Optimal sampling for estimating the size structure and mean size of abalone caught in a New South Wales fishery

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Abstract.–The fishery for blacklip abalone, *Haliotis rubra*, is one of the most valuable in New South Wales, Australia. An important part of the stock assessment process for this fishery is to quantify temporal changes in mean size and size structure of abalone in the landed catch. Variation in abalone growth over small spatial scales in this fishery and differences in harvest strategy among different divers result in large variations in sizes of abalone landed. Monte Carlo simulations were used to investigate the influence of these sources of variation on estimates of mean size and size structure. Different sampling scenarios were considered—from random sampling of all diver-days to a more realistic scheme where abalone were subsampled both within and among diver-days. For a given total number of abalone measured, error in estimated mean size and size structure declined asymptotically with increasing numbers of diver-days. By measuring at least 1,500 abalone from 100 diver-days, reliable estimates of size structure and mean size of abalone in the catch for the whole fishery were produced. This conclusion was robust with respect to the number of diver-days in the fishery. Estimated sampling intensity and probabilities of detecting differences based on simulated variances for the whole fishery are provided.

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Sample-size determination remains a crucial exercise in all aspects of ecology and fisheries biology, and the array of analytical tools available continues to grow (e.g. Gerrodette, 1987; Kimura, 1990; Peterman, 1990; Thompson, 1992). The great majority of these techniques are designed to optimize sampling for data derived from independent samples from a number of hierarchical sources of variation (e.g. Schweigert et al., 1985; Sen, 1986; Andrew and Mapstone, 1987; Kitada et al., 1992; Crone, 1995). Methods for determining sample sizes for describing size- or age-frequency distributions are less common (but see Smith and Sedransk, 1982; Schweigert and Sibert, 1983; Parkinson et al., 1988; Erzini, 1990).

Sample-size determination for the simultaneous estimation of different size classes is possible analytically only under limited circumstances in fisheries applications. If differences among individuals are the only source of variation to be contended with, then the proportion of individuals in each size class in a population may be estimated simultaneously by using the methods developed by Fitzpatrick and Scott (1987) and Thompson (1987), and the calculation of the variances of these estimates are simple.

In most situations facing fisheries biologists, however, there are many sources of variation confounding simple random sampling and sample-size determination for estimating mean size at harvest and the underlying size structure. Typically, catches come from many boats, fishermen, and fishing grounds, and samplers are almost always faced with far more fish than they could possibly measure. Under these circumstances there are many sources of variation that may bias sampling. Not least of these is the likelihood of underlying spatial and temporal heterogeneity in the fished populations and changes in fishing behavior. Monte Carlo simulations provide a relatively straightforward, although computation-intensive, means of determining appropriate schemes in these instances. Sample-size determination for multistage survey designs relies on apportioning sampling effort to various levels on the basis of variance or cost (or both).

The fishery and the problem

The fishery for abalone *Haliotis rubra* in New South Wales (NSW) is managed by using a combination of size limits, closures, and output controls. In 1995, each of 37 divers had an annual quota of 9 metric tons (t). Since 1974, divers have been required to provide details of daily catch weight and diving hours in each of 28 zones (Fig. 1). Divers may catch abalone in any of the zones, which range in length of coastline between 7 and 147 km. In 1994 there was a total of 3,129 diver-days in the fishery and an average of 104 diver-days per zone (Fig. 2A). Based on estimates of average weight per abalone, a catch of between 20 and 760 abalone was landed per diver-day (Fig. 2B). The mean size of abalone caught per diver-day ranged between 116 and 129 mm, although the majority were between 117 and 121 mm long (Fig. 2C). A minimum size limit of 115 mm has been applied to the fishery since 1987. Fishing pressure in this fishery is intense and the size structure of abalone in the landed catch in each zone may be described by negative exponential distributions of varying instantaneous slope (see examples in Fig. 3).

