A comparison of two underwater census methods for estimating the abundance of the commercially important blacklip abalone, *Haliotis rubra*

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Abstract.—The blacklip abalone, *Haliotis rubra*, fishery is the most commercially important in Victoria, Australia. Two underwater census methods have been used to survey the status of its stocks. Collection rates from timed searches and counts from radial transects were used to estimate abalone abundance at various locations along the Victoria coast. Radial transect surveys provided precise estimates of abalone abundance; these did not vary significantly between research divers under controlled conditions. During stock monitoring, there were no significant differences among nine of twelve research divers' estimates of abalone abundance from 1339 radial transects sampled at 60 sites during 1992–94. Monte Carlo simulations, used to estimate the probability of detecting annual changes in abalone abundance with each method, provided evidence that radial transects have the potential to detect smaller annual changes in abalone abundance than do timed searches. We suggest that radial transects provide a credible alternative to timed searches and are less subject to potential biases that affect the latter.

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Most analyses of fish stocks are based on catch per unit of effort (CPUE) as a measure of abundance. There appears, however, to be consensus among investigators of abalone that fisheries-dependent methods are inadequate for the estimation of the abundance of abalone stocks. Reasons for this are well documented (Breen, 1992; McShane and Smith, 1992; Prince and Guzmán del Próo, 1993) and include difficulties in estimating the true catch (due in no small part to the prevalence of illegal harvesting) and hyperstability in catch rates despite stock reduction (Hilborn and Walters, 1992). The latter stems from the highly efficient searching behavior of abalone divers who, by targeting large aggregations of abalone, may serially deplete substocks (Prince and Guzmán del Próo, 1993).

Victoria, Australia's second largest abalone-producing state, yields a total annual quota of 1440 metric tons (t) of abalone from approximately 121 km^2 of commercially productive reef complexes distributed along approximately 1500 km of coast (McShane et al., 1986). The Victorian abalone fishing grounds are subdivided into central, eastern, and western zones (Fig. 1), each with its own total allowable catch (TAC). Abundance estimation methods used to survey such an extensive distribution of abalone stocks must be simple so that they may be applied under often adverse sea conditions and so that several sites may be sampled per day.

A reliable survey method for the estimation of abalone abundance has yet to be determined although several diving-based methods are currently used to assess the status of stocks in southern Australia and New Zealand. These include timed searches (McShane, 1994), transect surveys, patch-size estimates (McShane, 1996), change-in-ratio (Nash et al., 1994), and Petersen mark-recapture surveys (Hart and Gorfine, 1997) to provide measures of relative abundance. The intention of such surveys is to provide trends in relative abundance necessary for assessment of stock status. These methods have the advantage of being fishery independent.

However, underwater census methods are characterized by variation between research divers. In particular, relative abundance estimates from timed searches must be standardized between research divers to achieve uniformity in the base sampling unit (10 minutes). Standardization of many research divers, each represented in the data for relatively few years of a long time series, is problematic. Strip transects can be time consuming and may traverse nonabalone habitat, such as sand; however they provide a consistent base sampling unit among research divers. Patch-size estimates have the advantage of providing a measure of the number and size of aggregations of abalone but are disadvantaged by difficulties in selecting appropriate patch-size categories and maintaining consistency in the area searched during surveys. Change-in-ratio (CIR) has the advantage of not being dependent upon a particular base sampling unit, such as time or area. However, CIR requires that there is no change in one of the two animal categories in the ratio, in this instance prerecruits. This means that the time interval between surveys must be sufficiently short that the effects of growth and natural mortality on the relative abundance of prerecruit abalone can be considered negligible. Mark-recapture (M-R) surveys are time consuming, require that many abalone be tagged, require an estimate of tag loss, may incur incidental mortality due to tagging, assume that the tagged abalone will disperse randomly within the untagged population, and can be affected by migration to and from the study site and into and out of cryptic habitat. If these limitations can be overcome, then M-R can be an effective abundance estimation technique that is free from the research diver effects that characterize other methods.

We introduce a new radial transect survey method for estimating the abundance of abalone and furnish the results of a preliminary comparison with timed searches previously used in Victoria. This new method was developed as an alternative to timed searches because 1) standardization of the effects of research divers who conducted surveys prior to 1992 with those involved in surveys from 1992 onwards was not possible and 2) the depths at many of the reefs surveyed were sufficient to warrant limiting the number of ascents made by research divers each day in order to reduce the divers' risk of decompression illness. We present an analysis of investigations into the effect of research divers on abundance estimates and the probability of detecting interannual changes in abundance with both survey methods. In Victoria, trends in interannual abundance for each management zone have been used as part of an adaptive management strategy. Several successive years of decrease in abundance will trigger consideration for decreasing annual quotas and similarly consideration will be give to increasing quotas where trends in abundance appear to be increasing. Whether quotas are changed and by how much will largely depend on the size of the change in abundance. It is anticipated that this approach will lead to the achievement of quotas that will minimize interannual changes in abalone abundance and thereby optimize sustainable yields from the fishery.

