Victorian Fisheries Research Institute

Evaluation of Methods to Assess Abalone Abundance

H.K. Gorfine, A.M. Hart and M.P. Callan

Project 93/100

FISHERIES RESEARCH & DEVELOPMENT CORPORATION

EVALUATION OF METHODS TO ASSESS ABALONE ABUNDANCE

Final Report to Fisheries Research and Development Corporation

(FRDC Project 93/100)

H.K. Gorfine[1], A.M. Hart[1,2] and M.P. Callan[1,3]

June 1996

This project was funded by the *Fisheries Research and Development Corporation* under the *Natural Fish Resources* program.

[1] Victorian Fisheries Research Institute
Department of Conservation and Natural Resources
PO Box 114, Queenscliff, Victoria, 3225.

[2] Present address: ICLARM CAC, PO Box 438, Honiara, Solomon Islands.

[3] Present address: 70 Reigate Road, Highton, Victoria, 3216.

Contents

Non-technical Summary

The issue of how best to survey abalone populations to obtain estimates of abundance has been the subject of debate among fisheries biologists for many years. In an attempt to resolve this issue we compared and evaluated abalone abundance estimated by the following methods: Transect survey, Timed-collection surveys, Mark-Recapture, Change-in-Ratio and Leslie (catch-effort) estimates. This study involved a fish-down of an abalone reef by commercial abalone divers. Estimates of abalone abundance were made by applying the different methods before, during and after the fish-down. The total catch (number of abalone harvested) was used as a bench-mark against which the differences between the before and after abundance estimates for each method could be compared. In addition the precision for each method was estimated and compared.

Previously, the use of area-based transects was thought to be limited for estimating the abundance of spatially aggregated animals such as abalone. However, the outcome of this study was that transect surveys are the preferred method because they accurately reflected absolute abundance, required a relatively small number of sampling days and were reasonably precise. It is recommended that a stratified random approach be adopted when using transect sampling. Timed-collections gave precise but inaccurate estimates of abundance which were somewhat more sensitive to diver (operator) effects. CIR methods using transect data to estimate proportions can be as efficient as transect-based abundance estimates, however they require more intensive data collection. If a cost-effective and quick tagging method can be identified, then a mark-recapture study will also work well, although a test for equal catchability of tagged and untagged animals should be included in the design of the experiment. CIR analysis using timed collection data is less certain due to possible violation of equal catchability of two animal types, but will still give a workable result. The use of catch and effort data as an index of abundance is not recommended for monitoring abalone abundance because, despite the controlled conditions during this study, estimates of abundance using these data could not be obtained in two out of three instances.

Future research should be directed towards a better understanding of the importance of aggregating behaviour in determining the impact of harvesting on blacklip abalone populations. The involvement of commercial abalone divers is crucial to the success of these types of studies. For this project, co-operation between managers, researchers and commercial divers was beneficial to all parties involved and it is hoped this will become a common occurrence in future research of the Victorian abalone fishery.

Background

Victoria's abalone resource forms part of a large blacklip abalone distribution extending from northern NSW southwards through the islands of Bass Strait to southern Tasmania, and westwards along the Victorian and South Australian coasts to Western Australia. Individual transferable quotas (ITQs) were introduced into the Victorian fishery during 1988 which provides a total annual catch of 1440 tonnes. Soon after the introduction of ITQs a stock monitoring program was established to determine trends in abalone abundance. This stock monitoring program stemmed from earlier FIRTA funded research (# 85/16) to assess the degree of exploitation of Victorian abalone stocks.

During 1993 it became evident that there was a need to review the methods used for estimating abalone abundance. This was because of problems associated with standardising the observation errors of research divers, issues of diver safety, and questions about the statistical power of the survey methods to detect changes in abalone abundance.

The need for a reliable method of estimating abalone abundance is common to all fisheries research agencies in the states of southern Australia producing abalone. All of these states manage their abalone fisheries through ITQs and consequently have a need to monitor changes in abalone abundance to determine the effectiveness of these quotas. It is anticipated that the results from investigations for this project will assist all states in selecting a suitable method for measuring inter-annual trends in abalone abundance.

Need

Assessments of fish stocks are often based on catch per unit effort (CPUE) as an index of abundance. There is a growing body of evidence that CPUE is often unresponsive to decreases in abalone abundance and tends to reflect divers' fishing behaviour (Breen 1980; Harrison 1983). Problems with estimating abalone abundance using direct counts by research divers include the patchy nature of their spatial distribution (Sainsbury 1982) and the complex reef topography that characterises their habitat. Abalone are often found aggregated in gutters that dissect the rocky substrate and have a tendency to occupy cryptic habitat (Nash et al. 1994), particularly as juveniles.

Several methods for estimating abalone abundance are currently being used in south-eastern Australia but their reliability needed to be determined. These methods include the application of timed collections, transect collections, mark-recapture (M-R) and CPUE to provide estimates or indices of relative abundance; comparisons of length-frequency distributions to describe stock composition and to estimate mortality rates; changes in the density, size and frequency of aggregations and the examination of changes in the ratio between those abalone larger than the legal minimum length (post-recruits) and those smaller than the LML (pre-recruits) in response to pulse fishing.

In Victoria, timed collections (McShane, 1994), contiguous quadrat sampling and M-R have been used independently at various times to assess the abalone stocks, but no comprehensive comparison has enabled the selection of the method with the greatest efficacy. Prince (1989), having applied both fishery independent and fishery dependent methods to the study of the fisheries biology of blacklip abalone stocks in Tasmania, concluded that research resources need to be directed at resolving the issue of reliably measuring abalone abundance prior to pursuing a description of the relationship between stock and recruitment.

For this project we chose to conduct a controlled pulse-fishing experiment involving commercial abalone divers. This approach facilitated the evaluation of a broad range of fishery independent and fishery dependent methods. In addition, information from pulse-fishing a stunted blacklip abalone stock was considered important because harvesting slow growing populations at reduced size limits might be a means of increasing sustainable catches of abalone without risking recruitment overfishing of faster growing stocks (Nash et al. 1994).

Objectives

To compare methods for estimating stock abundance through stock depletion experiments involving pulse fishing a stunted blacklip abalone population.

Methods

Detailed descriptions of the methods employed during this study are contained in the Part I and Part II papers appended to this report. The experimental design and study methodology were consistent with the methods described in the original project application. The only significant change was the use of marking rather than tagging the abalone. This meant that the incidental growth increment data referred to in the proposal was not obtained. However, this had no effect on the project attaining its main objective of evaluating abundance estimation methods.

This study aimed to compare and evaluate the following methods for their suitability in providing abundance estimates for abalone population assessments:

- Transect surveys
- Timed-collection surveys
- Mark-Recapture
- Change-in-Ratio
- Leslie (catch-effort) estimates

In consultation with commercial abalone divers a study site representative of a stunted blacklip abalone population was chosen at West Head, Flinders, Victoria. Commercial divers rarely fish this site because only a relatively small proportion of abalone (< 20%) attain the legal minimum length for this section of coast. The reef at this location is composed entirely of basalt that provides a complex underwater topography of high relief dissected by deep gutters and interspersed by tracts of coarse sand. Dense stands of the kelp *Phyllospora comosa*, commonly referred to as crayweed, dominated the upper surfaces of the reef. This habitat is typical of much of the abalone producing areas along the central Victorian coast.

A study plot of 15 hectares was selected from the 200 hectares of reef at this location. An outlying bombora, Bismarck Reef, provided some protection from high wave energies within the study plot, although some sections of the plot were more exposed to surge than others. It was critical to the success of the project that no extraneous fishing occur at the site during the study period. West Head had the advantage of providing ease of land-based surveillance for local fisheries enforcement officers and was readily accessible (5 minute boat trip) from the small fishing port at Flinders. The study plot was marked with a series of buoys and was subdivided into three replicate plots of five hectares (Fig 1).

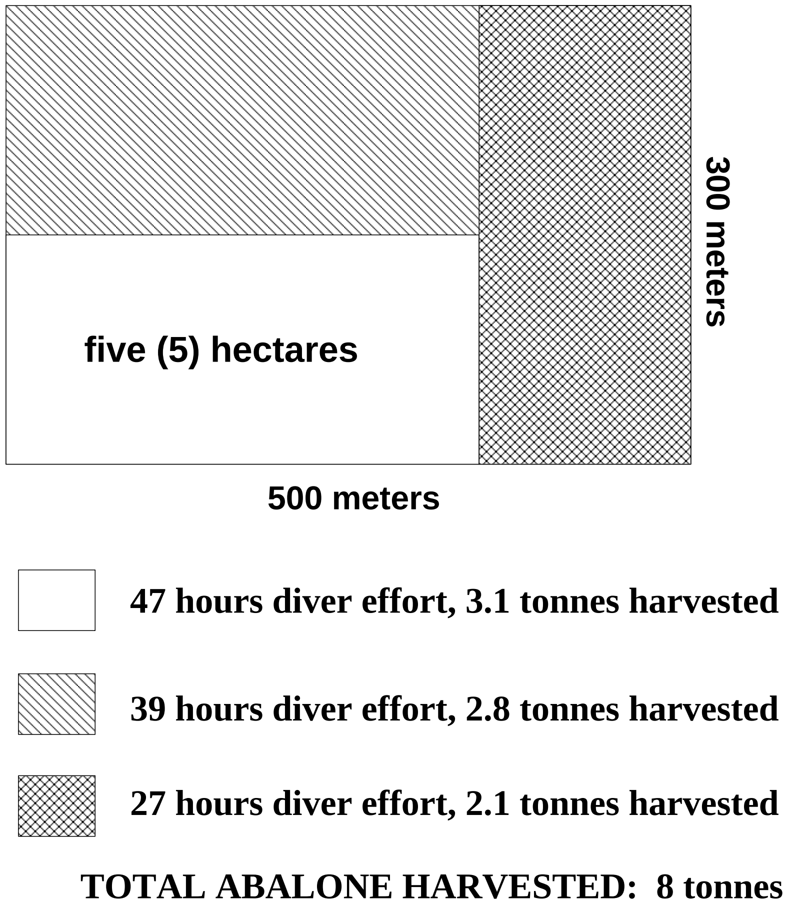


Fig. 1. Schematic illustration of how abalone were harvested from the study site

A pilot survey was completed initially to determine levels of replication required for the diver survey methods. A series of pre-fishing surveys then followed for each subplot during which as many abalone as possible were marked. The pre-fishing surveys provided initial estimates of population abundances, pre-recruit to post-recruit ratios and precision estimates for the diver-survey methods. Each subplot was fished sequentially and all subplots were re-surveyed between the three stock depletions. This enabled unfished plots to serve as controls for the first two stock depletions, and allowed for three consecutive pre-fishing surveys before the third stock depletion.

To ensure that the available stock was similar to that of highly productive abalone populations the legal minimum length was temporarily reduced from 11 to 10 cm for the participating abalone divers. This size limit reduction effectively increased the available stock from less than 20% to about two thirds of the emergent abalone population. During each stock depletion several commercial abalone divers fished within a designated subplot and onboard observers recorded the number of abalone in each catch bag brought to the surface, the time taken to fill each bag and the proportion of marked abalone. The observers also ensured that the divers remained within the designated subplot. Fishing continued until the cumulative total number of abalone in the catch approximated 50% of the mean abundance estimated for the particular subplot from transects during the pre-fishing surveys. A single post-fishing survey was completed immediately after each stock depletion. During post-fishing surveys the abundances of pre- and post-recruits were estimated from transects and timed collections.

The recapture rate of marked abalone and catch rates recorded during fishing provided additional estimates of initial population abundance to those from the pre-fishing surveys. The number of abalone in each catch provided a reference against which the accuracy of the differences between pre- and post-fishing abundance estimates for each method could be gauged.

There are two important methodological outcomes from this study that will be of benefit to those surveying demersal molluscs. The main development is the transect technique used during this study which is fully described in the technical paper appended to this report. The other is the marking method using Markal® oil-based crayons which are a cost-efficient approach for marking large number's of abalone (1000 per day) in a relatively short time period. Use of these is to be recommended for any short term study (< 1 month) of populations of gastropods.

Detailed Results

Comprehensive presentations of the results of this study are contained in the Part I and Part II papers appended to this report.

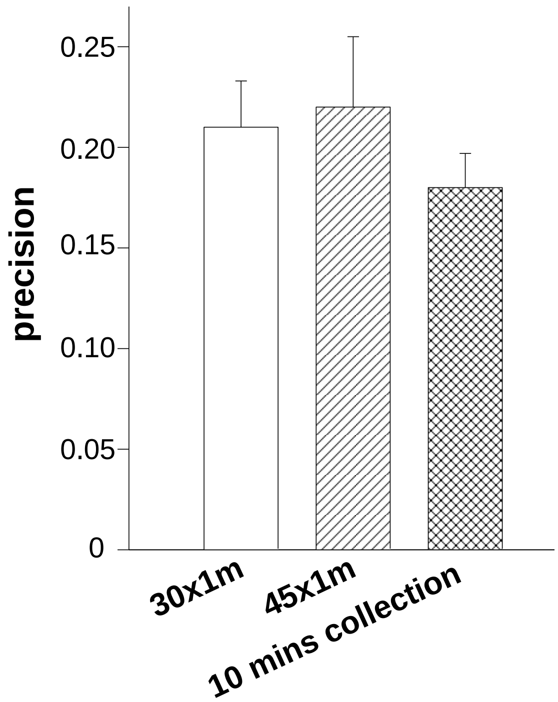
Comparison of Underwater Survey Methods

Both the transect and timed collection methods were able to detect a 50% drop in population size of fishable abalone (greater than 10cm length) and both methods showed that there was no change in population numbers of pre-recruit abalone (those less than 10 cm). However we conclude that the 30 m^2 transect is the more appropriate method to use in monitoring Victoria's abalone stocks because,

i. transects provide a more accurate measure of abalone abundance, and

ii. transects are less sensitive to diver effects compared with the 10 minute collection.

Differences in precision and accuracy between the transect and timed collection survey methods are illustrated in Fig 2. The were no statistically significant differences between the precision estimates for each method. Both transect estimates of abundance (in this case biomass) were within the range for the estimate of the true population size whereas the timed (10 minute) collection under-estimated abundance by at least 20%. Variation in abundance estimates between research divers when using transects was related to diver familiarity with the technique rather than relative searching efficiency. Clearly, the timed (10 minute) collection estimates were a function of diver searching efficiency (Fig 3).