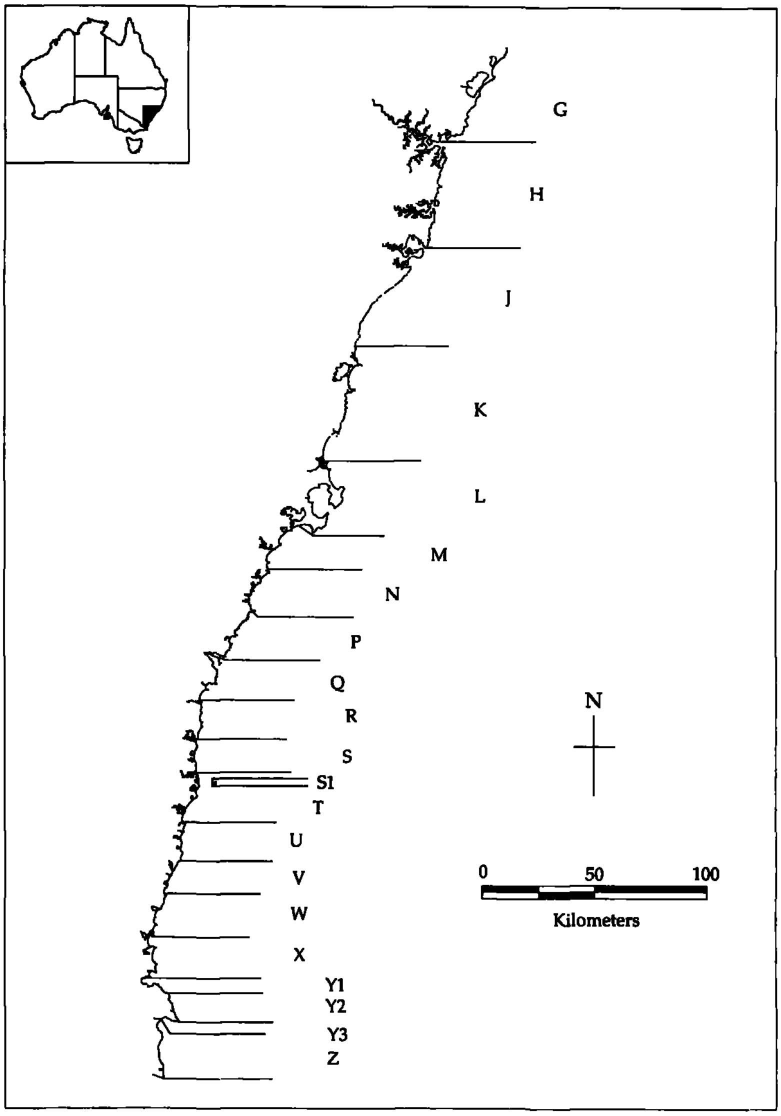

Figure 1

Map of the lower half of New South Wales showing zones in the abalone fishery. The zones are coded alphabetically from north to south.

Determining a sampling scheme to provide reliable estimates of the size structure and mean size of abalone in the landed catch is complicated by differences among diver-days. Worthington et al. (1995) and Worthington and Andrew (in press) have described large variations in demographic parameters, such as growth rate, maximum size, mortality, and fecundity, over a range of spatial scales. These studies report as much variation in the rates of growth and in the maximum sizes of abalone within sites separated by 2 km as there was among sites separated by hundreds of kilometers. Sizes of abalone in landed catches will therefore depend on how and where the diver worked as well as on the demographic attributes of the population being fished. For example, on any day, a diver may work areas where abalone are fast-growing and tend to be larger or areas where abalone are slow-growing and smaller (or both).

In this study we report the results of simulations in order to determine an appropriate allocation of sampling effort to estimate mean sizes and size structures of abalone in the landed catch in the New South Wales fishery. Sampling is considered for groups of zones and for the whole fishery. A simulation approach was adopted in preference to an analytical solution (e.g. Cochran, 1977) because we were interested in simultaneously optimizing sampling across a number of size classes—all of which were nonindependent. The simulation procedure allowed an estimation of the deviation of samples of different sizes from a known or true population. Parameters used in the simulations were based on preliminary sampling in 1993–94.

Materials and methods

Simulation study

A Monte Carlo simulation approach was used to estimate the relative efficiency of three strategies for sampling abalone:

1 Sample all abalone from randomly selected diver-days;
2 Sample a fixed number of abalone randomly from the catches of all diver-days; and

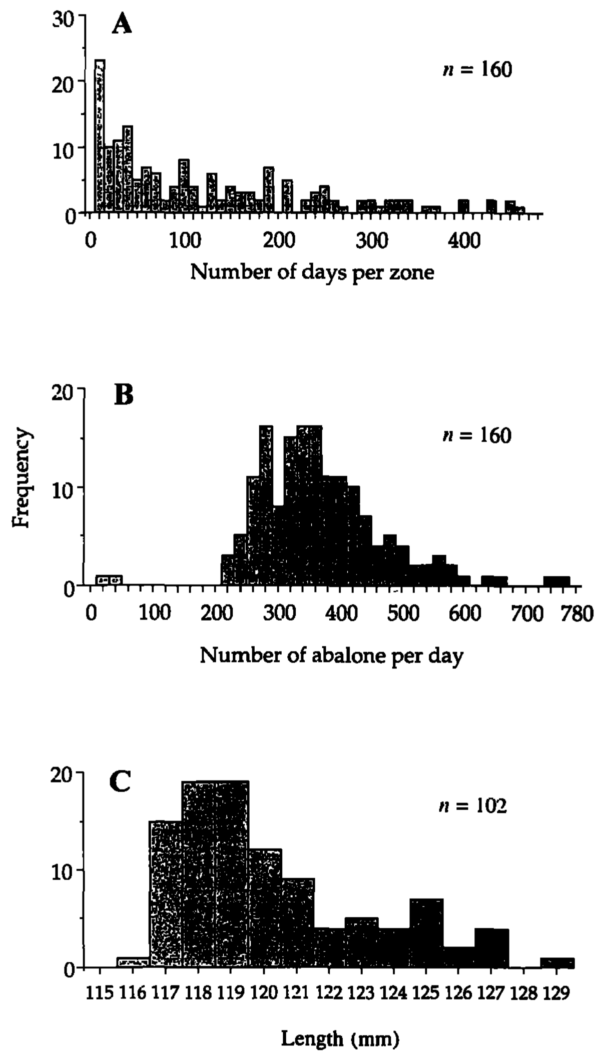

Figure 2

Summary statistics from the NSW abalone fishery for 1993 and 1994: (**A**) Frequency distribution of the number of days per zone, (**B**) Frequency distribution of the number of abalone per diver-day calculated from known average weights per abalone, (**C**) Frequency distribution of the mean length of abalone caught per diver-day. Sample sizes indicated are the number of diver-days.