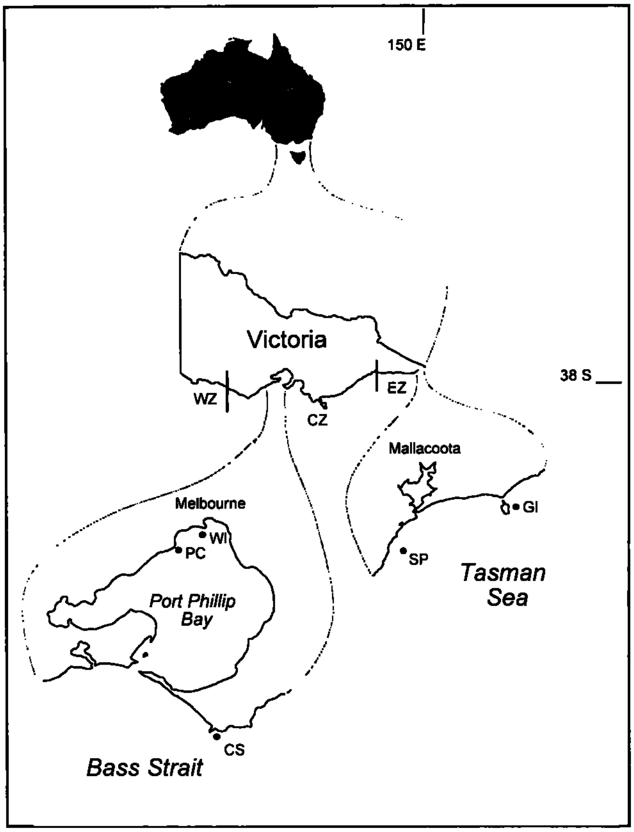

Figure 1

Location of study sites and management zones along the Victorian coast. CS = Cape Schanck; GI = Gabo Island; PC = Point Cook; WI = Williamstown (includes Sticks Reef); SP = Sandpatch Point; CZ = central zone; EZ = eastern zone; WZ = western zone.

Materials and methods

Survey methods

Radial transects Estimates of abalone abundance with radial transects were performed by research divers. At a particular site, a buoyed shot-line (a 20-mm-diameter line anchored by a 20-kg lead weight) was deployed. A stainless steel ring and swivel were used to connect a 35-m long transect-line of 20-mm-diameter line marked at 5-, 15-, and 20-m distances to the lead weight. The transect lines were made from a form of nylon rope that tends to float to the surface, thus decreasing the likelihood of the lines becoming tangled. Dives were made with a surface-supplied breathing apparatus (SSBA) with an umbilical length of 100 m.

Prior to a dive, each diver was randomly allocated three or four compass bearings. On the bottom, each diver oriented himself towards the appropriate compass bearing and tucked the floating transect-line under his arm. Each diver was instructed to use a plastic laboratory tally counter to count, or an abalone iron to collect (depending on the study), emergent abalone larger than 50-mm shell length within an approximately 1-m wide strip from the 5-m mark laterally along the transect line. Abalone smaller than 50 mm were ignored because previous experience had shown that these juveniles were difficult to locate and were likely to be subject to large sampling errors among divers. Where estimates of the abundance of juvenile abalone were required, cryptic habitat within the transect was searched thoroughly by overturning boulders and examining crevices. These searches for juveniles were relatively time consuming. The width of the transect was constrained by the distance from the transect line under the diver's armpit to the hand of the outstretched arm on the opposite side of the diver's body. When abalone were not collected, separate counts of prerecruit abalone, i.e. those individuals smaller than the legal minimum length (LML), and of postrecruited abalone (larger than the LML) were made with a simple measuring gauge for discrimination. Each diver covered a linear distance of 30 m to survey an area of about 30 m^2 per transect. Any part of an aggregation of abalone falling outside the designated 1-m width was not included in the count. Underwater counts were made in instances where the removal of abalone would have interfered with further surveys of the study sites. However, during routine stock monitoring, abalone were collected and taken aboard the research vessel to obtain length-frequency data.

Each diver made additional collections in different directions radiating from the same point before surfacing. Total bottom time for each dive was usually between 30 and 60 minutes.

Timed searches The timed search method was the same as that described by McShane (1994), where each diver made timed searches at randomly selected subsites within each site previously surveyed by radial transects. Commencing at the research vessel's anchor, a pair of divers independently collected as many abalone as possible within a subsite in 10 minutes, using a nylon mesh catch bag and an abalone iron for removing the abalone off rocky substrata. Divers were free to search as much area as their surface air supply hose would allow (about a 100-m radius from the research vessel).

Operator effects on methods

Diver effects on radial transects Variation among divers and each diver's precision with radial transects were investigated at Gabo Island near Mallacoota (Fig. 1). Precision was defined as the level of congruency among an individual diver's repeated counts of the same transect. A team of four scientific divers, each experienced in radial transects, completed two experiments at a fixed site. The objective of the first experiment was to estimate the precision of abalone counts by each diver. This was done by randomly assigning three transects from a set of twelve to each diver and by having them repeat abalone counts along the three allocated transects four times. Precision estimates for each diver were obtained as the quotients of the standard errors of the four counts for each transect divided by their mean count and were compared between divers by a one-way analysis of variance.

The second experiment compared differences among divers' abundance estimates. Each of the four divers completed counts along each of the twelve transects used in the first experiment. An analysis of variance was performed to test the hypothesis that differences among divers' mean abalone counts were not significantly different.

During both experiments, the reference shot-line remained undisturbed. Sea conditions were consistent throughout the day. Surge was slight and horizontal underwater visibility was about 10 m. The study site provided bottom topography that ranged from high relief with deep crevices to open ground with scattered boulders.

Comparison of diver effects on radial transect and timed search survey methods Timed search and radial transect methods were compared during abalone abundance surveys conducted on reefs at Cape Schanck, Point Cook, and Williamstown (Fig. 1). These reefs were selected to provide variety in topography, sea conditions, and abalone population structure. One site was selected at random on each of the three reefs. We tested the hypothesis that there were no significant differences in abalone abundance estimates between research divers for either sampling method. Sea conditions at each site were consistent between sampling methods but varied between the sites. In Port Phillip Bay (Point Cook and Williamstown) wind was slight, swell height was negligible, there was no surge, and horizontal underwater visibility was less than 3 m, whereas at Cape Schanck there was considerable surge (swell height 1–2 m) and underwater visibility was about 6 m.

Two experienced scientific divers, each expert in one of the techniques (>300 dives) but neither hav-

Table 1

Analysis of variance in density estimates, made from radial transect collections, among fifteen sites nested within three locations and among four divers for each of three size classes of *H. rubra* (type IV SS). ns = nonsignificant; * = $P<0.10$; ** = $P<0.05$; *** = $P<0.01$). ω^2 = relative magnitude of variance estimate (%). MS = mean square.