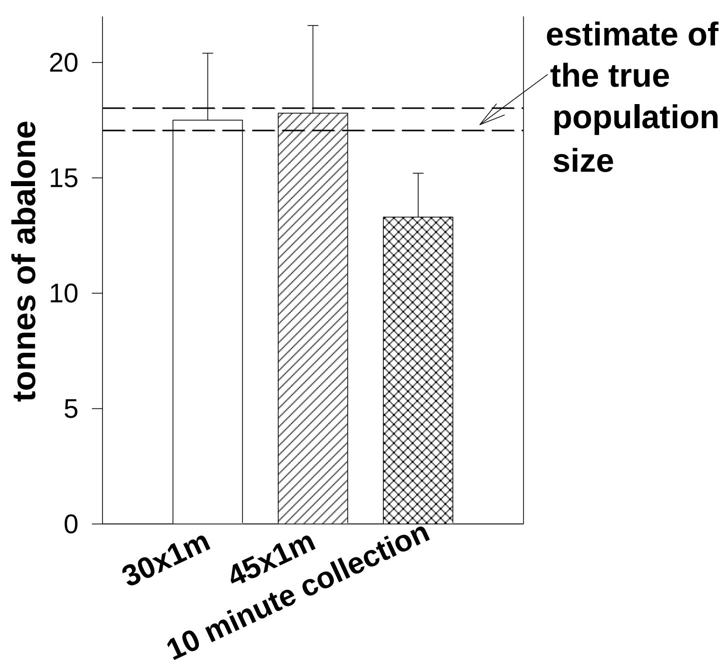
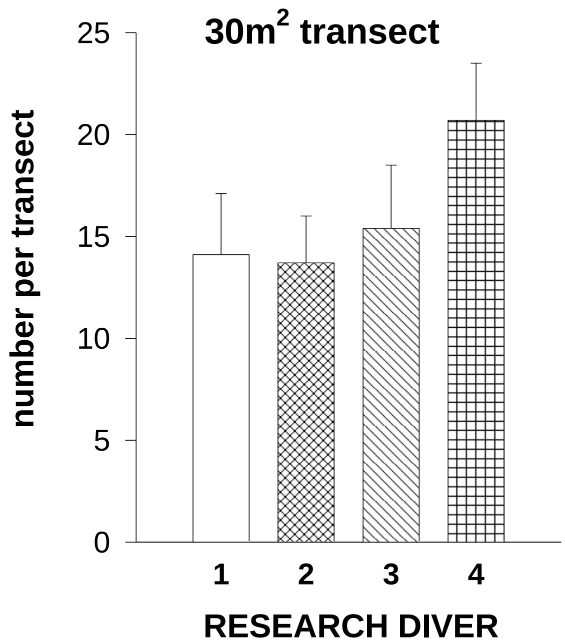


Fig 2. Precision and accuracy of each underwater survey method.



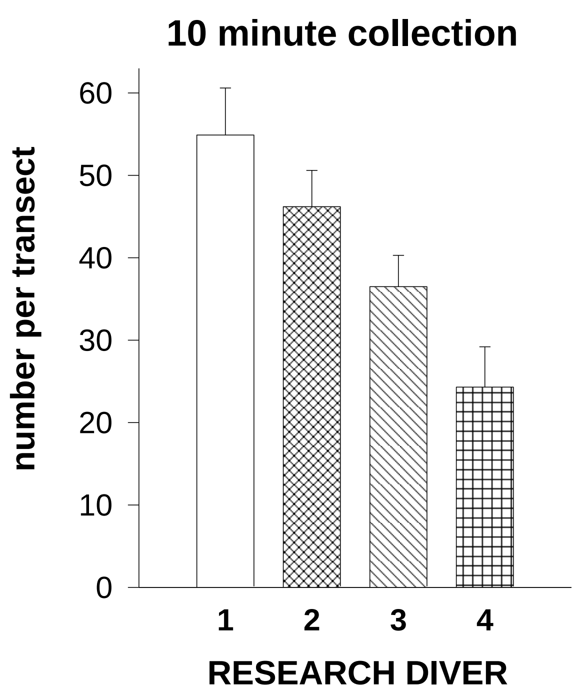


Fig 3. Variation between divers for each underwater survey method.

Comparative Evaluation of Population Assessment Methods

Leslie estimators

The Leslie population estimators performed poorly. This occurred principally because of significantly different catchability both between, and within, replicate populations, and the associated problem of hyperstability. In this study, the correction of effort to searching time which is assumed to be inversely proportional to density (Beinssen, 1979), did not improve the performance of the Leslie estimator. Fig 4 shows that the Leslie estimator adequately described the change in abalone abundance in only one instance out of three.

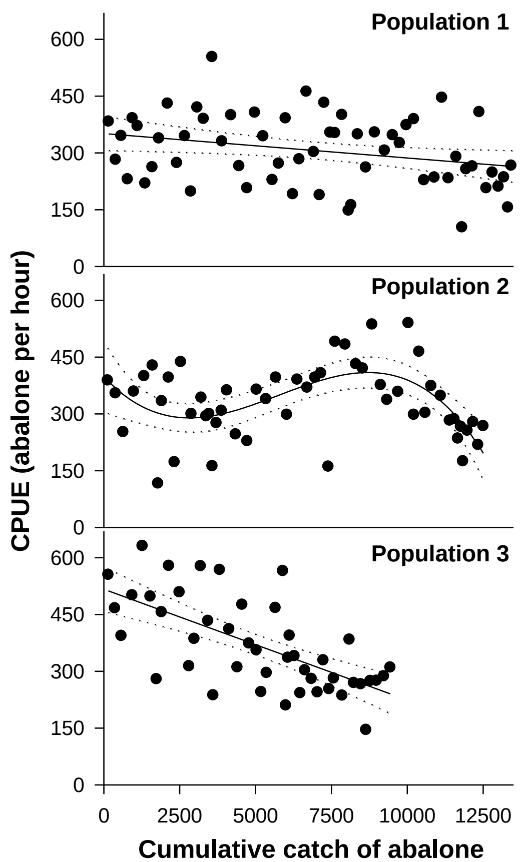


Fig 4. Comparison of Leslie plots from three adjacent populations of *Haliotis rubra*. Similar proportions of the total numbers were removed in each population.

Thus even under replicated, controlled, experimental conditions with precise measurements of catch and effort, catchability of abalone varies both within and between populations unpredictably.

Change-in-Ratio

The effectiveness of CIR analysis depends on the validity of the critical assumption of equal catchability between pre- and post-recruited abalone. The results for CIR using area based transects suggest that the assumption was reasonable in this instance, however this was not the case where timed collections were used as the CIR sample units. The natural tendency when using timed collections is to choose the more visible, aggregated and larger post-recruits at the expense of smaller, more cryptic pre-recruits present in the search area, thus violating the equal catchability assumption. When transects are used it is more likely that all abalone visible within the transect area will be counted.

Mark-Recapture

Mark-recapture (MR) techniques along with the area-based transect methods were given the highest rating for the study. In particular, the precision of the MR population estimates was extremely high, a consequence of high initial numbers tagged (5,527), and high recapture (2,510). The success of the tagging is attributed to the use of oil-based crayons which allowed fast and effective, *in situ* marking of abalone.

Transects

Transect techniques provided similar estimates of population size to CIR (transects) analysis for every population, however the theory and assumptions of the two techniques are very different and their close similarity in estimating population size underlies the accuracy and precision of the transect sampling unit. No such agreement occurred between the timed collections and the CIR (collections) techniques, again despite the data being collected simultaneously. Principally this occurred because the effectiveness of the conversion from a timed search to a density estimate was limited.

Timed collection

Overall the performance of the timed collection technique was unreliable in estimating abundance. Density conversions using Beinssen's (1979) values of area searched (19.9 m^2 min^{-1}) and handling time per abalone (5.1 secs $abalone^{-1}$) tended to decrease the precision of timed collection abundance estimates without any concomitant increase in accuracy.

Conclusions

Despite the aggregated nature of abalone distributions, area based transect methods combined with a stratified random sampling design did give accurate and precise estimates of population size. Timed-collections gave precise but inaccurate estimates of abundance which were somewhat more sensitive to diver (operator) effects. CIR methods using transect data to estimate proportions can be as efficient as transect-based abundance estimates, however they require more intensive data collection. If a cost-effective and quick tagging method can be identified, then a mark-recapture study will also work well, although a test for equal catchability of tagged and untagged animals should be included in the design of the experiment. CIR analysis using timed collection data is less certain due to possible violation of equal catchability of two animal types, but will still give a workable result. It has been used successfully for abalone in Tasmania by Nash et al. (1994). The use of catch and effort data as an index of abundance is not recommended for estimating population size in abalone.

Benefits

Australia's valuable abalone industry will benefit from improved techniques in the monitoring of abalone stocks that provide a basis for ecologically sustainable resource management. Benefits will flow to the wider community as economic rent and export earnings from sustainable management of abalone resources. Evaluation of methods for monitoring stocks will also benefit assessments of abalone in other parts of the world.

Intellectual property

No intellectual property has arisen from the research that is likely to lead to significant commercial benefits, patents or licences. Intellectual property associated with the data produced during the project will be shared between VFRI and FRDC.

Further Development

Methods applied during this project necessarily involved the assumption that abalone movement between surveys was minimal and that spatial distribution patterns changed only as a direct result of fishing mortality. There is some evidence that abalone may migrate in response to disturbance, that individual abalone move (often emerging from cryptic habitat, see Nash et al. 1994) to occupy homesites vacated by abalone that are caught and abalone re-aggregate after stock density is reduced by harvesting (McShane and Smith 1989; Nash et al. 1994). These theories need to be tested to determine the extent to which abalone movement and re-aggregation affects abundance estimates.

Abalone populations are generally managed over large geographic scales. Inevitably this leads to zonal management boundaries that straddle more than one unit of stock (metapopulation). However, contemporary catch and effort data are usually collected on a finer scale than that defined by management boundaries. This begs the question of 'At what scale and in what design should an abalone stock monitoring program be structured considering the constraints imposed by financial resources?'. Whilst the most reasonable approach is to conduct abalone abundance surveys at the scale of individual metapopulations, such population scales are perceived as both small and difficult to define. There is a need for further research in experimental design to maximise the capacity to adequately assess stocks. A trade-off between sampling intensity with power to detect change and coverage of the entire resource is required. Interannual variation in abundance needs to be linked to catches at an appropriate scale. In Victoria this scale is usually that of multiple reef complexes each covering several kilometres of coastline.

Staff

Mr. Harry Gorfine	Principal Investigator	1 Jan 94 - 30 Jun 95	15%
Mr. Anthony Hart	Marine Scientist	1 Jan 94 - 30 Jun 95	100%
Mr. Michael Callan	Technical Officer	1 Jan 94 - 30 Jun 95	100%
Mr. David Forbes	Technical Officer	1 Jan 94 - 30 Jun 95	20%
Mr. Cameron Dixon	Technical Assistant	1 Jan 94 - 30 Jun 95	20%
Mr Bruce Waters	Technical Assistant	1 Jan 94 - 30 Jun 95	20%

Final Costs

The following table provides a summary of the total funds and various contributions of FRDC, VFRI and industry contributions to the Project. In addition to the $166,101 allocated by FRDC, VFRI contributed an additional $22,191 to cover extra field sampling costs and the Victorian abalone industry contribution was $40,000 greater than predicted.

	ALLOCATED	EXPENDITURE	Explanatory notes
FRDC Contribution			
Salaries and on-costs	129,971	131,221	
Travel	7,780	13,015	$5K was transferred from capital as agreed (letter dated 22/3/95)
Operating	10,850	9,600	
Capital	17,500	12,265	
TOTAL FRDC	166,101	166,101	
VFRI Contribution			
Salaries and on-costs	21,233	31,850	Original budget based on 30 days' field work. Project took 45 days to complete.
Operating	23,141	34,712	
TOTAL VFRI	44,374	66,565	
Contribution by Industry ‘in-kind’ support by industry for fish-downs	50,000	90,000	Refer to VFRI contribution
TOTAL BUDGET	260,475	322,666	

Distribution

This report will be distributed to researchers who have an interest in abalone research, to several libraries and to each of the following organisations.

Abalone Fishermen's Co-operative Limited
PO Mallacoota VIC 3892.

Australian Bureau of Agricultural and Resource Economics
Macarthur House, Macarthur Avenue, Lyneham ACT 2602.

Australian Fisheries management Authority
Burns Centre, 28 National Circuit, Forrest ACT 2603.

Australian Institute of Marine Science
PMB No 3, Townsville QLD 4810.

Australian Maritime College
Beauty Point, TAS 7270.

Bureau of Resource Sciences, Fisheries Resources Branch
Curtin House, 22 Brisbane Avenue, Barton ACT 2601.

CSIRO Marine Laboratories, Division of Fisheries
Castray Esplanade, Hobart TAS 7001.

Demersal Mollusc Research Group
(Members: Neil Andrew, Harry Gorfine, Lindsay Joll, John Keesing, Warwick Nash, Sebastian Rainer and Scoresby Shepherd)

Marine Resources Division, Department of Primary industry and Fisheries
GPO Box 619F, Hobart TAS 7001.

National Seafood Council
Unit 1, 6 Phipps Place, Deakin ACT 2600.

New South Wales Fisheries Research Institute
PO Box 21, Cronulla NSW 2230.

Primary Industries (Fisheries) South Australia
GPO Box 1625, Adelaide SA 5001.

South Australian Fishing Industry Council
c/o Adrian Fletcher, 9 Angas Street, Port Lincoln SA 5606.

South Australian Research and Development Institute (Aquatic Sciences)
PO Box 1120, Henley Beach SA 5022.

Tasmanian Fishing Industry Council
c/o Bob Lister, PO Box 960, Sandy Bay TAS 7006.

Tasmanian Sea Fisheries Division, Marine Research Laboratories
Crayfish Point, Taroona TAS 7053.

Victorian Abalone Divers Association
PO Box 252, Mount Martha VIC 3934.

Victorian Fisheries Branch, Flora Fauna and Fisheries Division
Department of Conservation and Natural Resources
Sixth Floor, 240 Victoria Parade, East Melbourne VIC 3004.

Victorian Fishing Industry Federation
Suite 7, 20 Commercial Road, Melbourne VIC 3004.

Western Abalone Divers Association
PO Box 574, Warrnambool VIC 3280.

Western Australian Department of Fisheries
SGIO Atrium, St Georges Terrace 6001.