3 Sample a fixed number of abalone randomly from diver-days selected randomly.

Of the three strategies, the third is the most logistically and financially reasonable. There is considerable unpredictability in where and when divers will work both because of weather conditions and a reluctance by divers to specify where they will work on a given day. These facts conspire to make it difficult to sample in a truly random manner. Nor is it practical to stratify appropriately across either divers or days because the population of diver-days to be sampled can be determined only in retrospect. For these reasons we have used a "diver-day" as the unit of stratification. Three sources of variation are confounded in "diver-day." Differences among divers, as a result of their fishing behavior (e.g. experience and ability) could not be separated from the variation inherent in where they fished, and therefore in the abalone caught. The third source of variation pooled into diver-day is the day itself (e.g. weather and sea conditions). Although these sources of variation were inseparable within the present study, the inferences drawn about a representative sampling scheme are not confounded. Strategy 1, although desirable, would limit the number of diver-days that could be sampled given a fixed total sampling effort. Strategy 2 represents the "ideal" sampling scheme and is used as a standard from which the remaining, more realistic, schemes are judged.

Parameters of the simulation

Parameters were determined for the simulations by using information collected during the 1993–94 fishing years. We assumed that there is as much variability in parameters among diver-days within a zone as among zones. Sampling schemes for zones or groups of zones and for the whole fishery were assessed by varying the total number of diver-days in the "fishery" per year. We therefore ran simulations by using up to 600 diver-days to determine sampling schemes for zones and groups of zones and simulated a 4,000-d fishery to determine a sampling scheme for the fishery as a whole.

Step 1 (determination of the number of abalone caught per diver-day) Based on previous sampling (Fig. 2B), the numbers of abalone caught in all diver-days were grouped into different catch groups ranging from the midpoint of 20 to 760 abalone, with the interval of the catch groups being 20. Thus, the total number of catch groups is 38 (i.e. (760–20)/20 + 1 = 38). The frequency of the number of abalone caught per diver-day was then estimated. Based on these frequencies, the total catch per diver-day was determined by multinominal sampling described as follows. Let P_J = probability of the number of abalone harvested in a diver-day in catch group J, where J = 1, 2, ..., 38. The catch of diver-day i was determined by generating a random number R between 0 and 1 based on the uniform distribution and by assigning this number to one of the catch groups. The catch was assigned to catch group J if the random number followed

$$\sum_{k=1}^{J-1} P_k \le R < \sum_{k=1}^{J} P_k .$$

After determining the catch group (i.e. J) for abalone harvested in diver-day i, the number of abalone harvested in diver-day i was determined as

$$C_i = (J - 0.5)20 + 20U,$$

where U is a random number between 0 and 1 generated from a uniform distribution. Because J in this equation has been determined from the previous equation, we have omitted the subscript $_J$ from C_i for the sake of simplicity. This procedure was repeated for all diver-days in each simulation to determine the number of abalone harvested in each diver-day.

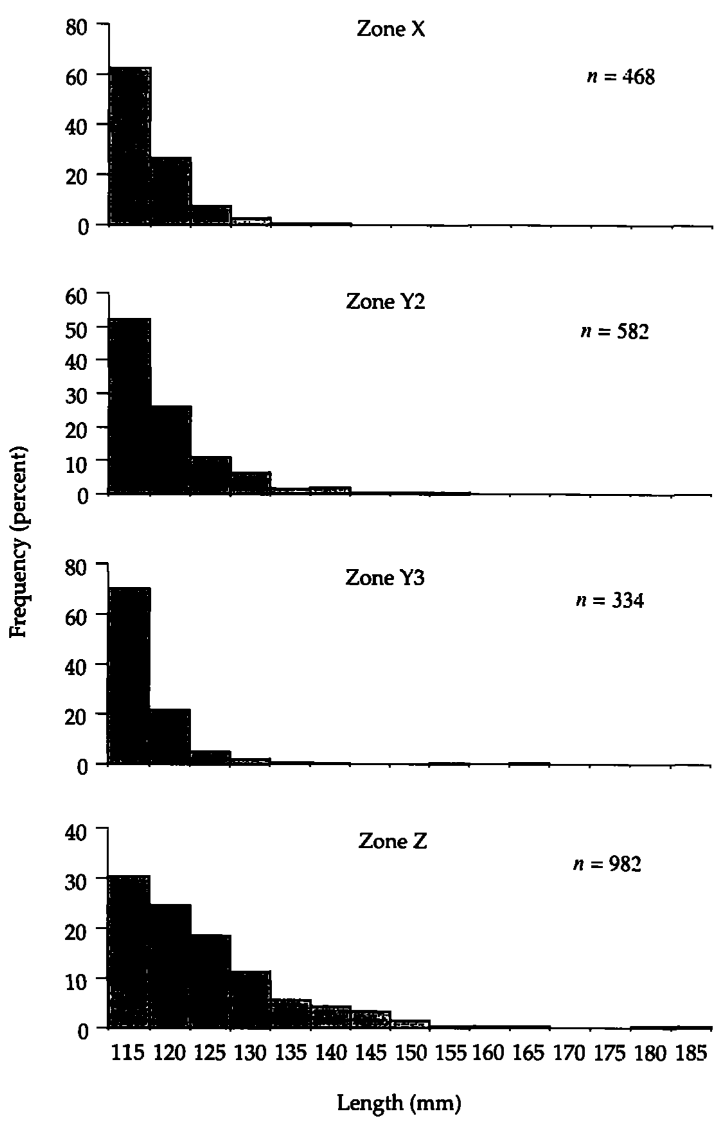

Figure 3

Examples of length-frequency distributions of abalone from four zones in the NSW abalone fishery. Data were pooled among diver-days from 1994.