Class	Source	df	MS	F	P	ω^2	Significance
Juvenile	Location	2	0.14	2.42	0.1312	14	ns
	Diver	3	0.05	1.92	0.1593	14	ns
	Location × diver	4	0.04	1.36	0.2822	3	ns
	Site (location)	12	0.06	1.69	0.0904	41	*
	Diver × site (location)	20	0.03	0.75	0.7631	25	ns
	Residual	63	0.04				
Prerecruit	Location	2	2.36	19.24	0.0002	44	***
	Diver	3	0.06	1.10	0.3723	0	ns
	Location × diver	4	0.08	1.32	0.2936	2	ns
	Site (location)	12	0.12	3.56	0.0003	37	***
	Diver × site (location)	21	0.06	1.70	0.0475	18	**
	Residual	81	0.03				
Postrecruit	Location	2	2.60	9.98	0.0028	43	***
	Diver	3	0.33	3.16	0.0461	16	**
	Location × diver	4	0.14	1.30	0.3027	3	ns
	Site (location)	12	0.26	1.95	0.0393	27	*
	Diver × site (location)	21	0.10	0.78	0.7390	11	ns
	Residual	90	0.13				

ing previously used the other method, performed both techniques to census abalone populations at each study site. Abalone counts in four radial transects and four timed collections of 10-min duration were made by each diver at each site so that the effects of divers and methods were fixed and the design balanced. Timed searches were performed after transect counts in each instance to avoid disturbance due to removal of abalone during timed searches.

Separate analyses for each method were made with general linear models to determine the significance of the effects of diver and site on abundance estimates. A combined analysis was not possible because of the different base sampling units for each method. Where Cochran's test indicated significant heterogeneity of variance, data were log-transformed prior to analysis to achieve homoscedasticity (Winer, 1971). Diver × site interaction was omitted from the analyses presented in Table 1 because preliminary analyses showed this effect to be nonsignificant.

Trial stock surveys

The effects of divers on the detection of differences in abundance were further investigated during trial surveys of substocks at Gabo Island and Sandpatch Point near Mallacoota and Sticks Reef near Altona in Port Phillip Bay (Fig. 1). These surveys were aimed at determining how well variation among several locations was detected with this method when it was applied over a spatial scale comparable to that used in routine stock surveys.

Five sampling sites were randomly selected at each location, and for each site, three out of five divers were selected to undertake the sampling depending on their availability and fitness to dive. Two to three sites at each location were sampled during each day of the surveys. At each site, each diver made three replicate radial transect collections of emergent prerecruit and postrecruited abalone. Each diver also collected juvenile abalone (<80 mm) in one of their three assigned transects by searching cryptic habitat and turning over small boulders. All abalone collected were brought on board the research vessel, and the maximum shell length of each was measured to the nearest mm.

Analysis of variance of the mixed linear model was used to test the effects of locations, sites nested within locations, and divers on abundance estimates. The SAS® general linear model (GLM) procedure was used (SAS Institute, Inc., 1989). Separate analyses were performed for three size classes of abalone (juvenile <80 mm, 80-mm ≤ prerecruit < LML, and postrecruit ≥ LML). Data were converted to number per m^2.

The relative treatment magnitude, omega squared (ω^2), for each effect in the GLM was calculated (Keppel, 1991).

Design of stock monitoring program

Abundance estimates of abalone stocks in Victoria were made annually at 60 sites, using radial transects during 1992 to 1994. These estimates were made during routine stock surveys for the Victorian program for abalone stock assessment. At each site, nine replicate abalone collections were made. Sites were selected from abalone habitat with commercial quantities of abalone. During 1992, sites for radial transect surveys were initially chosen at random from between the 5-m and 18-m isobaths to avoid the wave-break zone and to minimize hyperbaric exposure. Accurate navigational fixes were made at each site with a global positioning system (GPS). During successive years each site was resurveyed after having been located with GPS. This mixed sampling design has been shown to have greater power than nested designs for benthic monitoring and avoids the potential bias of fixed designs (Van der Meer, 1997).

Application of methods to stock monitoring

An analysis of variance was applied to results from stock monitoring surveys to determine the interannual variation in abundance for each zone. This was in the form of a mixed linear model in the SAS® general linear model procedure.

The relative treatment magnitude for each effect in the GLM was calculated with the same procedure as that used in the trial stock surveys.

The effect of differences between research divers on abalone abundance estimates from radial transects was further investigated (with two- and three-way interactions omitted) across all zones from an analysis of 1992–94 stock surveys. During each field survey of a group of adjacent sampling sites, the dive team was composed of three or four out of a possible twelve divers. Differences in the composition of dive teams between surveys occurred for logistical reasons. At each site three divers performed three radial transects each where the allocation of directions for these transects among divers was random. Differences among divers were compared by using Ryan's test (Day and Quinn, 1989), and the effect of diver experience on abundance estimates was determined by regressing divers' mean collections of abalone per transect against the number of transects each diver performed.

Power to detect changes in abundance

Monte Carlo simulations were made to estimate the probability of detecting cumulative annual changes in abundance. The simulations were based on data from stock surveys conducted during 1992 and 1993 that employed radial transects as well as data from 1989 and 1991 surveys based on timed searches. Scenarios involving different combinations of annual change increments (increases) and number of years sampled were each simulated 200 times for each management zone (i.e. central, eastern and western; Fig. 1). Divers were randomly selected from those who participated in the surveys, and the abundance estimates for each radial transect were adjusted for the diver factor and variation within each site, whereas the abundance estimates for timed searches were standardized by using a linear regression between pairs of divers (McShane, 1994). The respective analyses of variance used to analyze the stock survey data for each method were applied to each simulation, and the proportion of tests that showed a significant (α=0.05) annual change in abundance (year effect) was calculated. The proportion of significant results for each management zone was then plotted against the number of years simulated for each increment level. A smoothing function was applied to each curve to eliminate fluctuations due to changes in confidence levels among years in the series.

