasing the sample size in the survey. We believe a more cost-effective way to increase the precision of estimates of absolute abundance would be to improve the estimate of catchability by increasing the number of depletion experiments. Our results show that an estimate of catching efficiency based on a single experiment or on a few removal experiments would not represent the entire bay accurately because catchability is highly variable among sites owing to differences in bottom conditions and other factors. We included all the depletion estimates of catchability in our study, including those less than zero. We assumed that point estimates of catchability are estimated with a random error that is normally distributed around a mean: estimates in the tails of the distribution could be substantially higher or lower than the true mean catchability. An accurate estimate of catching efficiency, applicable to the entire Chesapeake Bay, requires conducting a large number of depletion experiments at representative locations. Although no statistical differences were found among the annual catchability coefficient estimates for the years analyzed in our study, we caution that interannual variation in q is likely. For example, an increase in water temperature during mild winters may affect crab behavior (they would cease hibernation) and hence probability of capture. We recommend, therefore, that depletion experiments be conducted yearly as part of an annual winter survey of blue crab population.

The conclusions of our study can be generalized and extended to similar resource assessment surveys of other slowly moving or sedentary bottom dwelling species with patchy distribution, such as scallops or clams. In surveys of target species, such as these, attention must be paid to variability in capture efficiency of the gear with respect to sediment type, depth, towing speed, and other factors (such as animal interactions) that affect the gear. Sediment or bottom type are often selected as stratification criteria in bottom surveys of benthic organisms. Properly designed removal experiments can provide reliable estimates of catchability coefficients for each sampling stratum, allowing adjustment of strata CPUE used in the estimator of absolute abundance. Sediment distribution, however, is often very patchy, and the exact area on the bottom of any type of sediment is typically not known. Accurate mapping of bottom sediment is expensive and thus it makes sediment-based stratification impractical. An alternative approach for taking sediment into account is to conduct a series of depletion experiments at locations that are representative of the entire survey area. If a sufficient number of experiments are conducted, the effects of sediment on catching efficiency will be accounted for. Although we agree that efficient stratification is an important aspect of designing cost-effective marine resource surveys, we stress that careful estimation of sampling gear efficiency through a series of depletion experiments could significantly improve the accuracy of absolute abundance estimates. Both elements are essential in designing effective sample survey programs for estimating vital characteristics of a population.

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