Step 2 (determination of the mean length of abalone caught per diver-day) The mean length of the catch for each diver-day was determined from the estimates derived from sampling 102 diver-days in 1993–94 (Fig. 2C). Lengths of abalone were measured to the nearest mm from catches from a range of zones and are assumed to be measured without error. The estimates of mean size ranged from 116 to 129 mm. Let P_I = probability of the mean length in length interval I (I = 1, 2, ..., 14). The mean length for diver-day i was determined by generating a random number R between 0 and 1 based on a uniform distribution and by assigning this number to one of the length intervals. The length was assigned to length interval I if the random number followed

$$\sum_{k=1}^{j-1} P_k \le R < \sum_{k=1}^{j} P_k .$$

After determining the length interval (I) for the mean length of abalone harvested in diver-day i, the mean length of diver-day i was determined as

$$L_i = I + 115(\text{mm}),$$

where 115 mm is the size limit. This procedure was repeated for all diver-days in each simulation to determine the mean length of abalone caught per diver-day.

Step 3 (determination of length composition of abalone caught per diver-day) The size distributions of abalone caught in a diver-day may be described by exponential distributions with varying slope, truncated at the lower limit by the legal size limit and at the upper limit by the value T, which was determined by random draws from the range of extreme values observed in preliminary sampling. The density function for such an exponential distribution can be written as

$$P(x) = Ae^{\frac{-(x-a)}{\sigma}},$$

where $a \le x \le T$, and A and σ are to be estimated. For an exponential distribution with the above density function, $E(x) = a + \sigma$ and A is a constant defined by a, σ, and T. For a discrete variable X with the interval width d, constant A can be approximately estimated from

$$A\sum_{i=1}^{N} e^{-\frac{(x_i-a)}{\sigma}} = 1,$$

where $$N = \frac{T-a}{d} + 1.$$

Solving this equation, we have

$$A = \frac{1}{\sum_{i=1}^{N} e^{-\frac{(x_i-a)}{\sigma}}}.$$

The lower bound (parameter a) is the size limit of 115 mm and is the same for all diver-days. Parameter T ranges from 117 to 150 mm among diver-days. For a diver-day i, parameter T_i was determined by randomly drawing an integer between 117 and 150 mm on the basis of the uniform distribution. For diver-day i, the mean size s_i was randomly selected from the frequency distribution of mean size estimated from data gathered in 1993–94 (Fig. 2C). The error σ for diver-day i is estimated as $\sigma_i = s_i - a$. Thus, the probability of abalone in length interval j being caught on diver-day i, $P^*_{i,j}$, was calculated. The number of abalone in length interval j caught in diver-day i, $C_{i,j}$, was then calculated as

$$C_{i,j} = C_i P^*_{i,j}.$$

Evaluation of the simulation

The size-frequency distribution and mean size of abalone at harvest calculated from the total catch of all diver-days were used as the "true" population of landed catch. Different sample sizes were used for each sampling scenario and compared to this known population. For each sampling scenario, 100 simulation runs were conducted. An error index, after measuring the difference between length-frequency distributions calculated from the catch of all diver-days in a year and from the sampled catch, was calculated as

$$\textit{Error index} = \frac{\sum_{h=1}^{100} \sqrt{\sum_{k=1}^{N} (T_k - O_{h,k})^2}}{100},$$

where T_k is the frequency of abalone in length interval k calculated from the total catch of all diver-days. This population was fixed among runs h calculated from the total catch of all diver-days, and $O_{h,k}$ is the frequency of abalone in length interval k in simulation run h calculated from the sampled catch. Thus the error index provides an index of the summed deviations from the true population across all size classes.

The difference between mean sizes of abalone estimated from the catch of all diver-days and from the sampled catch was evaluated by using an index defined as

$$\textit{Average absolute difference in mean} = \frac{\sum_{h=1}^{100} \left|\hat{M}_h - M\right|}{100},$$

where $\hat{M}_h$ is the estimated mean of the h^{th} simulation run for the sample catch and M is the mean of the total catch (i.e. the true mean size). The distribution of the calculated difference in means for 100 simulation runs was used to evaluate the variation in estimated average difference in mean size.

Results

We concentrated on results of simulations appropriate to estimating the size structure and mean size of abalone for the smaller spatial scale—that of zones or groups of zones. Results will be presented across a range of sample sizes for zones or groups of zones with up to 600 diver-days per year. We briefly discuss results for the whole fishery by sampling 100 diver-days in a fishery of 4,000 diver-days under scenario 3. Probabilities of detecting changes in mean size of abalone under this scheme are provided.

Under scenario 1, in which all abalone caught in a randomly selected diver-day are measured, there was a sharp decline in the error index of size composition as the number of diver-days sampled increased from 1 to 10 (Fig. 4). After 10 diver-days, the rate of decline in the error index slowed markedly. As expected, as the number of diver-days sampled approached the number of diver-days in the fishery, the error approached zero (Fig. 4). There was little variation in the error index among fisheries with 400 to 600 diver-days per year (Fig. 4). A similar pattern was observed in comparing differences in the mean size between the sampled catch and the total population for all sizes of the fishery (Fig. 4). For example, irrespective of the number of diver-days per year, when 10 diver-days were sampled, the average difference in mean size was 5 mm over 100 simulation runs.

Under scenario 2, diver-days were ignored as a source of variation and all abalone caught during the year had an equal probability of being sampled. This is not a reasonable sampling scheme for most fisheries but provides a standard against which the others may be judged. Many more abalone must be measured under scenario 1 than scenario 2 to achieve comparable error indices (Figs. 4 and 5). For example, if under scenario 1 a total of 10 diver-days are sampled (approximately 3,400 abalone measured), then the error index is approximately 0.04. This level of error could be achieved by measuring only 400 abalone randomly distributed across all diver-days. As an example of variation in sampling under scenario 2, consider the differences in error index and difference in mean size when sampling 100 abalone and 1,000 abalone in a fishery of 400 diver-days (Fig. 5). Across the range considered (100–600 diver-days), the size of the fishery made little difference to estimates of error in the size composition or mean size of individuals (Fig. 5).