Results

Operator effects on methods

Diver effects on radial transects During the first experiment at Gabo Island, the precision (SE/$\bar{x}$) of the divers' abalone counts for each transect ranged from 0.04 to 0.27. Cochran's test showed the divers' variances of precision to be homoscedastic (α=0.01). Differences among divers' mean precision values were not significantly different (F=1.43; df =3, 8; P>0.10). Collectively, the four groups of twelve estimates of abundance represent four identical surveys of the same site which yielded similar mean abundance estimates on each occasion (Fig. 2). Estimates of mean abalone abundance for the site during the second experiment were also similar (Fig. 3) and no significant differences were detected among the four divers (F=0.01; df=3, 33; P>0.10).

Comparison of diver effects on radial transect and timed search survey methods There were no significant differences between the two divers when using radial transects (F=0.19; df=1, 2; P>0.10) nor were there significant differences when using timed searches (F=7.31; df=1, 2; P>0.10). Notably, the differences between the divers' mean abundance estimates (Fig. 4) were much smaller for radial transects (effect size=9%) than for timed searches (effect size=44%); thus power in the analysis was likely to be low.

Trial stock surveys with radial transects

There were significant differences in density between all locations for the prerecruit and postrecruit size classes, but locations were not significantly different for juvenile abalone (Table 1). Locations and sites within locations accounted for most of the variation in density of pre- and postrecruit abalone. Significant differences between divers occurred for postrecruits, but the magnitude of the variance effect for divers was only about one third of the variance effect for sites. Sites varied significantly within locations for each size class; for juveniles and post recruits this was at the 10% confidence level, and for prerecruits at the 1% confidence level. Only one interaction effect, diver × site (location) for prerecruit density, was significant.

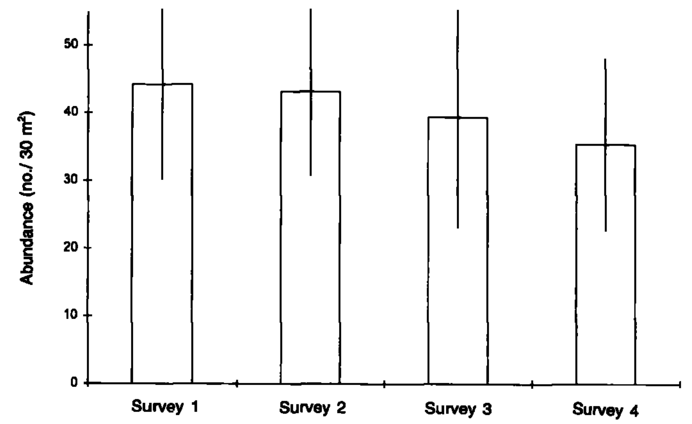

Figure 2

Comparison of mean abundance estimates of *H. rubra* at Gabo Island among surveys using radial transects. Error bars are 95% confidence limits.

Application of methods to stock monitoring

Variation in abalone abundance estimates from both methods showed significant diver effects in two out of three instances (Tables 2 and 3). However, the only significant year effect detected was for estimates from radial transect surveys in the central zone of the fishery. The lack of a significant diver effect in this instance may have increased the power to detect a year effect. Consistent with the high spatial variability that characterizes abalone populations, site effects were significant in all instances. Year × site interactions were significant in two instances for each method, indicating that interannual changes in abundance varied among sites within the affected zones. Only one year × diver interaction was significant and because some divers were not represented in each year, the interpretation of this effect in this instance is problematic.

For each method only a relatively small amount of the variation in abundance could be attributed to the effect of year. Sites generally accounted for most of

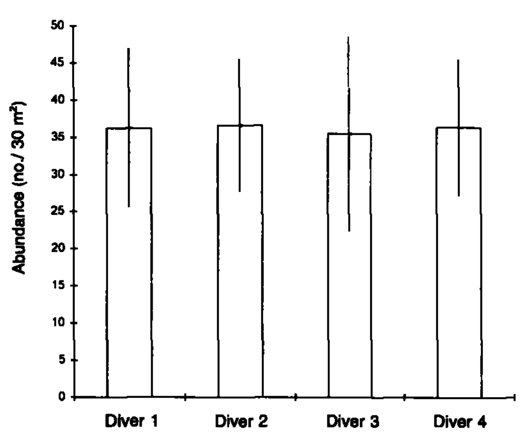

Figure 3

Comparison of mean abundance estimates of *H. rubra* at Gabo Island among divers using radial transects. Error bars are 95% confidence limits.

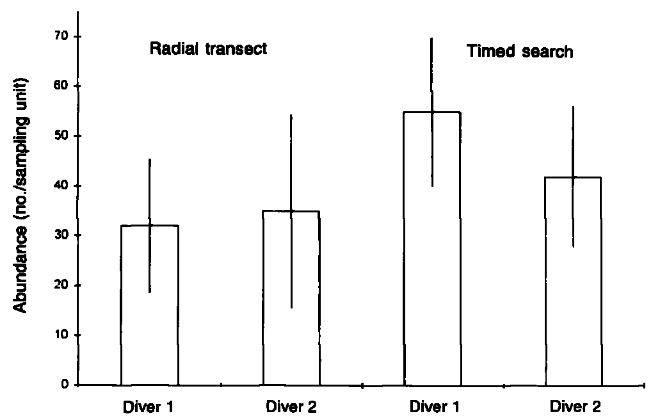

Figure 4

Diver effects on mean abundance estimates of *H. rubra* for each survey method. Error bars are 95% confidence limits; base sampling units were 30 m^2 for radial transects and 10 min for timed searches.

Table 2

Analysis of variance for interannual differences in abundance estimates of *H. rubra* for each of Victoria's fishery management zones, made from timed collection surveys, during 1989–91 (type IV SS). (ns = nonsignificant; * = $P<0.10$; ** = $P<0.05$; *** = $P<0.01$). ω^2 = relative magnitude of variance estimate (%).