Western Australian Marine Research Laboratories
West Coast Drive, Waterman WA 6020.

Acknowledgments

Without the support of the Victorian abalone industry this project would not have been possible. Industry representatives were involved from the early planning stages of the project and Konrad Beinssen, Phil Eather, Peter Johnston, Phil Plummer, Alan Taylor, Alex Ziolkowski all assisted during discussions about site suitability and commercial fishing arrangements.

Peter Johnston and Len McCall are thanked for giving up their time to show us potential sites for the project. Mick Shannessy deserves special thanks for his ideas, offers of assistance and motivation to participate in the project and see it through to the end. The seven divers and their respective deckhands who participated in the controlled fishing phase of the project also deserve special recognition for their generosity and willingness to co-operate within the constraints imposed by a controlled experiment.

Assistance was also provided from within the Department of Conservation and Natural Resources by Murray Donaldson and Rod Barber with regard to enforcement considerations, and by John Barker and Greg Aird with permit arrangements to take undersize abalone.

VFRI’s David Smith, Terry Walker, Nik Dow and Garth Newman provided much encouragement and advice both before and during the project and Anne Gason provided assistance with data analysis. Scientific advice was generously provided by Neil Andrew (NSWFRI) and Warwick Nash (Tasmanian Sea Fisheries Division). Terry Walker reviewed initial drafts of this manuscript and provided many valuable suggestions for its improvement.

Finally, acknowledgment must be made of the substantial effort made by the project’s field staff. David Forbes, Bruce Waters and Cameron Dixon spent nine consecutive weeks away from VFRI that involved arduous work with long hours underwater during mid-winter. Ian Duckworth is thanked for his support of the field team during this period in ensuring a consistent supply of fuel and spare parts for vessel operations.

References

Breen, P.A. (1980). Measuring fishing intensity and annual production in the abalone fishery of British Columbia. *Canadian Technical Report in Fisheries and Aquatic Sciences*, **947**.

Harrison, A.J. (1983). The Tasmanian abalone fishery. *Tasmanian Fisheries Research* No. **26**.

McShane, P.E. (1994). Estimating the abundance of abalone (*Haliotis* spp.) stocks: examples from Victoria and southern New Zealand. *Fisheries Research* **19**, 379-394.

McShane, P.E. and Smith, M.G. (1989). Direct measurement of fishing mortality in abalone (*Haliotis rubra* Leach) off southeastern Australia. *Fisheries Research* **8**, 93-102.

Nash, W.J., Sellers, T.L., Talbot, S.R., Cawthorn, A.J. and Ford, W.B. (1994). The population biology of abalone (*Haliotis* species) in Tasmania: I. Blacklip abalone (*H. rubra*) from the north coast and the islands of Bass Strait. Tasmanian Sea Fisheries Division, Technical Report No. **48**.

Prince, J.D. (1989). The fisheries biology of the Tasmanian stocks of *Haliotis rubra*. Ph.D. thesis, Zoology Department, University of Tasmania.

Sainsbury, K.J. (1982). Population dynamics and fishery management of the paua, *Haliotis iris*. 1. Population structure, growth and mortality. *New Zealand Journal of Marine and Freshwater Research* **33**, 147-161.

Appendices I - III

Part I

Abundance estimation of blacklip abalone (*Haliotis rubra*) I. An analysis of diver-survey methods used for large-scale monitoring.

Anthony M. Hart[1], Harry K. Gorfine and Michael P. Callan

Victorian Fisheries Research Institute, P.O. Box 114, Queenscliff, Victoria, Australia

1. Corresponding address:
   ICLARM Coastal Aquaculture Centre
   P.O. Box 438
   Honiara
   Solomon Islands
   ph: 677 29255 fax: 677 29130
   E-mail: iclarm@ffa.gov.sb

Abstract

A comparative evaluation of radial transect and timed collection methods used in large-scale monitoring of abalone stocks in Victoria was undertaken. Methods were assessed according to their accuracy, precision, robustness and sensitivity (ability to detect change). Sample size required to detect a 50% decrease was estimated using data from a pilot study, and three replicate stock depletion experiments were undertaken in a simple before/after design testing the null hypothesis of no change at the impacted sites. Harvesting was undertaken by commercial abalone divers. On all occasions, both methods were sensitive enough to detect the specified change and robust to both a significant effect of observer and violation of the assumption of equality of variances. No significant differences in precision occurred, however the 30m^2 transect estimated the actual number of abalone harvested to within 10% of the true value. Only a weak linear relationship (pre-recruits r^2 = 0.12; post-recruits r^2 = 0.39) was observed between relative abundance (timed collection data) and absolute abundance (30m^2 transect data). Importantly, the fishing behaviour (targeting of aggregations) of commercial abalone fishers resulted in much reduced variances for both transect estimates and timed collections, and consequently, increased power to detect a decrease in population size. In the long term however, this phenomenon may be offset byre-aggregation of populations, the extent of which needs to be thoroughly determined. Overall, the 30m^2 transect was considered the safer, more robust method for long-term monitoring of abalone stocks.

Keywords: *Haliotis rubra*, abundance methods, stock depletion, monitoring

Introduction

A desirable goal in abalone stock assessment is to obtain measures of abundance which are independent of commercial CPUE. As an index of abundance, commercial catch-effort data in abalone fisheries cannot be relied upon because of the problems of a) correct estimation of effort, b) variable catchability, and c) heterogeneous stock distribution, all of which have been well documented (Sloan and Breen, 1988; Breen, 1992; Prince and Guzman del Proo, 1993; McShane, 1994; Hart and Gorfine, 1996). In Australia there has been a concerted effort over the last decade to develop efficient diver-survey techniques as an integral component of the stock -assessment process (Beinssen, 1979; Shepherd, 1985; Andrew and Underwood, 1992; McShane, 1994; Nash, pers. comm). What is most needed is an unbiased technique for sampling both the recruited (those available to the fishery) and pre-recruited stages of abalone populations.

Blacklip abalone (*Haliotis rubra*) is Victoria's most valuable commercial fishery resource and large-scale stock monitoring using diver-surveys was initiated in 1988 as (McShane, 1994). A timed (10 minutes) collection method was the first sampling unit used for monitoring of abalone stocks (McShane, 1994). The rationale for adopting this particular method was based on the premise that use of traditional area-based transects would be prohibitive for large scale
surveys (McShane, 1994) because of the time taken to carry out individual transects. However it soon became evident that a considerable observer bias existed for the timed collection, necessitating the adoption of procedures for calibrating observers.

After 4 years, to avoid the necessity to calibrate divers, a radial transect technique was developed and found to be highly efficient for large scale surveys (Gorfine, unpublished data). To date however, no in-depth comparison of the radial transect and the timed collection has been undertaken, although preliminary work (Gorfine, unpublished data) confirmed earlier recognition of a considerable diver bias for the timed collection. To be a useful and easily interpretable measure of relative abundance, the timed collection data must exhibit both a linear and proportional relationship with true abundance. The primary objective of this study was to make a comprehensive evaluation of these methods with respect to their accuracy, precision, robustness and sensitivity. The two main methods compared were the 30m^2 radial transect, and the timed (10 minutes) collection. Additionally a 45m2 radial transect was also examined. This was accomplished by the use of replicate stock depletion experiments in which known quantities of abalone were harvested.

Materials And Methods

Study Site

The field experiments were carried out over 10 weeks during May-August 1994 at West Head, Flinders, Victoria (38° 29'S, 145° 01'E; Fig 1). For the purposes of this study, a 500m x 300m (15 hectares) rectangular plot was divided into three replicate abalone populations, each divided into two sites of 2.5 hectares in area. After a pilot study to examine variances of the estimated abundance, some sites were further stratified (see Table 2 of Hart and Gorfine, 1996). All corners of each site were fixed clearly with buoys anchored to the substratum. The area was closed to commercial and recreational abalone fishing for the duration of the experiment. Depth at the site ranged from 6m - 14m.

Overall Procedure

A pilot study compared precision between methods, examined for an effect of research diver on abalone abundance, and provided variance estimates to aid in the design of the main depletion experiments. Sample size required to detect a 50% change in abundance was calculated for the 30m^2 transect and the timed collection. A depletion experiment was carried out in each population (described in Hart and Gorfine; 1996), and ,data analysed in a simple before/after design testing the null hypothesis of no change in abundance (Green, 1989). Methods were assessed according to their accuracy, precision, robustness and sensitivity (ability to detect change; Rooseberry & Woolf 1991). Abalone abundance was examined separately for pre-recruits (<l0cm; and post-recruits >10cm).

Description of sampling methodologies

The radial transect method consists of 2 transect ropes (e.g. 30 and 45 m length) attached to a lead weight and dropped at random sampling points. Each of two divers was randomly allocated a series of surveys, e.g. 2 x 30m^2 transects, 1 x 45m^2 transect, 1 x timed collection. The divers simultaneously swam transects out-from the lead weight (starting 5m from the weight to avoid overlapping) in a pre-determined compass direction. Using a measuring gauge, all abalone were counted in two categories (pre-recruits<10cm; post-recruits >10cm) across a 1m wide band (estimated visually) for the specified length of transect. Transects of 45m^2 were swum only during the pilot study, to estimate precision. The 10 minute collection started upon observation of the first individual and proceeded in a random direction for 10 minutes with all animals being placed in the bag. These were subsequently measured aboard the research vessel, and returned to the reef.

Assessment of accuracy

It was *a priori* not possible to count the absolute number of abalone within the experimental plot. An estimate of the total population of post-recruited abalone in the plot was made using a stratified random sampling design (Krebs, 1989) both before and after the stock depletions (see table 2: Hart and Gorfine, 1996). To assess accuracy, the difference between these was compared with the actual number of abalone harvested. The same procedure was applied to pre-recruits, with the assumption that there was no pre-recruits harvested (observers on commercial vessels returned any undersized abalone to the reef). As the longest time between pre- and post-harvest surveys for any population was 3 weeks, populations were assumed to be closed. Densities from the timed collections were calculated by two methods. First, it was assumed that the timed collections swept an area of 100 m^2 (TC1) in 10 min (McShane, 1994). Second, the searching time (Shepherd, 1985; Beinssen, 1979) was estimated and converted to area swept, with the resulting density scaled to an area of 100m^2.

$$S_i = T_i - \frac{h}{60}.n_i \qquad (1)$$

where S_i = searching time (in minutes) for the *ith* sample, T_i is the total dive time (10 minutes for the timed collection), h is the handling time per abalone (in seconds), and n_i is the total number of abalone (pre- + post-recruits) collected in the *ith* sample. Total area searched was

$$A_i = r.S_i \qquad (2)$$

where A_i = area covered for the *ith* sample, r = fishing power of abalone divers. Our data (TC3: h - 2.1 seconds; r - 13.375 m^2 min^{-1}) was compared with that from Beinssen's (1979) earlier work (TC2: h - 5.1 seconds; r - 19.933 m^2 min^{-1}). However, for calculations of density using Beinssen's (1979) fishing power value's, it was necessary to omit 4 samples where total handling time estimated from assuming a h of 5.1 seconds per abalone exceeded 10 minutes, ie when total number collected was greater than 117. At this point the calculated density tends to infinity. To illustrate this, the relationship between number collected and calculated density for the different values of h and r are shown in Figure 2.

Analysis of precision

During the pilot study, eight replicates samples of each method were randomly taken within each site. Hence six estimates of precision ($p = S.E./\bar{x}$) were obtained for each method. A one-way ANOVA compared precision between methods for pre-recruits and post-recruits.

Robustness

Robustness refers to tolerance to biased input and/or violations of assumptions (Roosebery and Woolf, 1991). For this study we tested two important assumptions. First, that there was no effect of observer on estimates of abundance. Equal numbers of replicates for each method were randomly allocated to each diver. Data (pre-recruit and post-recruit abundance) were assessed with a one way ANOVA on three occasions, during the pilot study, before, and after the experimental harvests. Second, the explicit assumption in determining sample sizes required to detect an effect is that variances do not change (Green, 1989). Variances of pre-recruits, post-recruits and total numbers from before and after the abalone harvest were analysed with a two sample F-test (Zar, 1984)

Sensitivity

Sensitivity in an experimental sense is the ability to detect real difference from random error (Box et al. 1978), and is dependant on accuracy, precision and robustness. Sensitivity of methods in detecting change was assessed in the following manner. A) Variance estimates (for post-recruits) from the pilot study were used in calculating sample size required to detect a 50% decrease in abundance (procedure in Zar, 1984; Green, 1989). B) Three depletion experiments utilising commercial abalone divers were monitored until the actual number harvested was estimated to be 50% of the total population (Hart and Gorfine, 1996). Data were analysed with a two-sample *t*-test, the null hypothesis being: no change in mean abundance.

Absolute vs relative abundance

For an index of relative abundance (i.e. timed collections) to be useful it must be: (a) linearly and proportionally related to true densities (e.g. from area-based transects), and (b) this relationship must be the same for all size classes surveyed by the method. We examined this relationship separately for pre-recruits and post-recruits using bivariate plots of the means of each method within each strata. Slopes of the regressions for pre-recruits and post-recruits were compared with a *t* - test (Zar, 1984).

Results

Accuracy

For the entire plot the estimated number removed by the 30m^2 transect was within 10% of the actual number removed (Table 1). In populations 1 and 2, similar results were observed, however the 30m^2 transect was slightly less accurate in these instances, this being due to smaller sample size. Estimates of number removed by the timed collection (TC1, TC2, TC3) were generally inaccurate (Table 1). In particular TC2 was highly inaccurate. The reason for this is that when more than 60 individuals are collected in 10 minutes, the calculated density increases in an exponential manner (Fig 2). This results in large variances and very large estimates of total population size. Similar results were obtained for pre-recruits, with the $30m^2$ transect being the most accurate, and TC2 being inaccurate.

Precision

No significant difference in precision was detected between any of the methods for either pre-recruits or post-recruits (Table 2). However, the ANOVA was only capable of detecting a 35% - 40% difference at a power of 0.8. The timed collection produced the most precise estimates for pre-recruits and post-recruits (Table 2).

Effect of observer on abundance of abalone

For pre-recruits there was a significant difference between divers ($30m^2$ and $45m^2$ transects) during the pilot study, but not during the before and after surveys (Table 3). There was also a significant diver effect (on pre-recruits) for timed collections, but only during the before surveys. For post-recruits, diver differences with the $30m^2$ transect were not significant in the pilot study and after surveys, but were significant during the before surveys (Table 3). For both transect methods time spent completing the transects were positively correlated with abundance of abalone (Table 4). A highly significant diver effect (for post-recruits) for the timed collections occurred during the pilot study and the before surveys (Table 3), but not after the stock depletions. Minimal detectable differences between divers were in the order of 35 - 45% of the overall mean abundance at a power of 0.8 (Table 3).