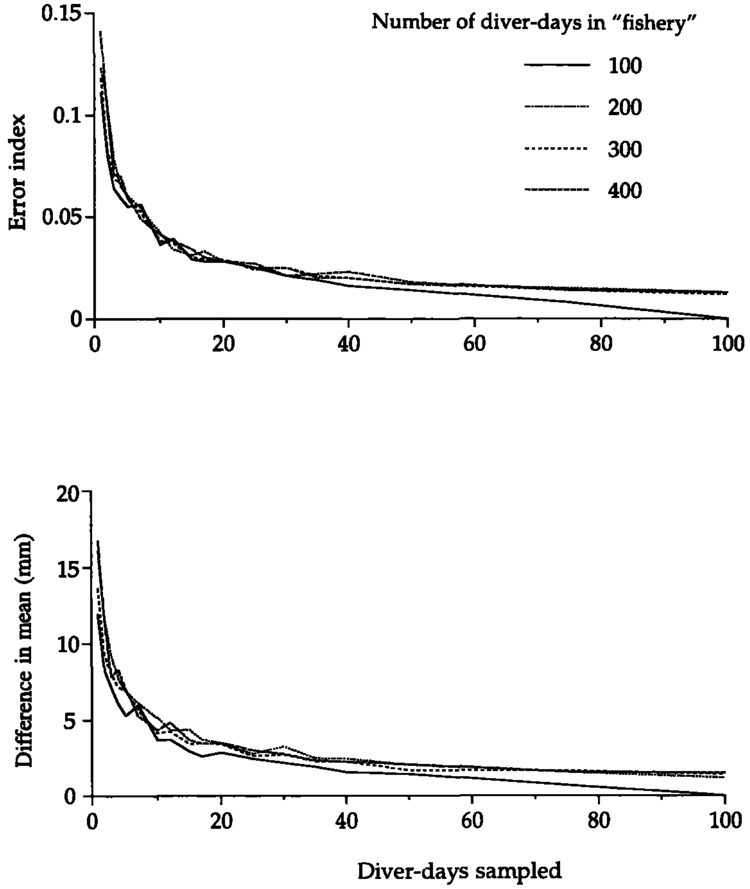

Figure 4

Errors in size composition and estimated mean size of abalone caught in different sizes of the "fishery" with sampling scenario 1. Calculation of the error index for the size composition and of the average difference in mean is described in the text.

Under scenario 3, the most realistic of the sampling schemes, there were large differences in the error index, depending both on the number of abalone sampled in total and the number of diver-days sampled (Fig. 6). The magnitude of error was not, however, greatly influenced by the total number of diver-days per year (Fig. 6). The results suggest that, although the error in estimating the size-frequency composition depended on the total number of abalone sampled, the rate of decline in the error index was similar among all sample sizes (Fig. 6). In all cases, the rate of decline in the error index reached an asymptote at approximately 20 diver-days. For zones or groups of zones with up to 600 diver-days per year, there was an approximate two-fold reduction in the error index by increasing the total number of abalone measured from 100 to 1,000 abalone (Fig. 6). There was little further reduction in the error index by increasing replication from 1,000 to 1,500 abalone (Fig. 6).

The average error in estimated mean size of abalone declined rapidly with increasing number of diver-days between 1 and 15 diver-days (Fig. 7). Further increases in simulated sampling effort produced relatively modest gains without large increases in the number of diver-days sampled. For example, doubling the sampling effort from 15 to 30 diver-days caused only minor increases in precision (Fig. 7). In contrast to the patterns in errors in estimated size composition, increases in the total number of abalone measured from 100 to 1,500 produced little reduction in the average difference in mean size (Fig. 7).

The relative importance of diver-days as a source of variation is demonstrated by the difference between sampling a total of 100 abalone spread across five days and sampling 2 abalone on each of 50 diver-days (Fig. 7). In the latter case, the average difference in mean size between the true and estimated distributions and the sample was approximately 2 mm, in contrast to 6 mm when 100 abalone were sampled in 5 diver-days. The difference between observed and expected means was considerably smaller in comparing 200 abalone in each of 5 diver-days with the same total number of abalone spread over 50 diver-days irrespective of the size of the fishery (Fig. 7).

In considering the sampling scheme required for the whole fishery, scenario

3 was scaled up to a larger number of diver-days per year. In 1994, there was a total of 3,129 diver-days in the fishery. We simulated the efficiency of measuring 50 abalone per day in 100 diver-days in a fishery of 4,000 diver-days. At this sampling intensity, the estimated error index for the size structure and average difference in estimated mean size of abalone were 0.018 and 1.5 mm respectively.

The cumulative frequency distribution (Fig. 8) presents the probability of correctly rejecting the hypothesis of no difference under two scenarios. In the first, the probability of detecting a "real" difference between an estimated mean size and a nominated size is given. This nominated size may be a management benchmark, significant deviation from which will cause a change in management, such as a quota reduction. If, for example, the difference between a management threshold and an estimated mean size is 3 mm, there is an 85% chance that the observed difference is "real" and not sampling error (Fig. 8, line b). If the observed difference is greater than 3 mm, then the probability of this being due to sampling error is less than 15%.