Management zone	Source	df	MS	*F*	*P*	ω^2	Significance
Central	Year	2	136.60	0.69	0.5141	1	ns
	Site	28	286.04	2.42	0.0008	45	***
	Diver	16	205.08	1.73	0.0525	13	*
	Diver × site	83	92.85	0.79	0.8714	20	ns
	Year × site	21	198.87	1.68	0.0468	16	*
	Year × diver	4	25.70	0.19	0.9404	4	ns
	Year × site × diver	10	138.32	1.17	0.3207	2	ns
	Residual	98	118.28				
Eastern	Year	2	203.64	1.30	0.2914	1	ns
	Site	13	181.97	1.99	0.0230	18	**
	Diver	8	54.01	0.59	0.7863	5	ns
	Diver × site	71	77.91	0.85	0.7872	15	ns
	Year × site	24	156.81	1.71	0.0241	24	**
	Year × diver	4	60.83	1.59	0.1961	3	ns
	Year × site × diver	41	38.34	0.42	0.9993	34	ns
	Residual	224	91.66				
Western	Year	2	160.84	1.40	0.2814	1	ns
	Site	15	836.77	5.32	0.0001	67	***
	Diver	5	779.21	4.95	0.0008	20	***
	Diver × site	43	186.48	1.18	0.2755	8	ns
	Year × site	13	114.87	0.73	0.7262	4	ns
	Year × diver	0	—	—	—	—	—
	Year × site × diver	0	—	—	—	—	—
	Residual	54	157.38				

the variation in the ANOVA model. For timed searches the variance estimate for diver effects was about one third that for sites; however for transects, the relativity between diver and site variance effects was more variable. The values for the relative magnitude of variance estimates attributable to divers were similar between the two methods.

Mean abundance estimates from radial transects during stock monitoring surveys varied significantly among divers; divers 4 and 5 in particular collected relatively fewer abalone per transect and diver 8 collecting more than the other divers (Table 4). Ryan's test did not reveal a significant difference between the remaining nine divers' mean relative abundance estimates (Table 4). A regression of the divers' mean relative abundance estimates against the respective numbers of radial transects performed (r^2=0.01, n=1339) showed that the slope of the relationship was not significantly different from zero (P>0.10).

Power to detect changes in abundance

The number of years of sampling required for an 80% or greater predicted probability of detecting a significant cumulative change in abundance with radial transects ranged from 1–3 years for all zones. The western zone required 3 years for 2.5% and 5% increments to become significant on 80% of occasions and 2 years for the 10% increment. The other two zones required only one year for all increments to become significant (Fig. 5A).

In contrast, timed searches (Fig. 5B) required three years to detect a cumulative annual increase of 10% in the central zone with 80% probability, and five years for the same size change in both the eastern and western zones. In the eastern zone the probability of detecting increases with timed searches was similar to that for the central zone with transects. In this instance only one year was required to have an 80% probability of detecting each increment of change.

Discussion

Radial transects provided precise estimates of abalone abundance and did not vary significantly between different divers in three of the investigations made during this study. However, the importance of selecting scientific divers with aptitude for these types of surveys is underscored by the fact that three

Table 3

Analysis of variance for interannual differences in abundance estimates of *H. rubra* for each of Victoria's fishery management zones, made from radial transect surveys, during 1992–94 (type IV SS). ns = nonsignificant; * = $P<0.10$; ** = $P<0.05$; *** = $P<0.01$. ω^2 = relative magnitude of variance estimate (%).

Management zone	Source	df	MS	F	P	ω^2	Significance
Central	Year	2	515.43	4.08	0.0222	3	**
	Site	29	378.00	5.04	0.0001	54	***
	Diver	10	93.24	1.24	0.2611	1	ns
	Diver × site	123	47.16	0.63	0.9989	21	ns
	Year × site	56	126.36	1.69	0.0022	18	***
	Year × diver	5	31.23	0.49	0.7842	1	ns
	Year × site × diver	35	64.17	0.86	0.7066	2	ns
	Residual	479	75.00				
Eastern	Year	2	130.23	0.87	0.4312	0	ns
	Site	14	801.99	5.33	0.0001	38	***
	Diver	5	1170.54	7.78	0.0001	21	***
	Diver × site	46	274.05	1.82	0.0021	23	***
	Year × site	28	150.21	1.00	0.4728	0	ns
	Year × diver	4	301.05	5.22	0.0057	11	***
	Year × site × diver	18	57.69	0.38	0.9899	7	ns
	Residual	242	150.48				
Western	Year	2	36.54	2.30	0.1214	1	ns
	Site	12	261.00	7.14	0.0001	41	***
	Diver	7	100.08	2.74	0.0096	7	***
	Diver × site	40	47.61	1.30	0.1201	7	ns
	Year × site	24	147.51	4.03	0.0001	40	***
	Year × diver	6	65.70	1.31	0.3016	1	ns
	Year × site × diver	18	50.04	1.37	0.1201	4	ns
	Residual	225	36.54				

divers' mean transect collections differed significantly from the remaining nine divers during three annual abalone stock surveys. During routine monitoring, two divers (4 and 5) consistently collected less abalone than the others and frequently aborted dives after having failed to complete all their allocated transects. Reasons given for terminating their dives included problems with middle ear equalization, difficulty coping with the surge and backwash created by waves, and fouling of lines and air hoses due to entanglement. These observations concur with Shepherd (1985) who found that surge and kelp density were two significant factors affecting research diver efficiency in underwater censuses of abalone populations. In contrast to divers 4 and 5, diver 8 consistently collected more abalone than the other research divers. However, diver 8 participated only in those parts of the study conducted in the eastern zone, where abalone stocks are generally more abundant. Also, as an ex-abalone diver, diver 8 could reasonably be expected to possess a superior ability in performing abalone searches and collections that may have biased his estimates.

These observations suggest that some divers may not possess the aptitude required to conduct underwater censuses and highlight the need for understanding the nature of research being conducted. The ability to work at sea in often arduous conditions, discipline in adherence to sampling protocols, and

Table 4

Mean number (least squares) of *H. rubra* collected per transect by each diver during 1992–94 Victorian abalone stock surveys. Vertical bars in "ns" column indicate groups of means that were not detected as significantly different by Ryan's test (α=0.05). ls = least squares; SE = standard error of the least squares means.

