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A Monte Carlo Computer Simulation Study for Blue Crab Capture Efficiency Experiment

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A Monte Carlo computer simulation study was conducted to determine the most efficient sampling design for the blue crab dredge capture efficiency experiment performed in Chesapeake Bay, Maryland, U. S. A. The input values were the number of dredge tracks in each experimental area, the number of tows per experiment, the number of experiments, the mean density of crabs per unit area, the negative binomial coefficient, the gear capture efficiency, and the tow error. As a result of the study, a four-track experiment with twenty to twenty-eight tows was estimated to be the best in terms of precision and accuracy of the gear capture efficiency.

Key words : Monte Carlo, simulation, blue crab, capture efficiency, Chesapeake Bay, dredge, tow

Introduction

The University of Maryland's Chesapeake Biological Laboratory (CBL) has conducted an annual survey to estimate the abundance of blue crabs, *Callinectes sapidus* Rathbun, in Chesapeake Bay since 1987 (Rothschild et al., 1991). The Virginia crab dredge was used as one of the sampling gears for capturing crabs in ths survey. In winter 1991~1992, CBL and the Maryland Department of Natural Resources (MDNR) conducted an experiment to estimate dredge capture efficiency using two chartered commercial dredge vessels (Endo, 1992; Zhang et al., 1993). A measure of survey gear capture efficiency was essential for estimating crab abundance. Before designing the efficiency experiment, a series of pilot experiments was conducted in winter 1990~1991 (Rothschild et al., 1991).

There were two criteria which need to be validated in the sampling protocol of the pilot experiments. An experimental area covered seven dredge tracks for most of the pilot experiments. However, no assessment of whether the "seven-track experiment" was superior to other potential designs (e.g., one-track experiment, three-track experiment, etc.) was undertaken. Secondarily, it was not proved that our stopping rule (an experiment stops when we get three consecutive zero catches from the sampling area) was reasonable. Fishing an area "out" usually required 21~28 tows.

To determine the number of dredge tracks and the number of tows in a given experiment needed to optimize accuracy and precision of the efficiency estimates, a computer simulation study was carried out based on the results of the pilot experiment.

Materials and Methods

To determine the most efficient sampling design in terms of the track numbers and the stopping rule criteria, a Monte Carlo computer simulation method of analysis was developed. The hypothetical sampling area used in the simulation contained an arbitrary number of dredge tracks and two "error tracks".

Each track was 2 m wide (approximately the width of the crab dredge) and 100 m long (Figure 1). Each track was divided into 10 subtracks and 20 perpendicular columns, yielding 200 subarea "units". Thus, each unit, 0.2 m in width and 5 m in length, was 1 m^2 in area.

The basic assumption of the analysis was that the distribution of blue crabs is either random or clustered. Simulation program was written to analyze both of these cases. If the crab distribution is spatially random, it can be described by a Poisson distribution in which the variance and the mean have the same value:

$$P(X_{ij}=x) = \frac{\lambda^{x} e^{-\lambda}}{x!}, \qquad (1)$$

where $P(X_{ij}=x)$ is the probability that the number of crabs in the unit area of subtrack i and column j equals x, and λ is the mean density of crabs per square meter. The negative binomial distribution, which is characterized by a variance greater than the mean, can be used for simulating clustered distributions:

$$P(X_{ij}=x)=\binom{x+r-1}{x}\left(\frac{r}{\lambda+r}\right)^{r}\left(\frac{\lambda}{\lambda+r}\right)^{x} \qquad (2)$$

where r is the negative binomial coefficient. In addition, if the variance is smaller than the mean, then, the distribution is uniform. This situation rarely occurs in the natural environment (Seber, 1982) and, in particular, winter crab distributions in the Chesapeake Bay were highly non-uniform (unpublished data).