In the second scenario, this logic is extended to situations in which differences among years are considered. In this instance, both estimates of mean size are measured with error. If, for example, there is a 3-mm difference in mean size between two years, the probability of incorrectly interpreting this as a real difference among years, i.e. more than sampling error, is 0.85 × 0.85 = 0.72 (Fig. 8, line a).

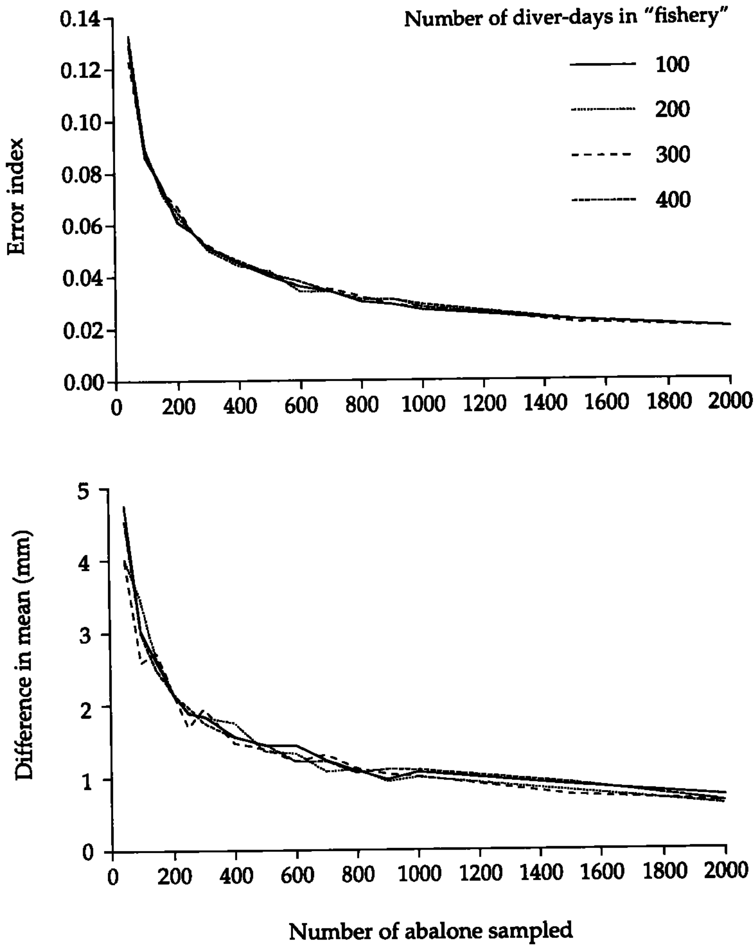

Figure 5

Errors in size composition and estimated mean size of abalone caught in different sizes of the "fishery" with sampling scenario 2.

Discussion

Many stock assessment methods rely on reconstructions of the demography of exploited populations, using age-structured information (e.g. Fournier and Archibald, 1982; Deriso et al., 1985; Megrey, 1989; Kimura, 1990; Terceiro et al., 1992). Stock assessment methods available for species that cannot be aged are more limited, although recent development in size-based analogues of age-structured models have expanded the range of methods available (e.g. Sullivan et al., 1990). Size-based methods have traditionally relied on reducing size-frequency distributions into cohorts (e.g. Bhattacharya, 1967; Schnute and Fournier, 1980; Grant et al., 1987; Castro and Erzini, 1988). The reliability of these methods depends in large part on the representativeness of the sample distributions and the shape of the size-frequency distribution (e.g. Smith and Maguire, 1983; Chen, 1996).

The sampling scheme described in this study is essentially a stratified random design, with diver-day being the intermediate stratified factor (see also Sen, 1986; Kitada et al., 1992; Crone, 1995). An alternative approach used in sample-size determination for estimating age composition has been described by Schweigert and Sibert (1983). Their approach was to determine sample-size requirements for each size and age class separately and to develop an overall sampling scheme as a compromise solu-