Diver	n	ls mean	± SE	ns
8	36	19.48	1.92	│
9	147	16.03	0.95	│ │
1	467	12.62	0.53	│ │
12	38	12.00	1.87	│ │
3	408	11.26	0.57	│ │
11	66	10.74	1.42	│ │
7	6	10.50	4.71	│ │
6	17	10.03	2.80	│ │
2	119	10.02	1.06	│ │
10	15	9.73	2.98	│ │
4	107	7.83	1.12	│
5	12	3.58	3.33	│

the importance of avoiding a competitive atmosphere in which bagging the most abalone becomes the objective are essential characteristics of an effective abalone survey team. The problem of competition implies that nondestructive sampling, such as counting, may reduce potential bias associated with col-

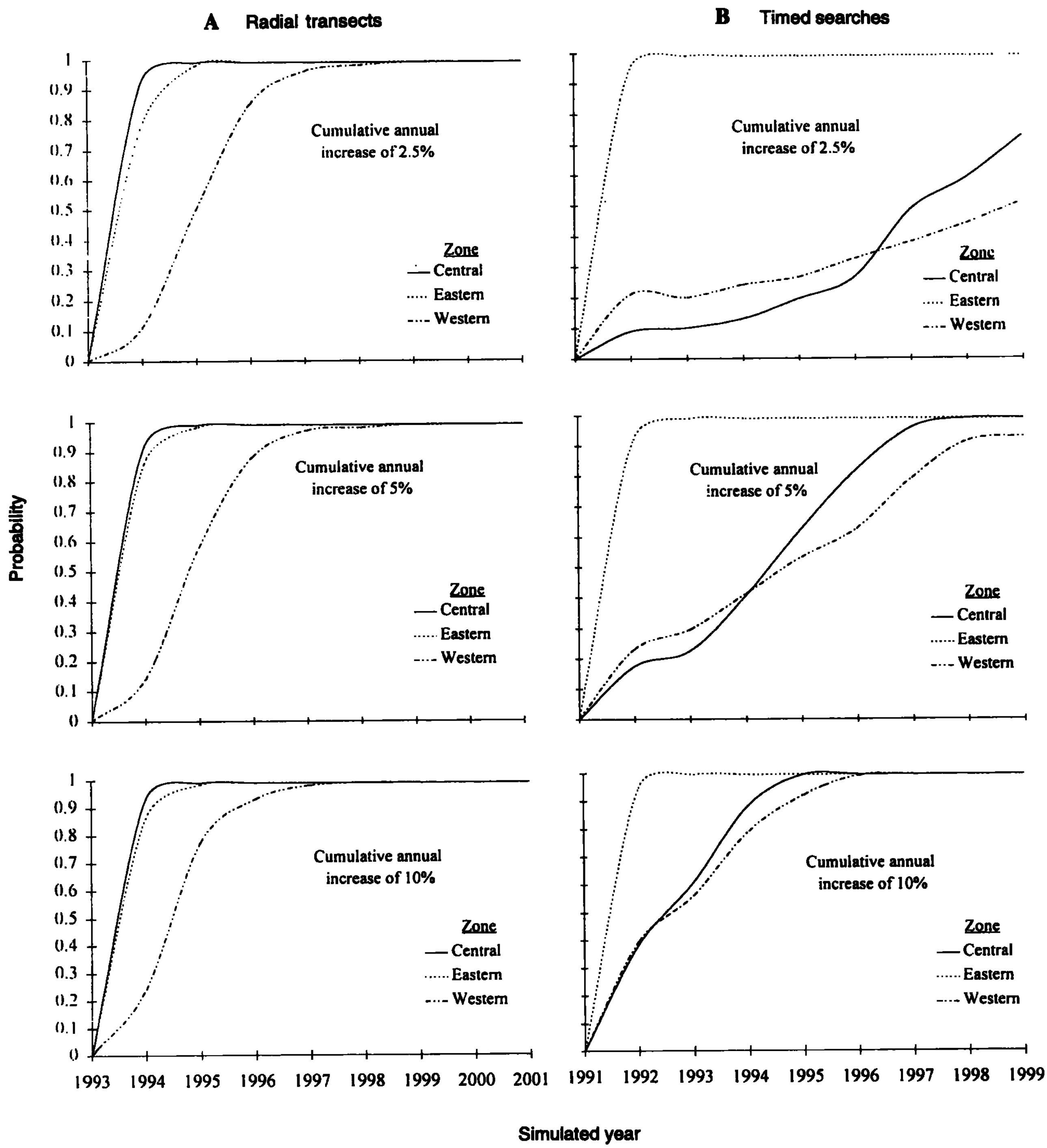

Figure 5

Predicted probabilities for detecting cumulative annual changes in *H. rubra* abundance from (**A**) radial transect surveys and (**B**) timed searches.

lecting. Indeed, the diver who consistently collected more abalone from transects during routine stock surveys was not significantly different from other members of the dive team when only counts of abalone were required. Similarly, McShane (1995) found that by reducing the handling time involved with the collection of large numbers of abalone from dense aggregations he reduced the operator bias in the estimation of patch frequency. Counting also has the advantage of considerably reducing the time needed to complete each transect. However, collecting becomes necessary when length-frequency data are required because in-situ measurements are impractical under the surgy conditions commonly encountered.

Experience in the radial transect method did not have a significant influence on the number of abalone estimated despite the fact that the number of transects completed per diver varyied over a wide range (6–438 transects). Differences among divers are expected when those who sampled at only a few locations are compared with divers who sampled over a larger range of abalone populations. This expectation is supported by the lower standard deviations associated with the mean collections per transect of the less experienced divers.