In the simulation program "tow error", which is the error inherent in controlling dredge placement within a given track, was incorporated. In each tow, if the dredge is positioned exactly on the track, the tow error is 0% to both left- and right-hand sides. If the dredge deflects to the left-hand side by one subtrack, the tow error is considered to be 10% for the left-hand side and 0% for the right-hand side. If the dredge deflects to the left-hand side by two subtracks and to right-hand side by three subtracks, then the tow error is considered to be 20% for the left-hand side and 30% for the right-hand side, etc.

Therefore, the inputs to the program were: (i) the number of tracks considered, (ii) the number of tows per experiment, (iii) the number of experiments, (iv)

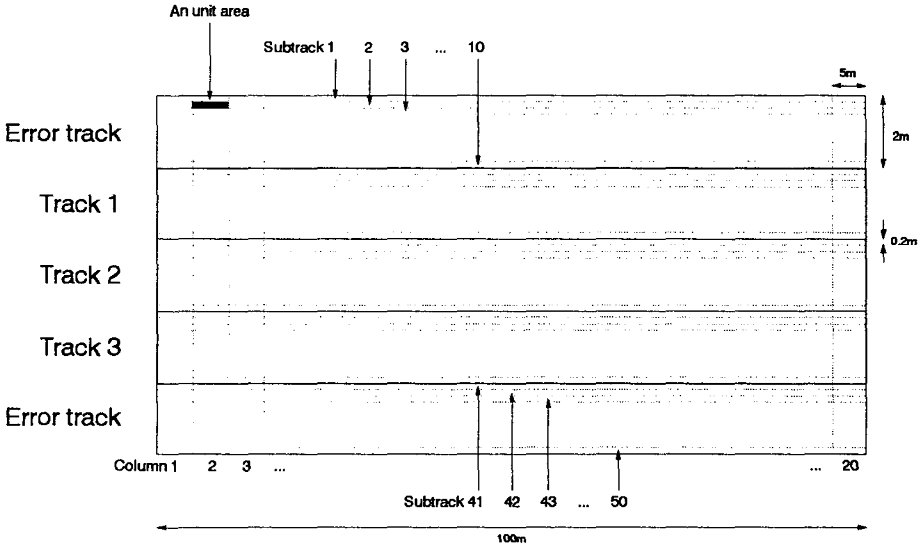


Fig. 1. A hypothetical sampling area used for a three-track gear efficiency simulation.

the mean density of crabs per square meter, (v) the negative binomial coefficient, (vi) the gear efficiency, and (vii) the tow error. In each simulation, either a Poisson or negative binomial distribution of crabs was assumed. The simulation was conducted in a nine step algorithm:

(i) Generate a Poisson or negative binomial random number according to a specified initial mean density and negative binomial coefficient. Assign this number to each of the unit area blocks in the hypothetical sampling area.
(ii) Randomly select the track to dredge.
(iii) Randomly select ten subtracks to tow within a specified range of tow error.
(iv) Dredge the subtracks, then calculate the number of crabs caught by the tow with the specified gear efficiency (i. e., the total number of crabs assigned in the subtracks multiplied by the gear efficiency).
(v) Generate a Poisson or negative binomial random number with the mean density reduced by the previous tow and assign this number to each of the unit area blocks in the dredged subtracks.
(vi) Repeat steps (ii) to (v) until the specified total number of tows are performed.
(vii) Estimate the gear efficiency and the standard error with modified Leslie method (Endo, 1992; Zhang et al., 1993) by using simulated catch data and calculate the deviation from the "true" gear efficiency.
(viii) Repeat steps (i) to (vii) until the specified number of experiments are conducted.
(ix) Calculate average estimates of gear efficiency, average standard error, and absolute deviation from the true gear efficiency (absolute bias).