Equality of variance before/after harvesting

On average there was a 75-80% (statistically significant) reduction in the variance of the estimated abundance of post-recruits for the $30m^2$ transect (Table 5). In population 1, the variance of the estimated pre-recruit abundance also significantly decreased after the harvest, but remained constant for other populations. When pre-recruit and recruit data are combined (total) there is also a significant decrease in variance of the sample estimate. For the timed collection, significant decreases in variance of post-recruits occurred, with the exception of population 3. Variance of pre-recruits, as measured by timed collections remained constant except for one instance (population 2) where it increased following the stock depletions (Table 5).

Sensitivity

Both the $30m^2$ radial transect and the 10 minute collection detected a significant decrease in abundance of recruited abalone for all populations (Table 6; Fig 3). However, the percent decrease measured by each method was quite different, averaging 51% for the $30m^2$ transect, compared to 36% for the timed collections (Fig 3). Furthermore the $30m^2$ transect detected a significant decrease in total numbers for population A and the entire plot (Table 6; Fig. 4), in spite of the test being designed to detect only a larger effect. No change in abundance of pre-recruits was detected by the $30m^2$ transect for any of the populations, however the 10 minute collection detected a significant increase in number of pre-recruits in population 1 following the stock reduction (Table 6; Fig 4).

Discussion

Current knowledge of the status of abalone stocks in Victoria derives from the monitoring program. This program is into its eighth year, however the change of methods between the fourth and fifth year made it difficult to compare results from the two periods. Thus it was important that a critical analysis of the methodologies be undertaken. Despite a significant diver effect, both methods were robust and sensitive enough to detect the specified Effect Size (ES) on three occasions. The main advantage of the $30m^2$ transect was that it estimated the actual number of abalone harvested to within 10% of the true value. Hence, a 50% decrease in total population size was represented by a 50% decrease in mean number per transect. On the other hand the mean number collected per 10 minutes decreased, on average, by only 35%. In fact, the timed collection was not a particularly good index of relative abundance, exhibiting only a weak proportional relationship with absolute abundance. Additionally, the timed collection method remained inaccurate on two out of three occasions, despite the use of three separate techniques for converting timed collections to density estimates. Contributing to this inaccuracy is the fact that area swept (planar) in complex topography underestimates the area of habitat sampled. Also, the relationship between actual number collected and calculated density was an exponential curve for both values of fishing power (S) and handling time (h) used in this study. Finally, the assumptions of $100m^2$ swept in 10 minutes, and constant values for parameters of diver fishing power (Beinssen, 1979) did not hold true for all populations (Hart and Gorfine, 1996). An important result for both methods, but particularly for the $30m^2$ transect is that the variances of the sample estimate significantly decreased on all occasions, in some cases by almost 90% (eg population 2). This represents an abrupt change from an aggregated distribution pattern to a more dispersed homogenous pattern after fishing. It happens partly because abalone naturally exhibit a Taylor's power law (Taylor, 1961) type distribution, but principally as a result of commercial abalone divers targeting and removing aggregations which cause high variability in the initial sample estimate. Any decrease in variance of the sample estimate results in increased power to detect change(Zar, 1984; Andrew & Mapstone, 1987; Green, 1989; Peterman, 1990). Thus the fishing behaviour of commercial abalone divers inadvertently increases the precision and power of diver survey methods to detect change in the downward direction. This is a positive result, highlighting the effectiveness of diver survey methods, however the potential for re-aggregation in abalone may diffuse this. Although traditionally viewed as sedentary stocks, there is evidence suggesting abalone will move a considerable distance if disturbed. Prince (1989) demonstrated movements in excess of 400 metres for individuals transplanted out of their home sites. During this study we observed smaller individuals migrating to the vacant home sites of harvested abalone. In particular, reaggregation may greatly affect the fixed site monitoring program in Victoria if it occurs to a large extent. Thus there is an urgent need for this issue to be examined.

A significant diver effect for the 30m^2 transect occurred only in one out of three instances, whilst diver differences for the timed collection were generally greater and occurred on two out of three occasions. However the "significance" of these effects requires clarification. Firstly, the relatively high minimum detectable differences (MDD) (35-45% of the mean of all divers) are the net result of setting the Type I error probability (α) at 0.05 and Type II error probability (β) at 0.2, thus immediately making a decision about which type of error is the most important. MDD's would decrease substantially if α and β were set equal to one another at 0.2. Secondly the 'significance' of the diver difference makes sense only relative to the size of the overall difference a method aims to detect, ie that which is deemed biologically important. If one is interested in detecting a 50% change, then diver differences less than this may or may not be important. So *a priori* consideration of a) the effect size of interest, and b) the relative costs of α and β must be carried out routinely in environmental monitoring (Peterman, 1990; McAllister and Peterman, 1992; Mapstone, in press).

For the timed collections, all attempts to improve the measure by converting the index to a density estimate by some assumption or calculation of area swept (Beinssen, 1979; Shepherd, 1985; McShane, 1994) fail as a result of diver differences and exogenous factors such as kelp density and swell. Significant diver differences will always exist because the technique is a skill in which experience and ability differs substantially between observers. If the group of observers was constant over time it would be possible to standardise divers by some procedure, for example against the 'best' observer, and this has been attempted (McShane, 1994). This dependence on particular observers however, introduces a rigidity to the process, thus compromising the flexibility needed for a long term approach. The $30m^2$ transect is an unbiased, relatively simple procedure in comparison, and more quickly mastered by an observer with limited experience. This is critically important in an on-going monitoring program where observers are continually changing.

It must be noted that for population 3, TC1 1 performed similarly to the $30m^2$ transect. That is, an index of relative abundance was a reliable measure of absolute abundance in this particular instance. This particular habitat consisted of many large aggregations, interspersed with small reefs of sparsely distributed abalone. In population 2, TC1 1 and TC2 performed similarly to the $30m^2$ transect in estimating abundance of pre-recruits, but not post-recruits (Table 1). This issue of unequal catchability of different animal types is discussed more thoroughly in Hart and Gorfine (1996). Thus it appears that the timed collection method can work well in some instances, however its reliability is uncertain. In summary we conclude that the decision to change methods was reasonable and we disagree with the assertions by McShane (1994) and McShane and Smith (1989) that transect methods have been proved to be inaccurate in estimating the abundance of abalone. To the contrary, we have demonstrated both in this study, and in a companion paper (Hart and Gorfine, 1996) that, combined with efficient field sampling strategies, transect censuses provide accurate measures of abalone abundance. In contrast, there is uncertainty surrounding the accuracy and validity of the timed collection method as an index of relative abundance. This is because of the interacting influences of diver skill, environmental habitat and conditions, abalone distribution patterns, and unreliable procedures for estimating 'true' effort. The $30m^2$ transect is considered the safer, more robust alternative for monitoring of abalone stocks in Victoria.

Acknowledgments

Members of the Victorian Abalone Divers Association selected the site and harvested the populations. We wish to thank Peter Johnston for actively promoting this collaboration, and to Mick Shannessy for leading the way. Many thanks go the abalone field monitoring team of Michael Callan, Dave Forbes, Bruce Waters, and Cameron Dixon for their tireless efforts during the intensive field component of this study. Dr Neil Andrew provided useful comments on an early draft. The project was funded from a grant by the Fisheries Research and Development Corporation (FRDC) to the Victorian Fisheries Research Institute.

References

Andrew, N.L., and Mapstone, B.D., 1987. Sampling and the description of spatial pattern in marine ecology. *Oceanogr. Mar. Biol. Ann. Rev.*, **25**: 39-90.

Andrew, N.L., and Underwood, A.J., 1992. Associations and abundance of sea urchins and abalone on shallow subtidal reefs in southern New South Wales. *Aust. J. Mar. Freshw. Res.*, **43**: 1547-1559.

Beinssen, K, 1979. Fishing power of divers in the abalone fishery of Victoria, Australia. *Rapp. P.-v. Réun. Cons. int. Explor. Mer.*, **175**: 20-22.

Box, G.E.P., Hunter, W.G., and Hunter, J.S., 1978. Statistics for experimenters. John Wiley and Sons. 653 pp.

Green, RH., 1979. Sampling design and statistical methods for environmental biologists. John Wiley & Sons. New York. N.Y. 257 pp.

Green, RH., 1989. Power analysis and practical strategies for environmental monitoring. *Env. Res.*, **50**: 195-205.

Hart, A.M and Gorfine H.K, 1996. Abundance estimation of blacklip abalone (*Haliotis rubra*) H. An empirical evaluation of catch-effort, change-in-ratio, mark-recapture and diver survey methods. *Fish. Res.*, (submitted)

Krebs, C.J., 1989. Ecological Methodology. Harper & Row. New York, N.Y. 654 pp.

Mapstone, B.D., in press. Scalable decision criteria for environmental impact assessment: Effect size, Type I, and Type II errors. *Ecol. Appl*,.

McAllister, M.K, and Peterman, R.M., 1992. Experimental design in the management of fisheries: A review. *N. Am. J. Fish. Manage*., **12**: 1-18

McShane, P.E., 1994. Estimating the abundance of abalone (*Haliotis* spp.) stocks - examples from Victoria and southern New Zealand. *Fish. Res*., **19**: 379-394.

McShane, P.E., and Smith, M.G., 1989. Direct measurement of fishing mortality in abalone(*Haliotis rubra*) off southeastern Australia. Fish. Res., **8**: 93-102

Peterman, RM., 1990. Statistical power analysis can improve fisheries research and management. Can. J. Fish. Aquat. Sci., **47**: 2-15.

Prince, J. D., and Guzman del Proo, S. A., 1993. A stock reduction analysis of the Mexican abalone (Haliotid) fishery. Fish. Res., **16**: 25-49.

Roseberry, J. L., and Woolf A., 1991. A comparative evaluation of techniques for analyzing white-tailed deer harvest data. Wildl. Monogr., **117**: 1-59.

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, 1985. American Academy of Underwater Science, La Jolla. pp 263-272.

Sloan, N.A., and Breen, P.A., 1988. Northern abalone, *Haliotis kamtschatkana*, in British Colombia: Fisheries and synopsis of life history information. Can. Spec. Publ. Fish. Aquat. Sci., **103**: 46 pp.

Taylor, L.R, 1961. Aggregation, variance and the mean. *Nature*., **189**: 732-735.

Zar, J.H., 1984. Biostatistical Analysis. Prentice-Hall, Englewood Cliffs, NJ. 718 pp.

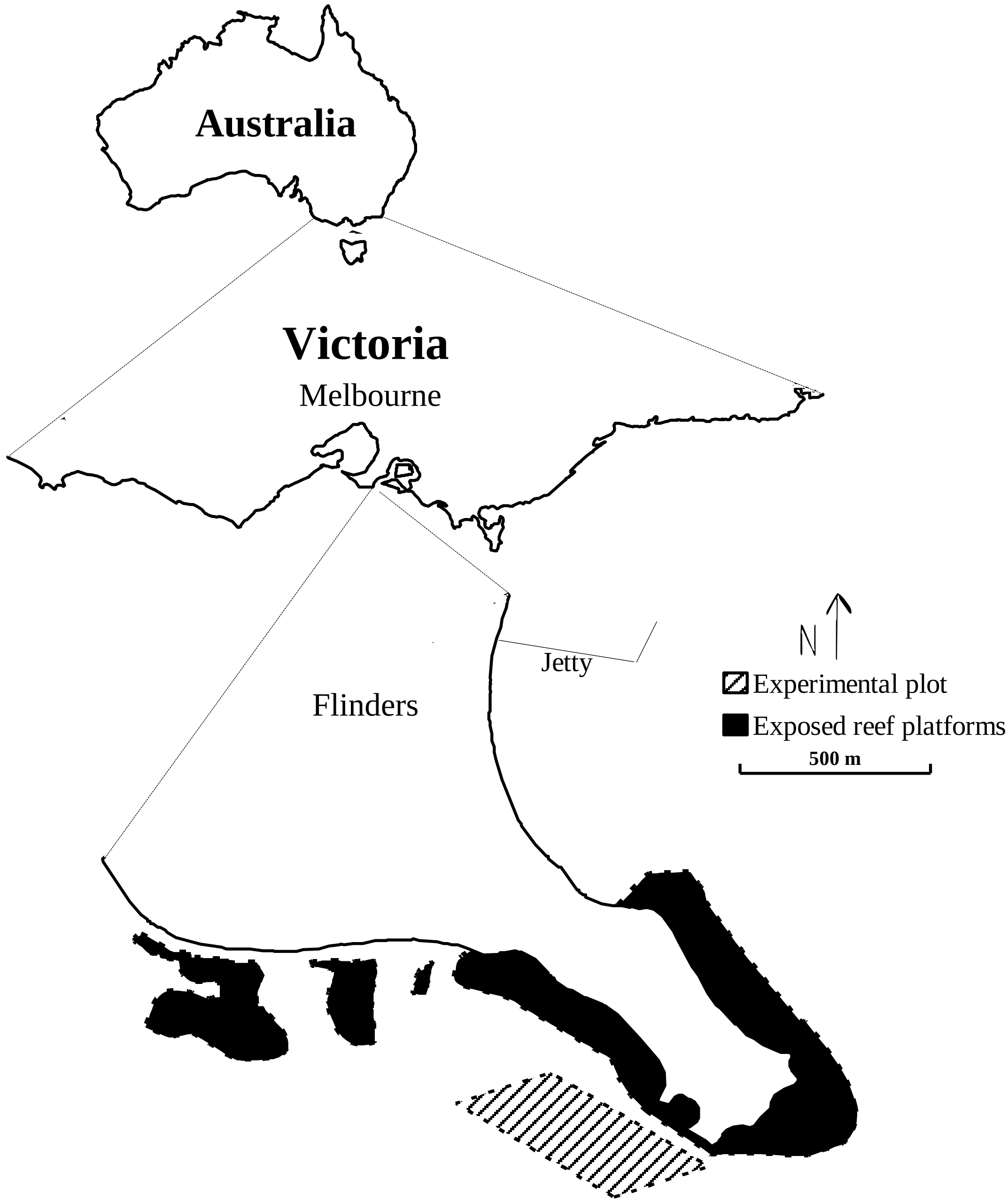


Fig. 1. Location of study site at Flinders, Victoria, Australia (38° 29’S, 145° 01’E).