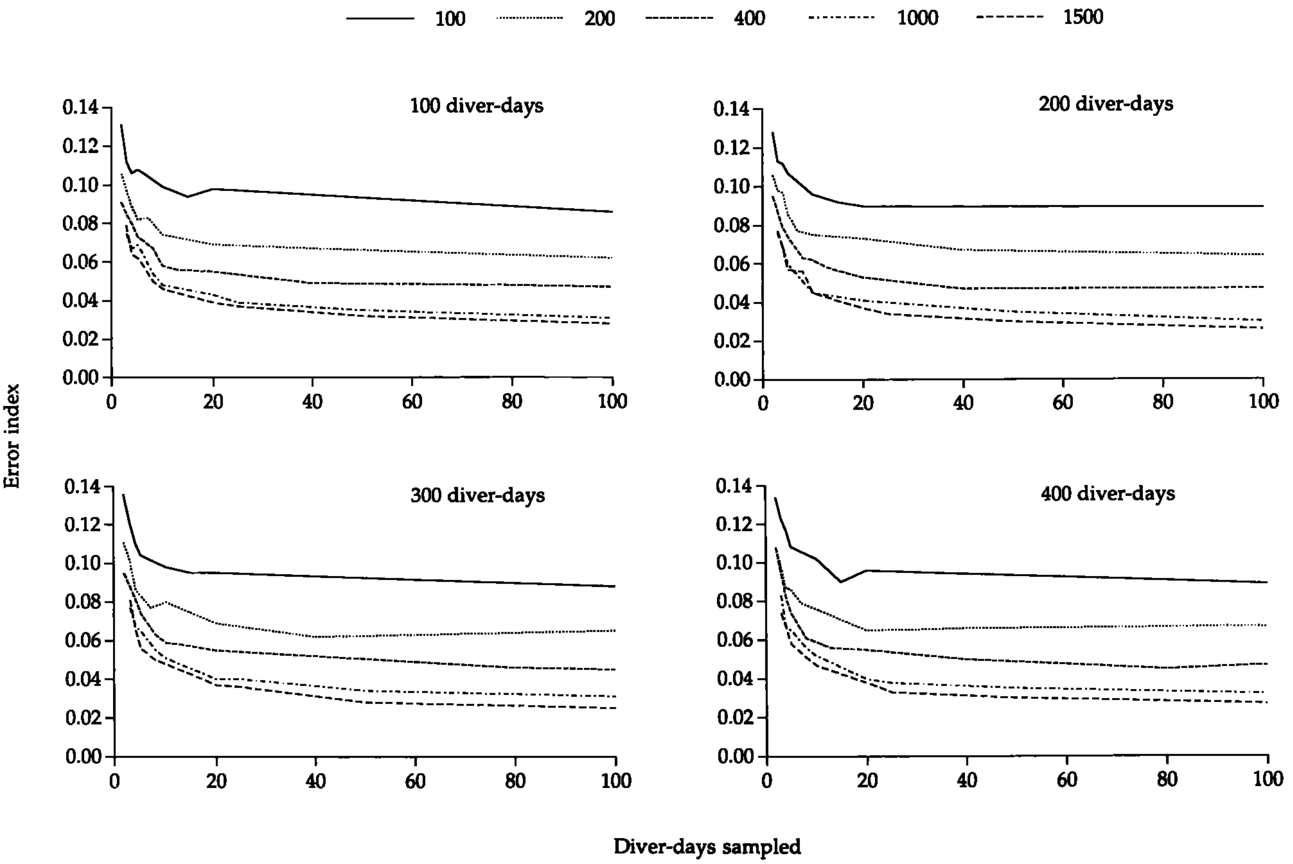

Figure 6

Errors in estimating the size composition of abalone caught in different sizes of the "fishery" with sampling scenario 3. "Fisheries" of 100, 200, 300, and 400 diver-days were considered. Sample sizes indicated on the figure are the total number of abalone measured.

tion among those classes (see also Horppila and Peltonen, 1992). This approach was not appropriate for our situation because we were interested only in the size structure of landed abalone—*Haliotis rubra* can not be reliably aged by analysis of growth rings (McShane and Smith, 1992). The Monte Carlo approach that was adopted allowed us to simulate the simultaneous estimation of all size classes in the population.

The simulations described were based on the assumption that the size structures of abalone within a diver-day were distributed as a negative exponential function. If the fishery declined, the mean size of abalone would probably decline and the slope of the fitted exponential curve would increase. If this occurred, then the sampling scheme described would be conservative. If, however, the fishery improved and larger abalone were caught, then the size-frequency distribution might depart from the negative exponential distribution. If such a departure was significant, then the simulations would need to be reparameterized and each sampling scenario reexamined to determine an appropriate sample size for estimating the size structure of abalone in catches.

One of the objectives of this simulation study was to estimate the probability of detecting varying changes in mean size of abalone at harvest. Advice on trends in mean size at harvest may be given at two spatial scales: that of the whole fishery and that for individual zones or groups of adjacent zones. At present, the NSW abalone fishery is managed as one stock— size limit regulations and quota allocations are made on a statewide basis. Management measures, such as closures, are, however, possible at the smaller spatial scale if there are declines in indices of abundance (including mean size at harvest). Indeed, abalone stocks are increasingly being seen as comprising metapopulations of relatively discrete populations (see references in Shepherd et al., 1992), and thus such management measures are likely to be effective.

The simulations suggest that sampling more than 1,500 abalone spread across 100 diver-days would