Individual estimates of gear efficiency, q, from each experiment (trial) were obtained from the usual least square method:

$$q_i = \frac{\sum_j (x_{ij} - \bar{x}_{i.})(y_{ij} - \bar{y}_{i.})}{\sum_j (x_{ij} - \bar{x}_{i.})^2} \qquad (3)$$

where x_{ij} is the jth cumulative catch of the ith trial, y_{ij} is the jth catch of the ith trial, $\bar{x}_{i.}$ is the mean cumulative catch of the ith trial, and $\bar{y}_{i.}$ is the mean catch per tow of the ith trial. The standard error of q_i is

$$s_{q_i} = \sqrt{\frac{\sum_j (y_{ij} - \hat{y}_{ij})^2/(n_i - 2)}{\sum_j (x_{ij} - \bar{x}_{i.})^2}} \qquad (4)$$

where $\hat{y}_{ij}$ is the jth predicted catch of the ith trial and n_i is the number of data points from the ith trial. The estimate of q averaged over all trials is (Sokal and Rohlf, 1981)

$$\bar{q} = \frac{\sum_i \sum_j (x_{ij} - \bar{x}_{i.})(y_{ij} - \bar{y}_{i.})}{\sum_i \sum_j (x_{ij} - \bar{x}_{i.})^2} \qquad (5)$$

and the average standard error is

$$\bar{s}_q = \sqrt{\frac{1}{t} \sum_i s_{q_i}^2} \qquad (6)$$

where t is the total number of trials.

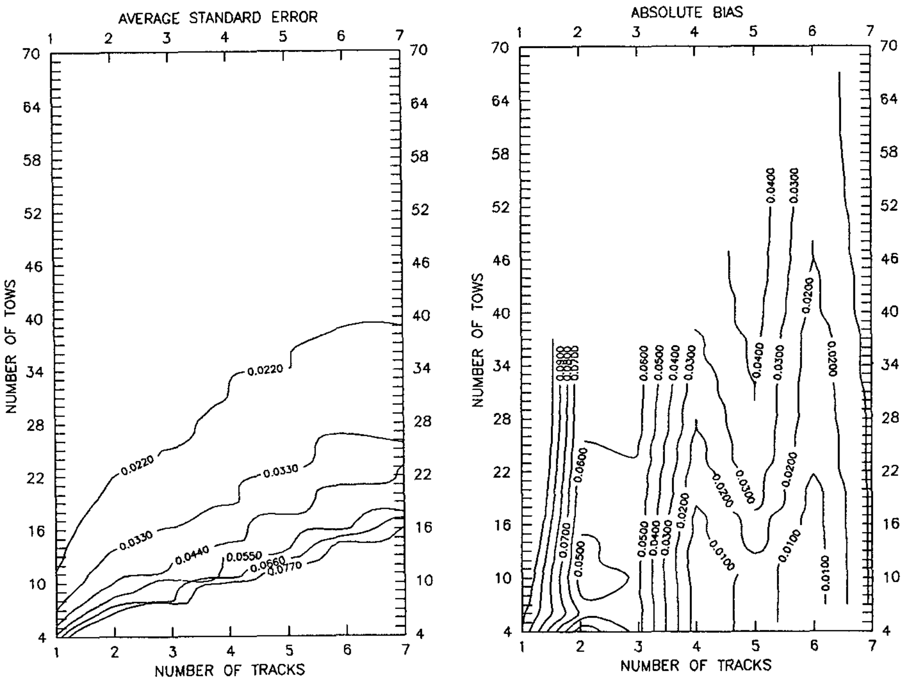
Estimates for each of the mean density, the gear efficiency, and the negative binomial coefficient were obtained from the 1990~1991 pilot experiments (Rothschild et al., 1991 and unpublished data). The mean density and the gear efficiency were calculated using the modified Leslie method (Endo, 1992; Zhang et al., 1993). The negative binomial coefficient was estimated using following formula (Bliss and Fisher, 1953; Moyle and Lound, 1960):

$$r = \frac{\bar{N}^2}{s_N^2 - \bar{N}} \qquad (7)$$

where $\bar{N}$ is the mean abundance per track, s_N^2 is the variance of $\bar{N}$, and

$$\bar{N} = \frac{\sum_{i=1}^{n} \frac{C_i'}{q}}{n} \qquad (8)$$

(A) POISSON (TOW ERROR 50%) (B) POISSON (TOW ERROR 50%)