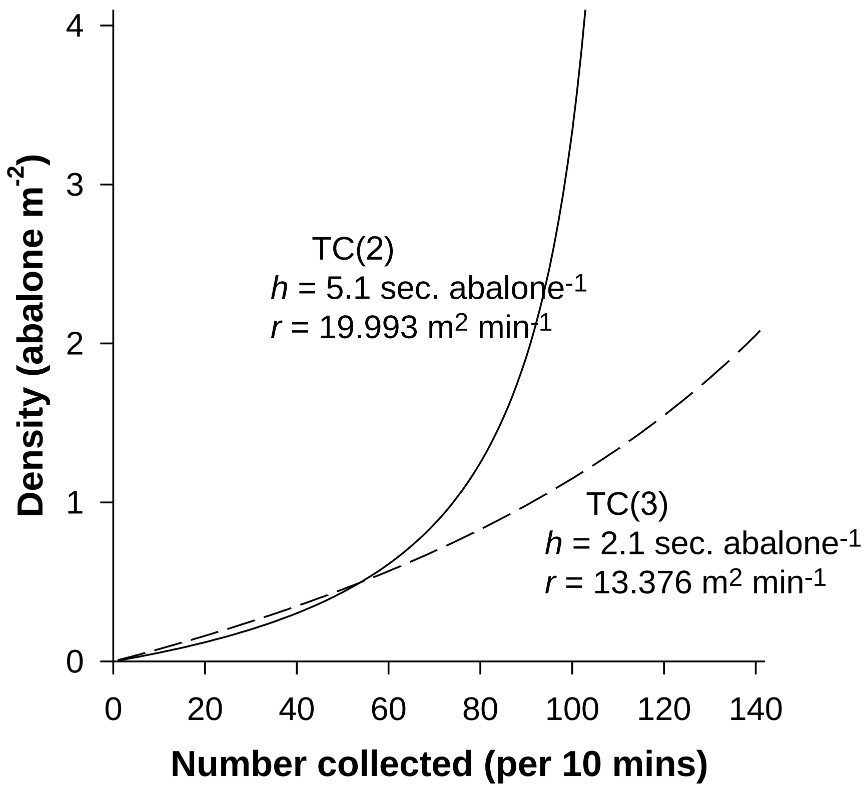


Fig. 2. Relationship between number of abalone collected per 10 minutes (the largest number of abalone collected was 142) and calculated density using the effort correction techniques of Beinssen (1979). Equations for TC2 and TC3 are given in the methods

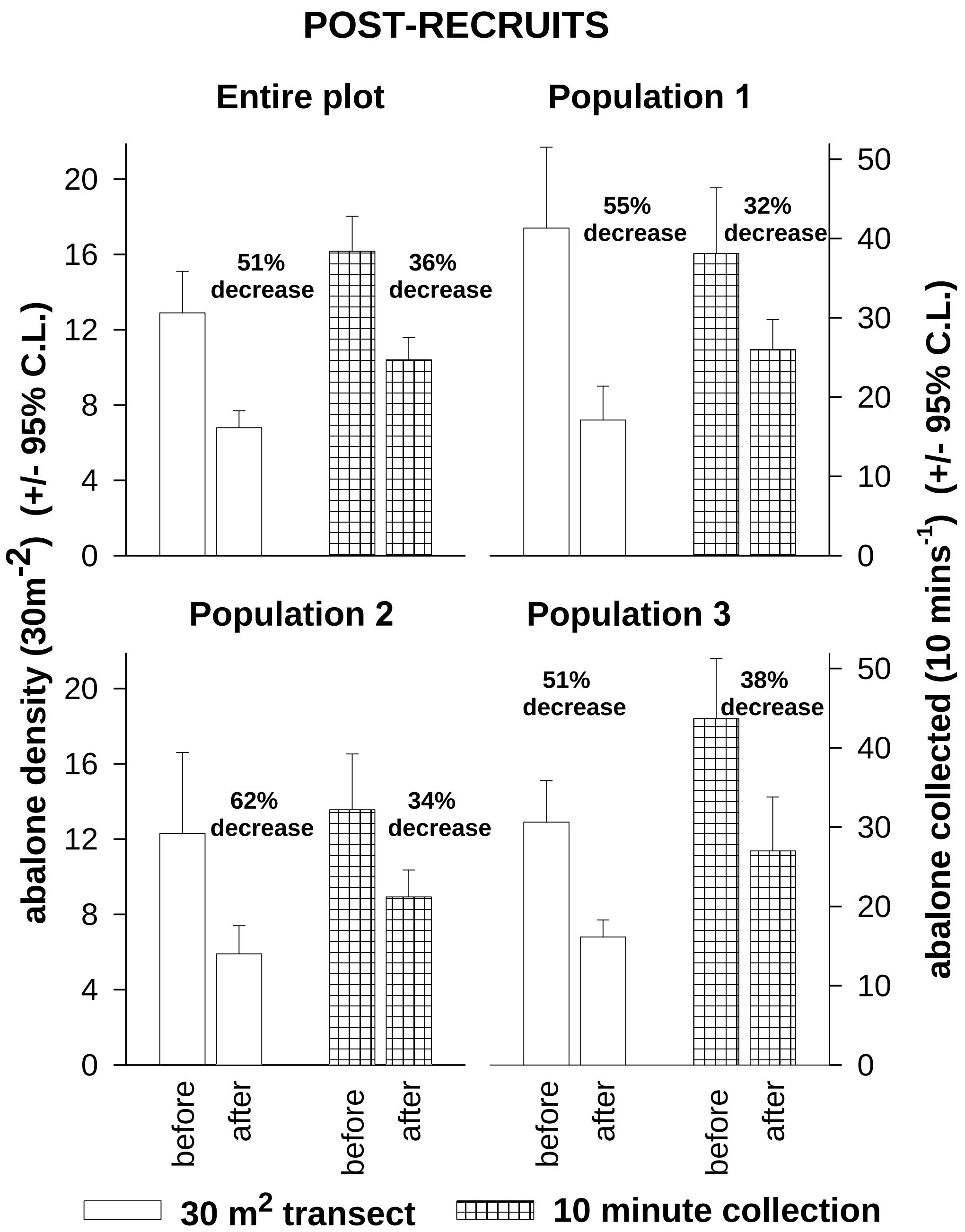


Fig. 3. Comparison of the $30m^2$ transect and the timed collection in estimating mean abundance (+ 95% CL) of post-recruited abalone from before and after harvesting.

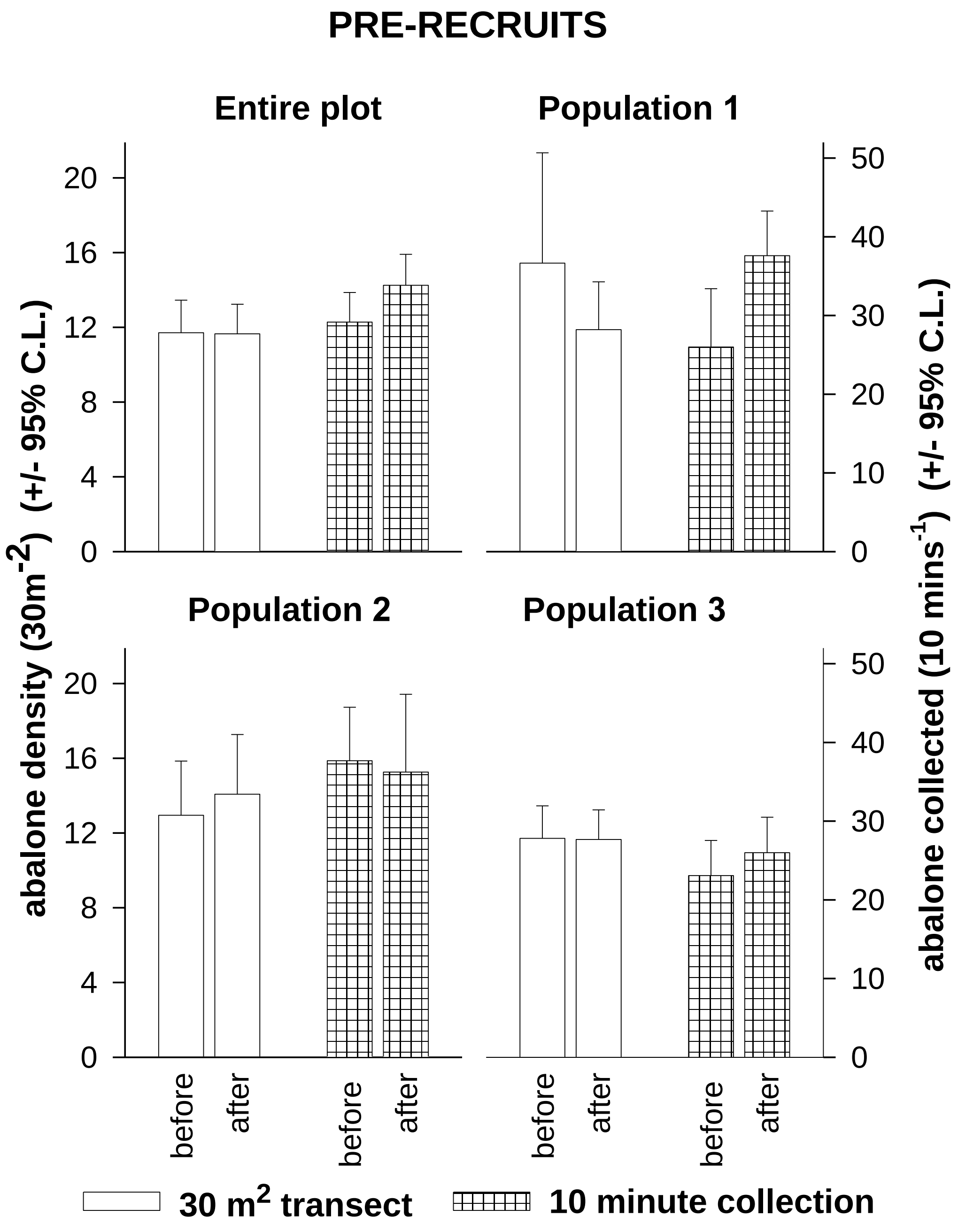


Fig. 4. Comparison of the 30m^2 transect and the timed collection in estimating mean abundance (+ 95% CL) of pre-recruit abalone from before and after harvesting.

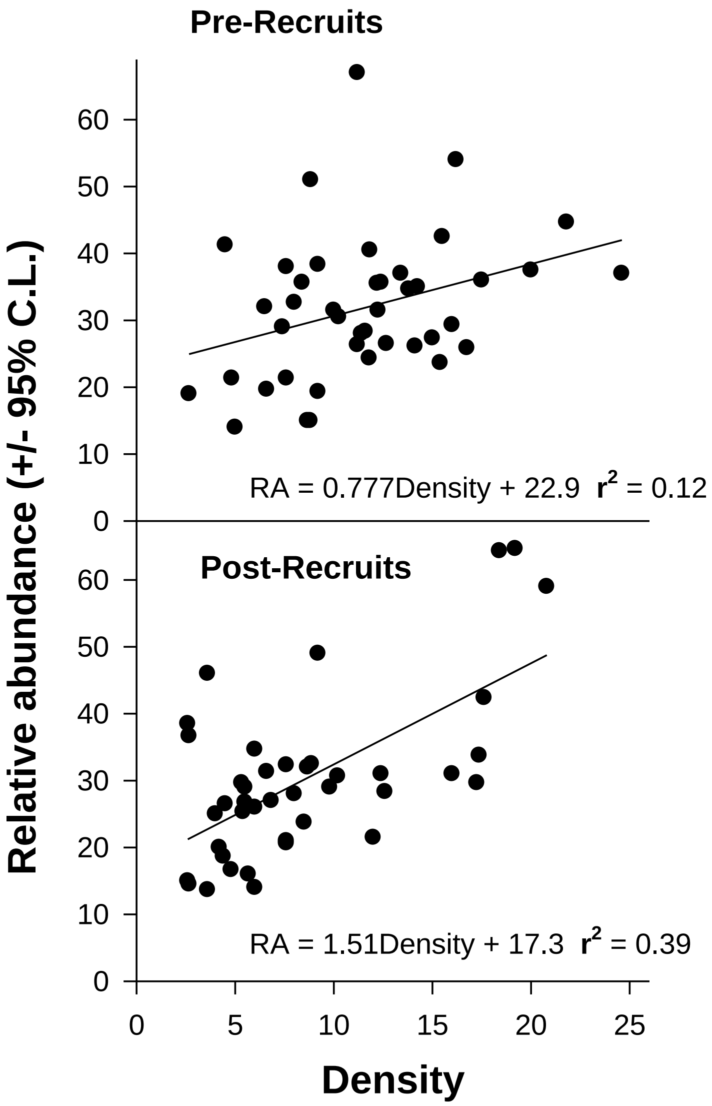


Fig. 5. Comparison of the timed collections as an index of relative abundance with absolute density estimates from the 30m^2 transect. Each data point represents the mean values of both

methods within the same strata. Data from before and after stock depletions are included, RA = Relative Abundance.

Table 1.

Assessment of accuracy of the 30m^2 transect and 10 minute collection in estimating actual number of post-recruits (≥ 10cm) and pre-recruits (< 10cm) harvested. For pre-recruits, actual number harvested was assumed to be zero. Three estimates of number harvested are made for the timed collection. TC1 assumes that the timed collection covers an area of 100m^2 (McShane, 1994); TC2 assumes h = 5.1 sec abalone^{-1} and r = 19.993 m^2 min^{-1} (see methods for a definition of h and r); TC3 assumes h = 2.1 and r = 13.376 m^2 min^{-1} (estimated from this study). Accuracy for post-recruits is shown as a ± % of actual number harvested, and for pre-recruits the difference between before (B) and after (A) population estimates is expressed as a percentage of the mean population estimate (from before and after fishing).