The standard deviations of the divers' mean relative abundance estimates from radial transects were relatively large, especially for those divers who had completed many such transects. This large range reflects the high spatial variability in abalone densities both within and between sampling sites which is evident from the relatively large proportion of variance contributed by location and site effects. During the trial stock surveys, variation among sites within locations was mostly similar to the variation among locations (except for juveniles). Although higher precision in abundance estimates may be obtained by sampling on a small scale, our results support the notion that abalone distributions are variable over the range of spatial scales commonly used to census abalone populations. Under these circumstances stratification of sites may provide little increase in the power of population surveys to detect interannual changes in abundance. The higher proportion of variance between sites in relation to locations with sampling juvenile abalone was not unexpected because of the smaller number of replicates and the greater degree of difficulty in observing this cryptic size class (Nash et al., 1994). The importance of adopting a sampling design that minimizes spatial effects is highlighted by the low proportion of the total variation attributable to the year effect. The mixed design we used provided a compromise between the advantages offered by fixed designs in reducing within-site variability and those offered by random designs in improving the precision of estimates of site means. The consequent increase in power over a random design has allowed us to economize on the number of sites sampled annually.

The use of transects to estimate the abundance of abalone stocks has been criticized (McShane, 1994) as a time-consuming approach that does not allow for the patchy nature of abalone distributions over relatively small spatial scales. However, strip transects provide an objective and reproducible approach to population surveys that appear to be somewhat less affected by research diver differences than are observations made against time. Our results demonstrate that variability among most scientific divers in the use of both radial transects and timed searches generally has a relatively small effect on variation in abalone abundance estimates. This finding suggests that standardization of abundance data from underwater censuses of abalone populations may be unnecessary. Because adaptive approaches to the setting of TACs require a time series of abundance indices, it is unlikely that all scientific dive team members will be retained for the required period. Thus effects of variation between diver and year will confound abundance estimates and interannual variation in abundance. The general linear model we used to analyze abalone abundance data includes the effect of variation among divers. For both methods, diver effects were smaller than site effects. Previous analyses of timed search estimates involved standardization to eliminate diver effects, with the assumption that all differences between within-site replicates were due to diver variation (McShane and Smith, 1990). With this approach there is a risk of underestimating the variances of mean abalone abundances because variation between divers is confounded with intrasite variation. Another problem with standardization of data to eliminate diver effects prior to analysis is the resulting confidence levels associated with performing multiple regressions between different diver pairs. The greater the number of divers the lower the level of confidence. This finding contrasts with the higher confidence level provided by the general linear models procedure, which takes account of diver × site interaction, thereby requiring only one comparison among divers.

The radial transect method is a credible alternative to timed searches for the conduct of underwater census of abalone. The notion that transect surveys are inefficient and time consuming ignores the importance of how the transects are applied. The number of radial transects that can be completed in a typical day of sampling compares favorably with the number of timed searches that can be completed within the same period. When timed searches were used to survey Victorian abalone stocks, about 20–28 samples were completed daily; the radial transect method provides 27 samples during a typical day and requires only one-third the number of ascents per diver, reducing the risk of decompression illness (Marks and Fallowfield, 1994; Oxer, 1994). As with timed searches, the radial transect method has been successfully applied under rough sea conditions typical of the exposed coastal reefs colonized by abalone.

McShane and Smith (1990) identified the similarity between the timed search method and the techniques employed by commercial abalone divers to target aggregations of abalone. From this similarity one can reasonably infer that in some instances the abalone collection rate of research divers may exhibit (albeit over a smaller spatial scale) the hyperstability that characterizes the catch per unit of effort of commercial abalone divers. Indeed, in a study involving intensive experimental fishing McShane and Smith (1989) could not detect a significant difference between pre- and postfishing abundance estimates of postrecruited abalone from timed searches despite a 50% decrease in CPUE. In his discussion of a patch-frequency estimation method, McShane (1995) noted the bias in timed searches when a large proportion of the search time is spent collecting abalone from dense aggregations. Radial transects target a specific area (30 m^2); consequently handling time does not affect the numbers of abalone counted or collected and divers are unable to target aggregations to the exclusion of more sparsely distributed abalone. Therefore it is reasonable to expect that surveys based on radial transects more accurately reflect true abalone abundance than do those based on timed searches.

Although there is no doubt that dense patches of abalone are important with respect to fishing and the maintenance of profitable catch rates (McShane, 1995), recent work on *H. rubra* in Victoria (Officer[1]) has demonstrated the importance of postfishing movement and reaggregation in maintaining these patches. The Victorian studies also showed that dense patches contributed most of the variation in abundance estimates and that the standard deviations of samples of sparsely distributed abalone were relatively small. It is from these sparsely distributed abalone, and those occupying cryptic habitat, that reaggregation appears to have occurred. Further research is required to determine the relative importance of sparsely distributed abalone in assessing the impact of fishing. Abundance estimates from transect sampling may prove to be more effective indicators of the size of stocks if dense aggregations are excluded from surveys.

Because the application of radial transects avoids targeting some emergent abalone to the exclusion of others, there is less potential for divers to bias their sample towards larger abalone as may occur with timed searches. By measuring the length of each abalone collected, separate estimates of abundance for prerecruit (shorter than the legal minimum length) and postrecruit (recruited to the stock) abalone can be made. Timed searches do not necessarily permit this separation of prerecruits from postrecruits because of the potential for divers to collect larger, more accessible abalone at the expense of smaller abalone. Timed search estimates of abundance reported in McShane and Smith (1989) show an almost threefold increase in prerecruits after fishing, suggesting that abundances of prerecruits may have been underestimated prior to fishing because of the prevalence of postrecruits.

Our trial stock surveys provided evidence that the transect method has the power to detect differences in abalone abundance (among locations and sites) and is robust in respect to differences in divers' abilities to perform the method. Moreover, annual stock surveys based on radial transects were able to detect a significant change in abundance between consecutive years and had a high power of detecting smaller effect sizes over 2–3 years, thus showing their usefulness as an effective stock monitoring tool. The radial transect method as it is currently applied for monitoring Victorian abalone stocks should have sufficient power to detect changes in abundance of about 10% after 3 years sampling. Monte Carlo simulations showed that surveys based on timed searches generally would require several years of sampling and consequently would have lower power than radial transect surveys in detecting the same rate of change. The simulation results for the eastern zone, where it was predicted that only one year would be required for a 2.5% change, proved to be the only exception. However, unlike the timed search sampling of the central and western zones, all sites in the eastern zone were sampled twice annually during 1989–91. This additional sampling would be expected to increase substantially the statistical power to detect changes in abundance.