(C) POISSON (TOW ERROR 100%) (D) POISSON (TOW ERROR 100%)

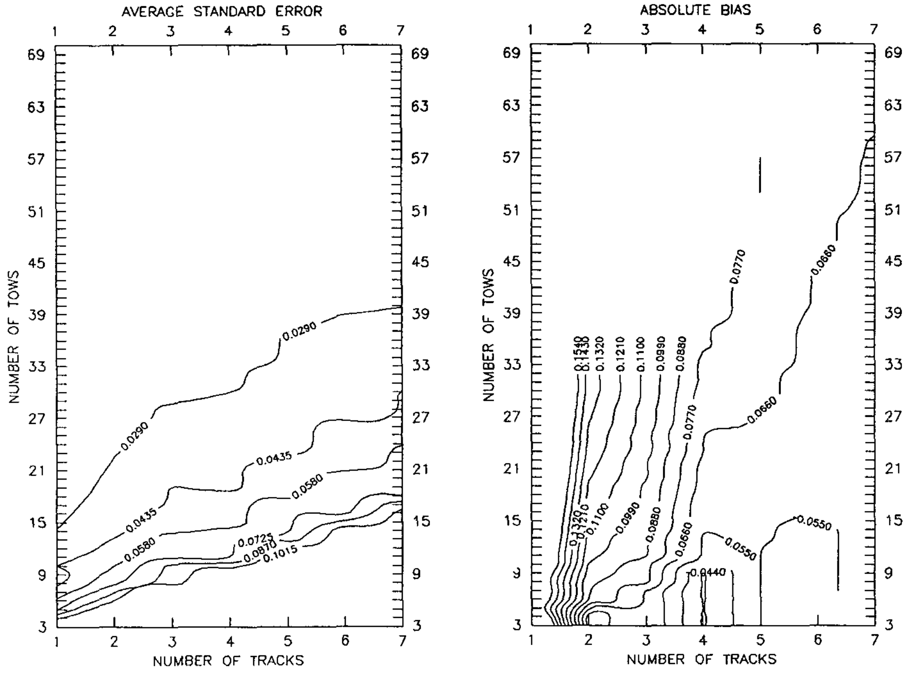


Fig. 2. Results of gear efficiency experiment simulation using Poisson distribution. (A) average standard error of q with 50% tow error, (B) absolute bias of q with 50% tow error, (C) average standard error of q with 100% tow error, and (D) absolute bias of q with 100% tow error.