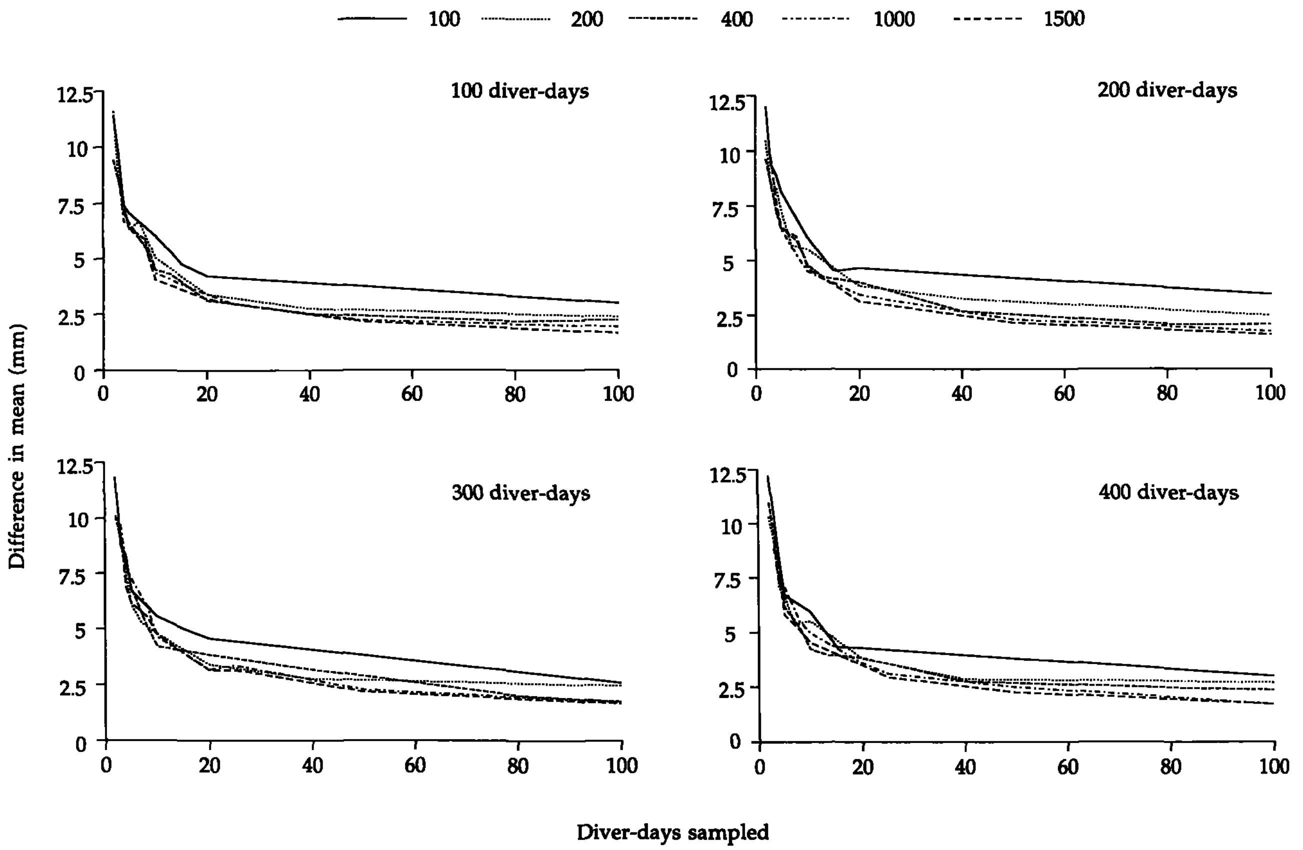

Figure 7

Errors in estimating mean size of abalone caught in different sizes of the "fishery" using sampling scenario 3. "Fisheries" of 100, 200, 300, and 400 diver-days were considered. Sample sizes indicated on the figure are the total number of abalone measured.

provide reliable estimates of the size structure of abalone in the landed catch and would detect relatively small changes in the mean size of abalone at harvest for the whole fishery. How small those changes are will be determined by how likely managers are prepared to accept the possibility of being wrong. At a smaller scale, 1,000 abalone from 20 diver-days would be needed to achieve a similar degree of discrimination. More intensive sampling did not greatly improve the reliability of these estimates over the range simulated. The simulations suggest that differences among diver-days were an important source of variation (see also Kitada et al., 1992; Crone, 1995).

Interpretation of trends in mean size of individuals among years requires some care. Divers may change their diving patterns among years, and fish populations may change with different demographic attributes. These patterns alone may produce changes in the composition of the landed catch independent of any underlying trend in the fishery. In essence, this problem is analogous to that in interpreting catch-rate information from heterogenous fisheries, such as abalone. Several authors have claimed that apparent stability of catch rate is possible despite declining abundance of abalone as a result of changing diver behavior (e.g. Hilborn and Walters, 1987).

In these simulations we did not weight sampling effort in scenario 3 for the number of abalone caught in a diver-day. We, therefore, assume that there is no relation between the size and number of abalone caught. Using data from 1993–94, we found that there is no significant relation between the number of abalone caught in a diver-day and the size of those abalone. The impact of weighting is further diminished by the fact that the fraction sampled per day is relatively high, irrespective of the number caught (usually >25%). We assume that this sampling fraction provides a reliable estimate of mean size within diver-days.

The results of these simulations suggest that the large sample sizes possible in estimating mean size

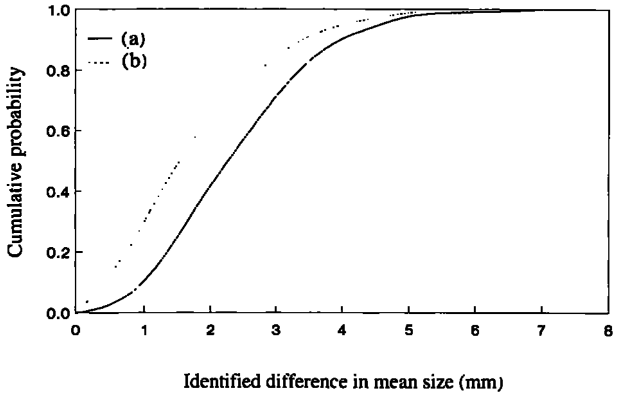

Figure 8

Cumulative distribution of the probability of correctly rejecting the null hypothesis of no difference between (A) two estimates, both measured with error and (B) an estimated mean size and a predefined value, measured without error. The distribution is based on 1,000 simulation runs with a sampling intensity of 50 abalone per day in 100 diver-days in a fishery of 4,000 diver-days.

of abalone at harvest may provide a false sense of reliability if higher level sources of variation are ignored. If variation above that found among abalone within a diver-day is not included, false conclusions may be drawn about the statistical significance of trends through time, both because of unrepresentative sampling and imprecise estimates of variability.

In the present study, the relatively large differences in sizes of abalone among diver-days meant that even relatively high sampling fractions (>10 %) would have a relatively low probability of detecting changes in mean size less than 3 mm. This conclusion appeared to be robust over a realistic range in the number of diver-days sampled. Given the broad similarities between the sampling scheme described for this fishery and those in many commercial fisheries, concerns may be raised about the reliability of samples taken from processing plants in the absence of an understanding of the contributions of higher level sources of variation. The simulation framework described may be directly expanded to accommodate more complex situations.

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