		Post-Recruits			Pre-Recruits	
Area	Method	Actual Removed	Estimated Removed	Accuracy Value	Difference A - B	Percent
Entire Plot	transect	35729	39080	+9%	-3408	6
	TC1	"	19950	-44%	+6475	14
	TC2	"	100634	+282%	-43918	53
	TC3	"	24094	-33%	+5245	11
Population 1	transect	13625	17290	+27%	-5536	25
	TC1	"	6070	-55%	+5793	36
	TC2	"	6820	-50%	+14499	62
	TC3	"	5771	-42%	+5526	34
Population 2	transect	12573	10598	-16%	+2121	9
	TC1	"	5523	-56%	-727	4
	TC2	"	48460	+385%	-43425	113
	TC3	"	6710	-53%	+948	4
Population 3	transect	9531	8117	-15%	-38	0
	TC1	"	8358	+12%	+1359	11
	TC2	"	45356	+476%	-15019	70
	TC3	"	11568	+21%	-666	6

Table 2

Summary of 1-way ANOVA's comparing precision of the diver-survey methods (30m^2, 45m^2 transects and the timed collection) for pre-recruits, post-recruits, and total numbers.

	Source of Variation	d.f.	MS	F-ratio	Result
Pre-recruits	method	2, 5	0.0093	1.63	ns
	residual	15	0.0057		
Recruits	method	2,15	0.0025	0.59	ns
	residual	15	0.0042		

Method	Data	mean precision (± S.E.)
30 m^2 transect	pre-recruits	0.25 ±
	recruits	0.20 ± 0.02
	total numbers	0.19 ± 0.01
45 m^2 transect	pre-recruits	0.19 ± 0.03
	recruits	0.22 ± 0.04
	total numbers	0.19 ± 0.03
10 minute collection	pre-recruits	0.17 ± 0.02
	recruits	0.18 ± 0.02
	total numbers	0.16 ± 0.02

Table 3

One-way ANOVA results for an observer effect. Four divers were used for the pilot study and before surveys, and five for the after surveys. For any non-significant results, minimal detectable differences (MDD's) were calculated for power (1-β) of 0.8, and expressed as a % of the overall mean abundance. Data ln(x+1) transformed indicated by @.

Experiment	Method	Data	d.f.	F-ratio	Result	MDD
Pilot Study	30 m^2 transect	pre-recruits	3,45	4.52	**	
		post-recruits	3,45	1.17	ns	44%
	$45m^2$ transect	pre-recruits@	3,45	4.67	**	
		post-recruits@	3,45	2.58	ns	46%
	Timed collection	pre-recruits	3,44	1.65	ns	39%
		post-recruits	3,44	8.09	***	
Before stock depletions	$30m^2$ transect	pre-recruits	3,80	0.95	ns	38%
		post-recruits@	3,80	3.32	*	
	Timed collection	pre-recruits	3,40	3.03	*	
		post-recruits	3,40	6.97	***	
After stock depletions	$30m^2$ transect	pre-recruits@	4,78	0.97	ns	45%
		post-recruits	4,78	0.83	ns	45%
	Timed Collection	pre-recruits@	4,78	0.8	ns	47%
		post-recruits@	4,78	2.09	ns	34%

Table 4

Pearson correlation coefficients between number of abalone and time taken to complete a transect. Sample sizes (*n*) are shown and all correlations are highly significantly positive, p < 0.001.

Method	*n*	pre-recruits	post-recruits	total numbers
$30m^2$ transect	289	0.41	0.58	0.54
$45m^2$ transect	48	0.66	0.55	0.64

Table 5
F-test for equality of variances in each population before (b) and after (a) harvesting of post-recruits.

	Entire Plot								Population 1							
	$30m^2$ Transect				Timed Collection				$30m^2$ Transect				Timed Collection			
		Variance	F	Result		Variance	F	Result		Variance	F	Result		Variance	F	Result
Pre-recruits	**b**	77.7	1.06	ns	**b**	215.6	1.37	ns	**b**	122.7	2.43	*	**b**	207.6	1.19	ns
	a	73.6			**a**	295.5			**a**	50.4			**a**	247.5		
Recruits	**b**	156.3	5.65	***	**b**	355.6	2.0	**	**b**	74.5	2.90	**	**b**	282.0	2.34	*
	a	27.6			**a**	177.7			**a**	25.7			**a**	120.5		
Total	**b**	381.9	2.74	***	**b**	636.2	1.17	ns	**b**	312.7	3.39	**	**b**	723.8	1.69	ns
	a	139.2			**a**	543.9			**a**	92.3			**a**	429.2		
	Population 2								Population 3							
	$30m^2$ Transect				Timed Collection				$30m^2$ Transect				Timed Collection			
		Variance	F	Result		Variance	F	Result		Variance	F	Result		Variance	F	Result
Pre-recruits	**b**	82.6	1.24	ns	**b**	234.3	2.12	*	**b**	45.1	1.18	ns	**b**	100.8	1.02	ns
	a	102.5			**a**	496.9			**a**	53.4			**a**	102.9		
Recruits	**b**	219.2	7.59	***	**b**	292.8	4.73	***	**b**	115.8	4.16	***	**b**	439.0	1.19	ns
	a	28.9			**a**	61.9			**a**	27.9			**a**	370.0		
Total	**b**	483.0	2.65	**	**b**	592.5	1.03	ns	**b**	268.3	2.17	**	**b**	657.0	1.02	ns
	a	182.4			**a**	575.1			**a**	123.9			**a**	671.7		

Table 6
Result of *t*-tests comparing densities of abalone before and after experimental stock depletions. (+) = increase, (-) = decrease.

	Radial Transect			Timed Collection		
	d.f.	t	Result	d.f.	t	Result
Entire Plot						
Pre-recruits	213	0.05	ns	135	-1.69	ns
Recruits	129	4.64	***(-)	104	4.48	***(-)
Total	158	2.81	**(-)	135	1.96	ns
Population 1						
Pre-recruits	21	1.17	ns	47	-2.53	*(+)
Recruits	20	4.37	***(-)	23	2.63	*(-)
Total	20	2.91	**(-)	47	0.04	ns
Population 2						
Pre-recruits	81	-0.59	ns	37	0.25	ns
Recruits	52	2.63	*(-)	30	2.75	**(-)
Total	68	1.29	ns	42	1.72	ns
Population 3						
Pre-recruits	52	0.03	ns	42	-0.96	ns
Recruits	82	2.61	*(-)	42	2.62	*(-)
Total	72	1.60	ns	42	1.67	ns

Part II

Abundance estimation of blacklip abalone (*Haliotis rubra*) II: A comparative evaluation of catch-effort, change-in-ratio, mark-recapture and diver-survey methods

Anthony M. Hart[1] and Harry K. Gorfine

Victorian Fisheries Research Institute, PO Box 114, Queenscliff, Victoria, Australia

1. Corresponding address:
ICLARM Coastal Aquaculture Centre
PO Box 438
Honiara
Solomon Islands
ph: 677 29255 fax: 677 29130
E-mail: iclarm@ffa.gov.sb

Abstract

Assessments of three replicate populations of blacklip abalone (*Haliotis rubra*) were made utilising a range of techniques, enabling critical assumptions to be tested empirically. Methods included catch-effort (Leslie), Change-in-ratio (CIR), mark-recapture (MR) and diver-survey techniques. Population assessments were carried out under the same experimental protocol and within adjacent, closed areas of 5 hectares. To establish a Leslie estimate, a 50% stock reduction of each population was carried out using commercial abalone divers. The principal objective was to make a comparative evaluation of methods with respect to their accuracy, precision, robustness and data requirements. A total of 8 tonnes (35,729 individuals) of abalone (≥ 10 cm) was harvested. The diver-survey (30m^2 transect), MR and CIR (using 30m^2 transect data) methods were given the highest overall rating. In general, the CIR (using timed collection data) did not perform as well as the CIR (using transect data). Leslie estimators were inaccurate and imprecise for two out of the three populations. Furthermore, the correction of unit effort from total dive time into searching and handling time for both the Leslie and timed collection population estimators did not improve the reliability of the estimate. The timed collection diver-surveys, while precise, were highly inaccurate and their use for abundance estimation in abalone is not recommended.

Keywords: *Haliotis rubra*, estimating abundance, stock depletion, change-in-ratio

Introduction

Agreement among methods lends support to the accuracy of the estimates, while disagreement will bring the assumptions under scrutiny. In abalone fisheries, both fisheries dependent (in which either catch or both catch and effort may be required) and fisheries independent methods have been utilised. Some examples of these include Leslie and DeLury regression techniques (Kojima and Ishibasi 1985; Hirayama et al. 1989), Change-in-ratio (CIR) analysis (Nash, 1994) and diver survey methods (McShane, 1994; 1995). Recently, Dawe et al. (1993) advocated further use of CIR methods in assessment of benthic invertebrate fisheries.

Current views in abalone fisheries are that CPUE does not give a reliable index of abundance (Sloan and Breen, 1988; Breen, 1992; Prince and Guzman del Proo, 1993; McShane, 1994). Effort is difficult to establish accurately as it consists of two components, searching and handling time (Shepherd, 1985; Beinssen, 1979), and the fishery (commercial divers) targets aggregations of adults. These factors may lead to the condition of hyperstability in CPUE (Hilborn and Walters, 1992; Mohn and Elner, 1987), where CPUE is maintained, despite decreasing abundance. The effort correction techniques of Beinssen (1979) and Shepherd (1985) are designed to overcome this problem, however to date there is no instance of their application. Furthermore, there has been no comparative study of CPUE methods in conjunction with other types of assessment techniques for abalone populations.

In this paper we undertake a comparative evaluation of methods for estimating abundance based on the criteria of accuracy, precision, robustness and data requirements (*sensu* Rooseberry and Woolf,1991). To enable a controlled comparison, evaluations were carried out within three replicate closed populations of blacklip abalone. Methods chosen for the study were: the Leslie technique (Leslie and Davis, 1939; Mahon, 1980; Seber, 1982; Polovina, 1986; Mohn and Elner, 1987; Crittenden and Thomas, 1989), a regression of CPUE on cumulative catch, the x intercept providing an estimate of population size; Change-in-ratio analysis (Chapman, 1955; Paulik and Robson, 1969; Seber, 1982; Pollock et al. 1985; Krebs, 1989; Dawe et a1. 1993) which works with selective removal of one type of animal from a population of two types of animal; mark-recapture in its simplest form, Petersen's estimate (Seber, 1982); and three diver survey methods, which are applied in a stratified random sampling design to establish a population estimate. All methods are presented and applied to *Haliotis rubra* populations near Flinders, Victoria, Australia.

Materials And Methods

Study Site

The study was carried out on three replicate abalone populations, each covering an area of 5 hectares near Flinders, Victoria, Australia (38° 29'S, 145° 01'E). For further details refer to the companion paper (Hart et al. 1996).

Catch-effort estimators

Stock-depletion experiments were carried out within each of the populations of *Haliotis rubra*, with abalone harvested being ≥ 10 cm length (post-recruits). Harvesting was done by seven licensed commercial abalone divers who volunteered their services. Divers were instructed to fish in their normal pattern, the only constraint being to stay within the experimental plots. To enable a comparison of the performance of the Leslie estimator between adjacent populations, and to obtain a Leslie estimate for the entire plot, we attempted to harvest the same proportion of total population in each area. An arbitrary figure of 0.5 was chosen and two independent techniques were utilised to ascertain when 50% of each population had been removed and thus fishing would to cease. 1) By observing when approximately half of the total number of tagged abalone (see Petersen mark- recapture) had been returned in the catch. 2) By comparing the number harvested with estimates of total population obtained from diver-surveys prior to fishing. Catch (number per bag) and effort (dive time in minutes) was monitored by observers on the commercial abalone vessels.

The linear regression technique of Leslie and Davis (1939) and DeLury (1947) were applied to estimate total population and catchability (q). Only the Leslie results are presented here as the DeLury estimates were very similar (Hart, unpublished data). Modifications of these techniques suggested by Braaten (1969) have been applied. This involves estimating cumulative catch and effort up to the middle of each sampling period, rather than the beginning. Equations and variance estimates for the relevant parameters are from Seber (1982).

The estimate for the total population size $\hat{N}$ is given by

$$\hat{N} = \overline{C} + \left(\overline{Y} / \hat{q}_L\right) \quad (1)$$

where $\hat{q}_L$ is the Leslie catchability coefficient, and $\overline{C}$ and $\overline{Y}$ are the mean cumulative catch and mean CPUE (abalone hr^{-1}) respectively.

$$\hat{q}_L = \frac{-\sum_{i=1}^{S} Y_i \left(\sum_{t=0}^{t=i} C_t - \overline{C} \right)}{\sum_{i=1}^{S} \left(\sum_{t=0}^{t=i} C_t - \overline{C} \right)^2} \quad (2)$$

where s = total number of samples, $\sum_{t=0}^{t=i} C_t$ is the cumulative catch at time i and Y_i is the CPUE at time *I*. Three values of effort were used to derive Y_i . E1) total dive time, E2) searching time assuming a constant handling time of 5.1 secs (Beinssen, 1979), and E3) searching time assuming a constant handling time of 2.1 secs (see Hart et al. 1996). Note that at the end of the first sampling period, according to Braaten's (1969) modifications the value of $\sum_{t=0}^{t=i} C_t$ will be half the catch rather than zero.

The variance for the population estimate is

$$V\left[\hat{N}\right] = \frac{\sigma_L^2}{\hat{q}_L^{\,2}}\left[\frac{1}{s} + \frac{\left(\hat{N} - \overline{C}\right)^2}{\sum_{i=1}^{S}\left(\sum_{t=0}^{t=i} C_t - \overline{C}\right)^2}\right] \tag{3}$$

where

$$\sigma^2{}_L = \frac{\sum_{i-1}^{S}\left[Y_i - \hat{q}_L\left(\hat{N} - \sum_{t=0}^{t=i} C_t\right)\right]^2}{s-2} \tag{4}$$

The 95% confidence limits for estimate of $\hat{N}$ is given by

$$\hat{N} \pm 1.96\sqrt{V\left[\hat{N}\right]} \tag{5}$$

Estimates were made each population (5 hectares) and the entire plot (15 hectares).