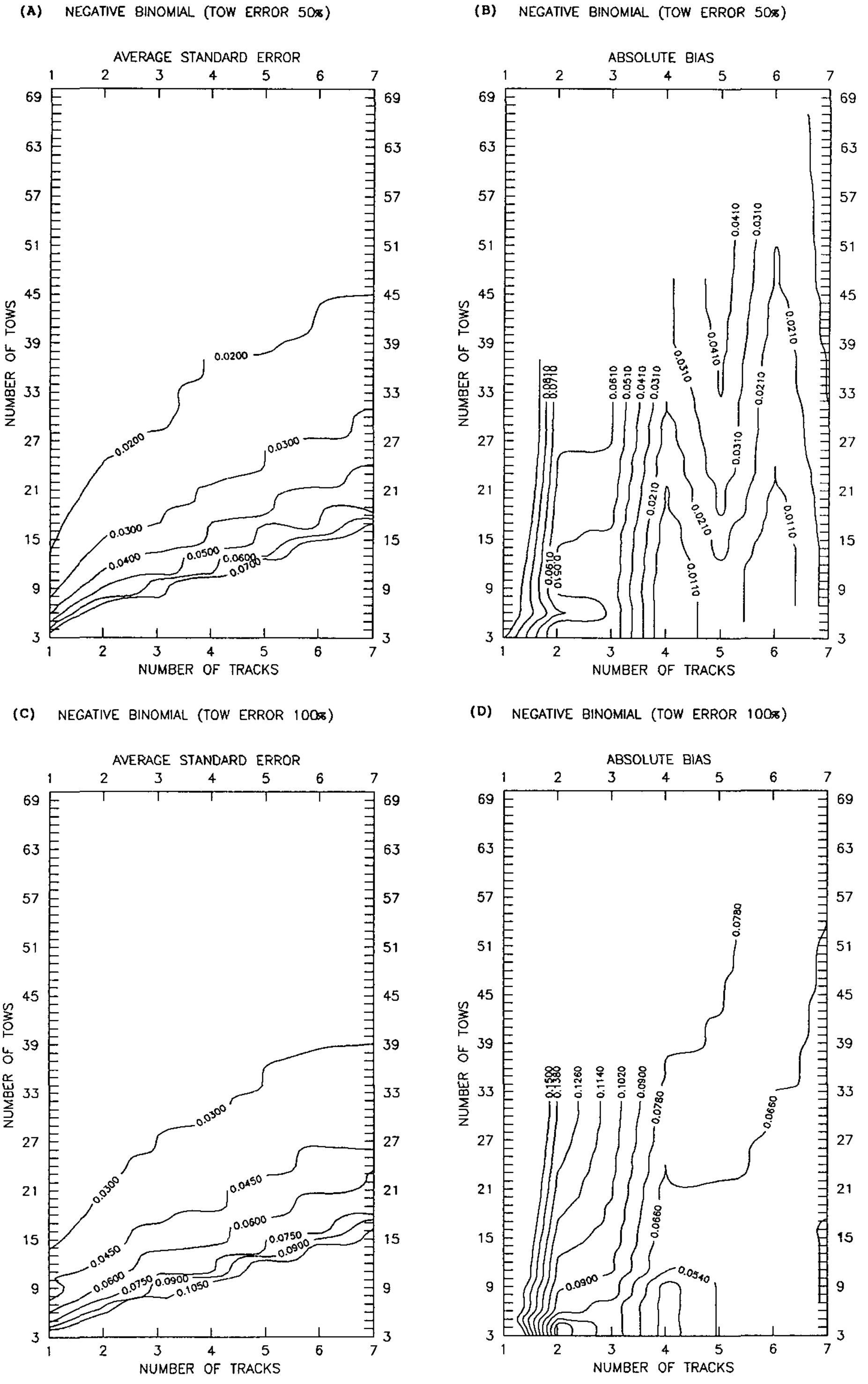


Fig. 3. Results of gear efficiency experiment simulation using negative binomial distribution. (A) average standard error of q with 50% tow error, (B) absolute bias of q with 50% tow error, (C) average standard error of q with 100% tow error, and (D) absolute bias of q with 100% tow error.

where C'_i is the catch from the first tow of the ith dredge track and q is the estimate of gear efficiency. The means of the estimates were used for the simulation input values: 0.284 crabs per square meter as the mean density, 0.438 as the true gear efficiency, and 2.950 as the negative binomial coefficient. The negative binomial coefficient determines the shape of the distribution; as the variance approaches the mean, r increases, and the shape of the negative binomial distribution approaches that of the Poisson distribution.

After specifying the values of these parameters, experiments were compared for various combinations of the number of tracks (from one to seven), the number of runs (maximum 30 runs for one-track experiments, 15 runs for two-track experiments, and 10 runs for other experiments), and the tow error (from 0% to 200%). For each combination, 300 trial experiments were simulated.