Surveys based on radial transects have been used to monitor *H. rubra* stocks in the Victorian abalone fishery since 1992 with the objective of establishing a temporal series of abundance data to assist managers in determining sustainable levels of fishing. In monitoring Victoria's abalone stocks, the aim is to detect an overall change in abundance across a man-

[1] Officer, R. 1997. Marine and Freshwater Resources Institute, PO Box 114, Queenscliff, Victoria 3225, Australia. Unpubl. manuscript.

agement zone against a background of increases and decreases at different sites within that zone. Although the Monte Carlo simulations predict that, with the use of transects, such overall changes should become detectable within several years, it is obvious that a much longer time series than three years is required to determine if significant interannual changes form part of a trend in abundance. In addition to the temporal scale required for effective monitoring of abalone stocks, there is also the issue of selecting an appropriate spatial scale over which to sample. Many abalone fisheries are managed in spatial units involving several hundreds of kilometres of coastline, and the relatively high cost of fishery-independent surveys ensures that compromises must be made to maximize the benefits from stock assessment programs. Consequently, the biologist investigating abalone is faced with selecting between a limited number of intensive surveys of substocks over small spatial scales and extensive surveys that are less detailed but at the scale over which the fishery is managed (McShane et al., 1994). In their discussion of the design of surveys for abundance indices, Hilborn and Walters (1992) favored extensive surveys with low sampling intensities that cover the entire fishing grounds. Their preference for many sampling stations and minimal effort per station has recently been supported by Van der Meer's (1997) study. This is the approach we are currently using to survey abalone stocks in Victoria, although we maintain relatively high within-site replication to allow greater precision for site means. Whether power is traded off against precision depends on the extent to which inferences are to be drawn regarding individual sites.

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Literature cited

Breen, P. A.
1992. A review of models used for stock assessment in abalone fisheries. *In* S. A. Shepherd, M. J. Tegner, and S. A. Guzmán del Próo (eds.), Abalone of the world: biology, fisheries and culture, p. 253–275. Blackwells, Oxford.

Day, R. W., and G. P. Quinn.
1989. Comparisons of treatments after an analysis of variance in ecology. Ecol. Mono. 59:433–463.

Hart, A. M., and H. K. Gorfine.
1997. Abundance estimation of blacklip abalone (*Haliotis rubra*) II. A comparative evaluation of catch-effort, change-in-ratio, mark-recapture and diver-survey methods. Fish. Res. 29:171–183.

Hilborn, R., and C. J. Walters.
1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York, NY, 570 p.

Keppel, G.
1991. Design and analysis: a researcher's handbook, 3rd ed. Prentice-Hall, Englewood Cliffs, NJ, 594 p.

Marks, A. D., and T. L. Fallowfield.
1994. A retrospective study of decompression illness in recreational SCUBA divers and SCUBA instructors in Queensland. *In* Queensland diving industry workplace health and safety committee, proceedings of safe limits: an international dive symposium, Cairns, October 1994, p. 52–59. Worksafe, Australia.

McShane, P. E.
1994. Estimating the abundance of abalone (*Haliotis* spp.) stocks—examples from Victoria and southern New Zealand. Fish. Res. 19: 379–94.
1995. Estimating the abundance of abalone: the importance of patch size. Mar. Freshwater Res. 46:657–62.

McShane, P. E., K. H. H. Beinssen, and S. Foley.
1986. Abalone reefs in Victoria: a resource atlas. Victorian Department of Conservation, Forests and Lands, Marine Science Laboratories Technical Report Series 47, 50 p.

McShane, P. E., S. F. Mercer, and J. R. Naylor.
1994. Spatial variation and commercial fishing of New Zealand abalone (*Haliotis iris* and *H. australis*). N. Z. J. Mar. Freshwater Res. 28:345–55.

McShane, P. E., and M. G. Smith.
1989. Direct measurement of fishing mortality in abalone (*Haliotis rubra* Leach) off southeastern Australia. Fish. Res. 8:93–102.
1990. Victorian abalone monitoring: first review August 1990. Victorian Department of Conservation, Forests and Lands, Marine Science Laboratories, Program Review Series 100, 47 p.
1992. Shell growth checks are unreliable indicators of age of the abalone *Haliotis rubra* (Mollusca: Gastropoda). Aust. J. Mar. Freshwater Res. 43:1215–19.

Nash, W. J., T. L. Sellers, S. R. Talbot, A. J. Cawthorn, and W. B. Ford.
1994. The population biology of abalone (*Haliotis* species) in Tasmania. I. Blacklip abalone (*H. rubra*) from the north

coast and islands of Bass Strait. Sea Fisheries Division, Tasmania, Tech. Rep. 48, 69 p.

Oxer, H. F.
1994. Safe limits—assessing the risks. *In* Queensland diving industry workplace health and safety committee, Proceedings of safe limits: an international dive symposium, Cairns, October 1994, p. 86–92. Worksafe, Australia.

Prince, J. D., and S. A. Guzmán del Próo.
1993. A stock reduction analysis of the Mexican abalone (haliotid) fishery. Fish. Res. 16:25–49.

SAS Institute, Inc.
1989. SAS/STAT user's guide, version 6, 4th ed, vol. 2. SAS Institute, Inc., Cary, NC, 846 p.

Shepherd, S. A.
1985. Power and efficiency of a research diver, with a description of a rapid underwater measuring gauge: their use in measuring recruitment and density of an abalone population. *In* C. T. Mitchell (ed.), Diving for science, p. 263–272. Am. Acad. Underwater Science, La Jolla, CA.

Van der Meer, J.
1997. Sampling design of monitoring programmes for marine benthos: a comparison between the use of fixed versus randomly selected stations. J. Sea Res. 37: 67–79.

Winer, B. L.
1971. Statistical principles in experimental design, 2nd ed. McGraw-Hill, New York, NY, 907 p.