Change-in-ratio (CIR) analysis

In this study, the two types of animal in the population were pre-recruits (c-types; <10 cm) and post-recruits (d-types; ≥ 10 cm). Separate CIR estimates were made for data from the 30m2 transect and the 10 minute collection (see Diver-survey methods). The total population size before the stock depletion (N_B) and the number of post-recruits (D_B) can be estimated by

$$\hat{N}_B = \frac{\hat{R}_D - \hat{P}_A\hat{R}_D}{\hat{P}_B - \hat{P}_A} \tag{6}$$

$$\hat{D}_B = \hat{P}_B \hat{N}_B \tag{7}$$

where $\hat{R}_D$ is the total number of post-recruits removed from the population and $\hat{P}_B$ and $\hat{P}_A$ are the proportion of post-recruits from before and after fishing respectively. Variances for $\hat{N}_B$ and $\hat{D}_B$ (from Seber, 1982 p.355) are

$$V\left[\hat{N}_B\right] \approx \left(\hat{P}_B - \hat{P}_A\right)^{-2}\left(N_A^2 V\left[\hat{P}_B\right] + \hat{N}_A^2 V\left[\hat{P}_B\right]\right) \tag{8}$$

$$V\left[\hat{D}_B\right] \approx \left(\hat{P}_B - \hat{P}_A\right)^{-2}\left(\hat{N}_B^2 \hat{P}_A^2 V\left[\hat{P}_B\right] + \hat{N}_A^2 \hat{P}_B^2 V\left[\hat{P}_A\right]\right) \tag{9}$$

Two techniques for estimating the proportions and variances of proportions were examined.

Firstly, treating $\hat{P}_j$ (*j* = before, after) as a point estimator (Pollock et al. 1985),

$$\hat{P}_j = \frac{\sum_{i=1}^{n} p_{ij}}{n_j} \tag{10}$$

where p_{ij} is the proportion of post-recruits in the *ith* sample of survey *j*, and n_j is the number of samples in survey *j*. The variance of $\hat{P}_j$ in this instance is

$$\hat{V}\left[\hat{P}_j\right] = \frac{\hat{P}_j\left(1 - \hat{P}_j\right)}{\sum_{i=1}^{n} z_{ij}} \tag{11}$$

where z_{ij} is the total number of abalone caught in the *ith* sample. The second technique is to treat $\hat{P}_j$ as a ratio estimator (Cochran, 1977; Dawe et al. 1993). For example, the proportion of post-recruits in survey *j* was estimated for each method by:

$$\hat{P}_j = \frac{\sum_{i=1}^{n} d_{ij}}{\sum_{i=1}^{n} z_{ij}} \qquad (12)$$

where d_{ij} is the number of post-recruits caught in the *ith* sample (i = 1, 2,...n_j).

The variance of $\hat{P}_j$ is

$$\hat{V}\left[\hat{P}_j\right] = \frac{\sum_{i=1}^{n}\left(d_{ij} - \hat{P}_j z_{ij}\right)^2}{n_j\left(n_j - 1\right)\bar{z}_j^{\,2}} \qquad (13)$$

.

where $\bar{z}_j$ is the mean number of abalone found in survey *j*, ie

$$\bar{z}_j = \frac{\sum_{i=1}^{n} z_{ij}}{n_j} \qquad (14)$$

Thus the 95% confidence limits (assuming normality) for $\hat{N}_B$ and $\hat{D}_B$ are

$$\hat{N} \pm 1.96\sqrt{\hat{V}} \qquad (15)$$

Petersen Mark-Recapture

Immediately prior to fishing, each population was searched and abalone were tagged (marked) *in situ* with Markal® oil paint crayons, the total number tagged being recorded with hand-held tally counters. These crayons are semi-permanent and tags on abalone in captivity have remained for over 4 months. During the experiments, the longest period between marking of abalone and recapture was 3 weeks. Petersens population estimator with Chaprnan's (1954) modifications is

$$\hat{N} = \frac{(n_1+1)(n_2+1)}{m_2+1} \tag{16}$$

where n_1 = initial number of animals marked, n_2 = number of animals harvested, and m_2 = number of marked animals among n_2. Table 1 shows the tagging-recapture history for the depletion experiments.

$$V[\hat{N}] = \frac{(n_1+1)(n_2+1)(n_1-m_2)(n_2-m_2)}{(m_2+1)^2(m_2+2)} \tag{17}$$

The 95% confidence limits for $\hat{N}$ are

$$95\%L = N \pm 1.96\sqrt{V} \tag{18}$$

Diver-survey methods

A stratified random sampling design was used to obtain an estimate of total population size for pre- and post-recruits, equations are summarised in Table 2. Data were obtained from two radial transects (30m^2; 45m^2) and a l0 minute collection (see Hart et al. 1996). To obtain a population estimate for the timed collection, numbers collected per l0 minutes were converted to density values (per l00m^2) by a) assuming l00m^2 searched in 10 minutes collecting (McShane, 1994), and using equations 1 and 2 described in Hart et al. (1996). Estimates were obtained for the entire plot (15 hectares) and each population (5 hectares).

Assessment and comparison of methods

The methods were assessed according to accuracy, precision, robustness, and data requirements (sensu Rooseberry and Woolf, l991).

Accuracy

As stated in Hart et al. (1996), it was *a priori* not possible to know the true population sizes. For the diver survey methods, accuracy was inferred from a comparison of a) estimated harvest of post-recruits with actual harvest, and b) before and after population estimates of pre-recruits, which were not harvested. However this could not be achieved for the fishing-dependent methods. Consequently a series of categories of relative accuracy was developed against which the ‘accuracy’ of the Leslie, CIR, and MR population estimators could be established. These are described in Table 3. The procedure was to compare an estimate with the most accurate diver-survey method as determined in Hart et al. (1996). The subjectivity of this is noted; it is merely intended as a guide to aid comparative evaluation of the methods.

Precision

For each population (1, 2, 3), the precision of each method was calculated as $p = S.E./\hat{N}$, where *S.E.* is $\sqrt{V}$, *V* being the variance of each estimate (Seber, 1982). A Kruskal-Wallis ANOVA tested the hypothesis that the mean ranks of the precision of the methods were the same (n = 3 for each method; n = 2 for Leslie estimates which did not establish an $\hat{N}$ for population 2).

Robustness

Robustness refers to tolerance to biased input data, and, to violations of assumptions (Rooseberry and Woolf, 1991). Robustness of the diver-survey methods was tested in a companion paper (Hart et al. 1996), while the crucial assumption for the fishing dependent methods which could be tested was that of constant catchability (*q*). The assumption of constant Leslie catchability coefficients for all depletion experiments was tested by ANCOVA. For CIR methods, constant *q* implies that both types of animal have the same probability of capture (Seber, 1982). If this holds true for both transect and timed collection data, then the proportions of pre- and post-recruits estimated by both techniques should be very similar before and after fishing. Finally, to test the assumption of equal catchability of marked and un-marked animals, Leslie catchability coefficients were obtained separately for tagged and untagged abalone for each population, and compared using the t statistic, Zar (1984). Examination of residuals demonstrated that the data from population 3 were slightly heteroscedastic, hence the CPUE were $\ln(x + 1)$ transformed. (Zar, 1984). It was assumed that each population was closed, removals were known exactly, and all tags were observed.

Data Requirements

The daily costs of running these experiments were essentially the same, requiring a 4-person research team and research vessel. Thus data requirements to obtain each population estimate are calculated in number of personnel days. A comparative evaluation of techniques was undertaken, with a formal rating (Excellent, Good, Fair, Poor) being applied. If a method was categorised inaccurate on at least one occasion, the highest accuracy rating it reached was F (fair). An accuracy rating of G (good) was given for any method which was categorised A at least once, but never less than B. For precision, a value < 0.05 was rated excellent, 0.05 - 0.10 good, 0.10 - 0.2 fair, and > 0.2 poor. Evaluation of robustness was more subjective. If an assumption was violated, but the estimate was still accurate and precise, then robustness was rated G. Any method that was inaccurate and imprecise was rated poor or fair for robustness. The overall rating is the “average” of the accuracy, precision, robustness ratings, plus a bonus if requiring one set of data, or a penalty if requiring 3 sets (summarised in Table 7).

Results

The total number of abalone harvested during the experiments was 35,729 (~8 tonnes); 13,625 from population 1, 12,573 from population 2 and 9,531 from population 3. A comparison of population size estimates from each method is shown for the entire plot, and individual locations (Fig 1). The population estimate

(+ 95% CL) of the CIR, mark-recapture, and transect methods encompassed our best guess of the 'true' value, although a notable exception was the CIR (timed collection) estimate in population 2 (Fig 1). No Leslie estimates of population size could be obtained in this population as the slope of the regression was not significantly different from 0 (n = 53; Pearson r = -0.04; p > 0.05). In 5 out of 12 instances, the 'true' population value did not lie within the 95% confidence limits of the timed collection estimates.

Accuracy

The most accurate methods were the 30m^2 transect and the CIR (transects) method, neither being classified a C, ie. inaccurate (Table 4). All other methods were inaccurate on at least one occasion. Leslie estimators were almost always inaccurate, while the timed collections varied between accurate and inaccurate, depending on the population and the assumptions. The CIR method using the timed collection data and the Petersen mark- recapture method were similar in accuracy (Table 4). The most reliable density conversion for the timed collections was to assume l00m^2 swept in 10 minutes (TC1), although TC3 performed similarly.

Precision

A significant difference in precision between methods was detected (Kruskal-Wallis H = 25.7, p = 0.01). The mark-recapture technique was the most precise, followed by the CIR using transect data and TC1 (Fig 2). The transect techniques also showed good precision (~0.15). Importantly, the CIR method was less precise if calculation of variance of the proportions (Eqs. 11 and 13) treats $\hat{p}_j$ is a ratio estimator. In particular, the mean precision of the CIR (timed collection) fell from 0.1 ($\hat{p}_j$ as a point estimator) to 0.27 ($\hat{p}_j$ as a ratio estimator) (Fig 2). The Leslie estimates were the least precise.

Constant catchability (q)

There was a significant difference in catchability between populations (df = 2, 151; F = 14.3; p < 0.001). In population 2, a 3rd order polynomial regression was more appropriate than a linear regression in describing the relationship between cumulative catch and CPUE (Fig 3). This is indicative of high variability in catchability within population 2. In all instances except one (CIR ratio estimate, before surveys in population 2), the timed collections detected a greater proportion of post-recruits, than the $30m^2$ transect (Table 5). In 6 out of 8 occasions, the proportional change (Δp) in post-recruits was greater according to the $30m^2$ transect (Table 5). In particular Δp in Population 2 as shown by the CIR (timed collection) was half that shown by the CIR (transects). This resulted in an over estimate of population in this area by the CIR (timed collection) analysis (Fig 1). Finally, tagging significantly affected catchability in population 3, but not in any of the other populations (Table 6).

Data requirements

The least costly estimates were the $45m^2$ transect and the timed collection, requiring only 7 and 8 personnel days respectively, prior to fishing. $30m^2$ transects required 13 days while the CIR (timed collection) needed 41 days. At the other extreme, the CIR (transects) method needed 51 personnel days, requiring both catch data and before/after surveys. The mark-recapture technique needed 46 personnel days.

A comparative evaluation of the methods is shown in Table 7, and is a summary of the overall performance of the methods during all depletion experiments. Most of the discussion will be focused on this table.

Discussion

This study represents the first detailed analysis of methods for evaluating abundance of abalone, one of the most valuable single-species fisheries in Australia. In doing so we have provided an important empirical test of various methods for evaluating animal abundance. Although the objectives were to make a critical evaluation and comparison of the methodology, it must be recognised that final ratings are dependent on the specific nature of this study. The extent that the results can be generalised to other animals will depend entirely on the similarity of the species and their ecological distributions. The novelty of this project was that the methods were compared for three populations subjected to the same experimental protocol and conditions. This enabled critical assumptions (eg. constant catchability) to be tested empirically.

The Leslie (E1) and effort-corrected Leslie (E2, E3) population estimators performed poorly (Table 7). This occurred principally because of significantly different catchability both between, and within, replicate populations, and the associated problem of hyperstability (see Population 2, Fig 3). Mohn and Elner (1987) demonstrated that the Leslie estimator will generally underestimate N when the stock is heterogeneously distributed, as is the case for abalone. This is corroborated by theoretical (Braaten, 1969), and empirical (Mahon, 1980), studies which found that the upper 95% confidence limits of both the DeLury and Leslie methods are not reliable indicators of maximum N. Typically this is because catchability (*q*) declines progressively as the depletion proceeds, the first animals caught having a higher *q* (Hilborn and Walters, 1992). This phenomenon almost certainly occurred in population 3, as the divers targeted dense aggregations initially, and then moved to the more sparsely distributed individuals. In population 2, *q* appears to have oscillated markedly during the depletion. Both the environmental conditions (eg wave intensity) and the spatial distributions of abalone were extremely heterogeneous in this population during the harvest, and the combined effects of these most likely affected catchability. To overcome violation of constant *q*, a number of authors have introduced variable *q* into their models. This has been attempted for abalone (Hirayama et al. 1989), a multispecies finfish fishery (Polovina, 1986), and a spiny lobster fishery (Yamakawa et al. 1994). For example, Yamakawa et al. (1994) specifically accounted for environmental factors such as wave intensity, seawater temperature, and moon phase in their calculations of *q*. In this study, the correction of effort to searching time which is assumed to be inversely proportional to density (Beinssen, 1979), did not improve the performance of the Leslie estimator. While addressing the same problem in Japan, Hirayama et al. (1989) introduced a non-linear multiplier term for *q*, based on the ratio of searching time to total fishing time. Applied over two years, they appeared to establish a precise estimate of abundance (3.5 ± 0.5 tonnes). However it was not made clear whether the errors represented 95% confidence limits, and the accuracy is unknown. Separation of total dive time into searching and handling time is theoretically justified. Yet attempts so far (Beinssen, 1979; Shepherd, 1985; this study), have not proved effective in establishing an index of abundance more reliable than that which currently exists using total dive time in the calculation of effort. Thus even under replicated, controlled, experimental conditions with precise measurements of catch and effort, catchability of abalone varies both within and between populations unpredictably. It is probable that this situation also applies in the Victorian commercial fishery, with a further disadvantage of far less precise measurements of effort.

The critical assumption of equal catchability of pre- and post-recruited abalone determined the effectiveness of CIR analysis, given that a substantial proportion of post- recruits was removed. This was highlighted by the fact that use of area based transects performed consistently better than a timed collection sample unit. For the former, the assumption of constant q is more likely to have held true as all abalone falling within the transect area will be counted. For the timed collection a mutual exclusivity arises. The natural tendency is to choose the more visible, aggregated and larger post-recruits at the expense of smaller, more cryptic pre-recruits present in the search area, thus violating the equal catchability assumption. Moreover, the extent to which this violation of constant q occurs, varies considerably. For example, the CIR (timed collection) method was deemed accurate in population 3, but inaccurate in population 2 (Table 4).