Results

Contour maps were constructed from results for the cases of 50% and 100% tow error for both the Poisson and the negative binomial models (Figs. 2, 3). Actual tow error was most likely between 50% and 100%.

The standard error of the estimates gradually increased as the number of tracks increased keeping the number of tows constant (Figs. 2A, 2C, 3A, 3C). As the number of tows increased, the standard error decreased. Standard error increased with tow error, but the effect was not substantial. The negative binomial model had higher standard error than the Poisson model for given combinations of tow error, number of tracks, and number of tows, but the difference was also small.

While standard error was little affected, increases in tow error resulted in substantially increased bias (underestimation) of estimates for given numbers of tracks (Figs. 2B, 2D, 3B, 3D). The number of tows had little effect on the bias. Notably, the bias decreased rapidly from the one-track to four-track simulations and became relatively stable above four-tracks for both 50% and 100% tow error cases.

There were no differences in standard error and bias between one-sided tow error and two-sided tow error for a given constant total error.

Also, two extreme cases were simulated: the low density ($0.094/m^2$) with high q (0.713) and the high density ($0.622/m^2$) with low q (0.366). These densities and values of q were the highest and the lowest estimates obtained from the pilot experiments. The former case raised, while the latter case decreased both in the standard error and in the bias. Nevertheless, the relationships among the number of tracks, the number of tows, the tow error, and the crab distribution did not change.

Discussion

The increases in standard error of the estimates of q with the increases in number of tracks are mainly due to the decreases in the range of cumulative catch; the more tracks, the fewer runs for a given total number of tows. This, in turn, leads to decreases in the denominator of Equation (4), the sum of squares of x, and the resulting increases in standard error. The lower standard error with increasing number of tows resulted simply from the larger sample size.

The total area to be sampled is proportional to the tow error because of error tracks. The more area you have, the more crabs. This delays decreases in catch with higher tow error. This is the principal reason why the tow error increased bias of q estimates for a given number of tracks. The proportion of the extra area in error tracks to the total area decreases as the number of tracks increases. This might have caused the observed decreases in bias relative to the number of tracks. The change in this "edge effect" was greater when the number of tracks was lower and smaller when the number of tracks was higher, e. g., for the 100% tow error case, the changes in the proportion of the extra area to the total area from one-track to two-track is 0.167 (=1/2~1/3) while the changes from six-track to seven-track is 0.018 (=1/7~1/8).

From the above results and discussion, it was concluded that the four-track experiment was the best on the basis of the precision and accuracy. The four-track experiment yielded q estimates four to nine times more accurate than the one-track experiment. On the other hand the standard error of estimates from the four-track experiments was not more than twice that produced by the one-track experiments. The experiments employing five to seven tracks did not provide much gain in accuracy compared to the four-track experiment even though their standard error was higher.

The simulation results also suggested that the increases in total tow numbers may cause lower accuracy. The standard error decreased rapidly from 8 to 28 tows and became relatively stable for the four-track experiment. Therefore, 20 to 28 tows (or five to seven runs) seems sufficient for a four-track experiment. This would be our new stopping criteria.

Dredging areas of higher crab density resulted in higher standard error for the q estimates but did not affect the bias when q remained constant. The standard error and the bias were proportional to the changes in q when the initial density was the same. However neither crab density nor predesignated q affect the superiority of the four-track experiment.

Even though the four-track experiment was the best in terms of precision and accuracy, the three-track experiment was employed in the actual efficiency experiment for practical reasons. We had to conduct experiments in several types of bottom sediment and depth (Endo, 1992; Zhang et al., 1993). In order to obtain a sufficient number of replications in each category of sediment type and depth, we needed to conduct at least two experiments each day. However, the four-track experimental design with an average of roughly 28 tows would have exceeded these experimental time constraints.

For the three-track experiment, fifteen to eighteen tows was sufficient and this size of experiment seemed more applicable to our purpose. Then, finally, three-track experiment with maximum eighteen tows were determined to employ.

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