Precision of CIR estimators decreased considerably (Fig 2) when $\hat{p}_j$ was treated mathematically as a ratio estimate (Dawe et al. 1993), as opposed to a point estimate (Pollock et al. 1985). In this study, a large component of the between-sample variability in proportions of pre- and post-recruits occurs as a result of firstly, the specificity of the unit samples which individually, cover a relatively small area (30 - 100 m^2). This is important in terms of different habitat requirements of each animal type. Secondly, the aggregated distribution of abalone will also exacerbate variation in the measurement of p_{ij}. However, when summed over many unit samples, the mean proportion of pre- and post-recruits should be representative of the entire population. Thus $\hat{p}_j$ can be treated as a point estimate, and corresponding variances calculated, resulting in a precise estimate of population size. Although we believe our argument is relevant and pertinent for the transect unit sample, it may not be as convincing for the CIR (timed collections) because of the reasons discussed above. The CIR (timed collection) technique appears to have been useful when applied to isolated pulse fisheries in the north-west of Tasmania (Nash et al. 1994).

Mark-recapture (MR) techniques along with the area-based transect methods were given the highest rating for the study. In particular, the precision of the MR population estimates was extremely high, a consequence of high initial numbers tagged (5,527), and high recapture (2,510). The success of the tagging is attributed to the use of oil-based crayons which allowed fast and effective, *in situ* marking of abalone. On one occasion (population 3), tagging significantly affected catchability, yet the population estimate was rated as accurate. This indicates an underlying robustness in the estimator, not surprising considering the large number of animals tagged and recaptured.

Transect techniques provided similar estimates of population size to CIR (transects) analysis for every population. Intuitively this may be expected, mainly because the data (number of post r-recruits per $30m^2$; proportion of post-recruits per $30m^2$ were collected simultaneously. However the theory and assumptions of the two techniques are very different and their close similarity in estimating population size underlies the accuracy and precision of the transect sampling unit. No such agreement occurred between the timed collections and the CIR (collections) techniques, again despite the data being collected simultaneously. Principally this occurred because the effectiveness of the conversion from a timed search to a density estimate was limited.

Overall the performance of the timed collection technique was unreliable in estimating abundance. On one occasion (population 3), TC1 and TC3 resulted in an accurate population estimate (Table 4). Density conversions using r (19.9 m2 min^{-1}) and h (5.1 secs $abalone^{-1}$) of Beinssen (1979) tended to decrease the precision without any concomitant increase in accuracy. Fishing power and efficiency of abalone research divers was assessed by Shepherd (1985) who calculated r ranging from 15 - 27 m^2 min^{-1} and h from 2.9 - 6.2 secs $abalone^{-1}$, suggesting a non-constancy of the h and r ‘constants’. Also, h is the y-intercept of a linear (geometric mean) regression of inverse CPUE (time $abalone^{-1}$ - from commercial divers) on inverse density (area $abalone^{-1}$). Thus h is the time spent on harvesting each individual when inverse density is 0, or equivalently, density is infinite. In a practical sense this amounts to many abalone positioned next to each other such that they can be collected quite quickly. Viewed in this context the value of h estimated from the present study (2.1 secs) is quite realistic.

Despite the aggregated nature of abalone distributions, area based transect methods combined with a stratified random sampling design did give accurate and precise estimates of population size. CIR methods using transect data to estimate proportions can be equally efficient, however they require more intensive data collection. If a cost-effective and quick tagging method can be identified, then a mark-recapture study will also work well, although a test for equal catchability of tagged and untagged animals should be included in the design of the experiment. CIR analysis using timed collection data is less certain due to possible violation of equal catchability of two animal types, but will still give a workable result. It has been used successfully for abalone by Nash et al. (1994). Use of catch-effort or relative abundance data is not recommended for estimating population size in abalone if other alternatives are available. However Prince (1989) did establish reasonable agreement between MR and Leslie population estimates for population size. The critical component in that study was a very high density reduction (> 70%). Often it is desirable to obtain a population assessment without inflicting a heavy mortality.

Acknowledgments

Members of the Victorian Abalone Divers Association selected the site and harvested the populations. We wish to thank Peter Johnson for actively promoting this collaboration, and to Mick Shannessy for leading the way. Many thanks go the abalone field monitoring team of Michael Callan, Dave Forbes, Bruce Waters, and

Cameron Dixon for their tireless efforts during the intensive field component of this study. Dr Neil Andrew provided useful comments on an early draft. The project was funded from a grant by the Fisheries Research and Development Corporation (FRDC) to the Victorian Fisheries Research Institute.

References

Beinssen, K., 1979. Fishing power of divers in the abalone fishery of Victoria, Australia. *Rapp. P.-v. Réun. Cons. int. Explor. Mer*., 175: 20-22.

Braaten, D.O., 1969. Robustness of the DeLury population estimator. *J. Fish. Res. Board. Can*., 26: 339-355.

Breen, P.A., 1992. A review of models used for stock assessment in abalone fisheries. In: Shepherd, S.A., Tegner, M.J., and S.A. Guzmán del Próo. (Editors). Abalone of the World: biology, fisheries and culture, pp. 253-275. Blackwell: Oxford. 608 p.

Chapman, D.G., 1954. The estimation of biological populations. *Ann. Math. Stat*., **25**: 1-15.

Chapman, D.G., 1955. Population estimation based on change of composition caused by selective removal. Biometrika, 42: 279-290.

Cochran, W.G., 1977. Sampling techniques. 3rd. ed. John Wiley and Sons, New York, N.Y. 428pp.

Crittenden, RN., and Thomas, G.L., 1989. A conditional generalized least squares method for estimating size of a closed population. *Can. J. Fish. Aquat. Sci*., 46: 818-823.

Dawe, E.G., Hoenig, J.M.; and Xu, X., 1993. Change-in-Ratio and Index-Removal methods for population assessment and their application to snow crab (*Chionoecetes opilio*). *Can. J. Fish. Aquat. Sci*., **50**: 1467-1476.

DeLury, D.B., 1947. On the estimation of biological populations. *Biometrics*, **3**: 145-167.

Hart, A.M., Gorfne, H.K., and Callan, M.P., 1996. Abundance estimation in blacklip abalone (*Haliotis rubra*) I. An analysis of diver-survey methods used for large-scale monitoring. *Fish. Res*. (submitted)

Hilborn, R, and Walters, C.J., 1992. Quantitative Fisheries Stock assessment: Choice, Dynamics, and Uncertainty. Chapman and Hall, New York. 570 p.

Hirayama, N., Yamada, S., Kikuchi, H., and Yamada, J., 1989. A modification of DeLury method to abalone fishery. *Nippon Suisan Gakkashi*, **55**(3): 409-416.

Kojima, H., and Ishibashi, K., 1985. The estimation of population parameters on the stock of Japanese black abalone, *Haliotis discus discus* in Tokushima prefecture. *Bull. Tokai Reg. Fish. Res. Lab*., **118**: 11-20.

Krebs, C.J., 1989. Ecological Methodology. Harper and Row. New York, N.Y. 654 p.

Leslie, P.H., and Davis, D.H.S., 1939. An attempt to determine the absolute number of rats on a given area. *J. Anim. Ecol*., **8**: 94-113.

Mahon, R., 1980. Accuracy of catch-effort methods for estimating fish density and biomass in streams. *Env. Biol. Fish*., **5**: 343-360.

McShane, P.E., 1994. Estimating the abundance of abalone (*Haliotis* spp.) stocks - examples from Victoria and southern New Zealand. *Fish. Res*., **19**: 379-394.

McShane, P.E., 1995. Estimating the abundance of abalone populations: the importance of patch size. *Mar. Freshw. Res*., **46**(3): 657-662

Mohn, R.K., and Elner, R.W., 1987. A simulation of the Cape Breton snow crab, *Chionoecetes opilio*, fishery for testing the robustness of the Leslie method.

Nash, W.J., Sellers, T.L., Talbot, S.R., Cawthorn, A.J., and Ford, W.B., 1994. The population biology of abalone (Haliotis species) in Tasmania. I. Blacklip abalone (H. rubra) from the north coast and Furneaux group of islands. Sea Fisheries Division Technical Report, **48**: 69 pp.

Paulik, G.J., and Robson, D.S., 1969. Statistical calculations for change-in-ratio estimators of population parameters. *J. Wildl. Manage*., **33**: 1-27.

Pollock, K.H., Lancia, RA., Conner, M.C., and Wood, B.L., 1985. A new change-in-ratio procedure robust to unequal catchability of types of animal. *Biometrics*, **41**: 653-662.

Polovina, J.J., 1986. A variable catchability version of the Leslie model with application to an intensive fishing experiment on a multispecies stock. *Fish. Bull*., **84**: 423-428.

Prince, J. D., 1989. The fisheries biology of the Tasmanian stocks of Haliotis rubra. Unpublished PhD. Thesis, Dept. of Zoology, University of Tasmania., 220 p.

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

Rooseberry, J. L., Woolf, A., 1991. A comparative evaluation of techniques for analyzing white-tailed deer harvest data. *Wildl. Monogr.,* **117**: 1-59.

Seber, G.A.F., 1982. The estimation of animal abundance and related parameters. 2nd ed. Macmillan, New York, N.Y. 654 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, 1985. American Academy of Underwater Science, La Jolla. pp 263-272.

Sloan, N.A., and Breen, P.A., 1988. Northern abalone, Haliotis kamtchatkana, in British Colombia: Fisheries and synopsis of life history information. *Can. Spec. Publ. Fish. Aquat. Sci*., **103**: 46 pp.

Yamakawa, T., Matsumiya, Y., Nishimura, M., and Ohnishi, S., 1994. Expanded DeLury's method with variable catchability and its application to catch-effort data from spiny lobster gillnet fishery. *Jap. Fish. Sci*., **60**(1): 59-63.

Zar, J.H., 1984. Biostatistical Analysis. Prentice-Hall, Englewood Cliffs, NJ. 718pp.

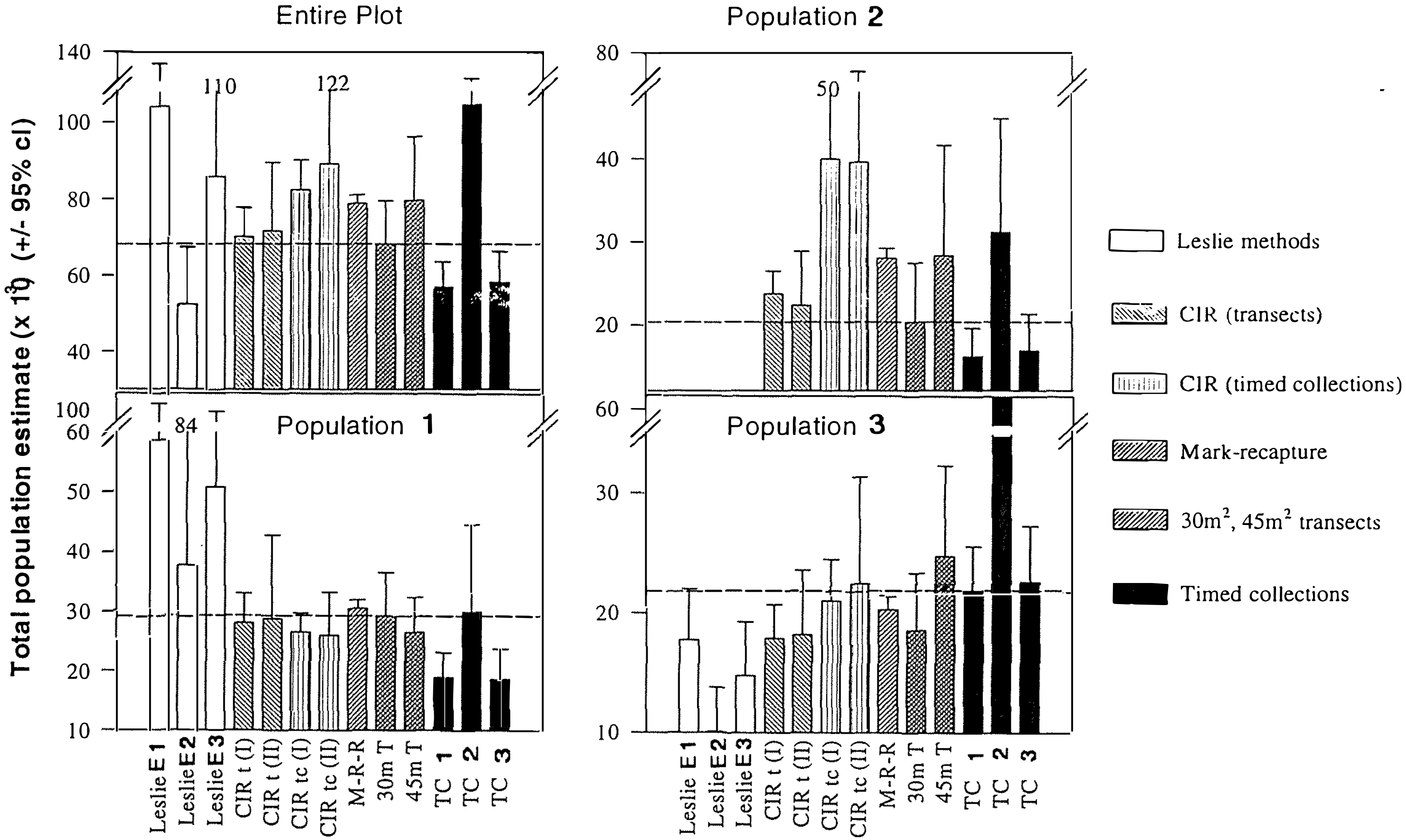


Fig. 1. Population estimates (± 95% C.L.) of post-recruited abalone (≥ 10cm) for the experimental populations. Leslie estimate: Values are given for three types of effort: E1) total diving time; E2) searching time using a (h) of 5.1 sec abalone^{-1} (from Beinssen,1979); E3) searching time using (h) of 2.1 sec abalone^{-1} (this study). Change-in-ratio: (I) treating $\hat{p}_j$ as a point estimator, (II) treating $\hat{p}_j$ as a ratio estimator. Separate CIR analyses are made from the 30m^2 transect and the timed collections. For the timed collections, TC1 is assuming 100m^2 swept in 10 minutes; TC2 assumes h = 5.1 sec. abalone^{-1} and r = 19.993 m^2 min^{-1}; TC3 assumes h = 2.1 and r = 13.376 m^2 min^{-1} (see Hart et al. 1996 for definition of h and r.). For reference purposes, our best 'estimate' of the true population sizes is highlighted by the dotted line.

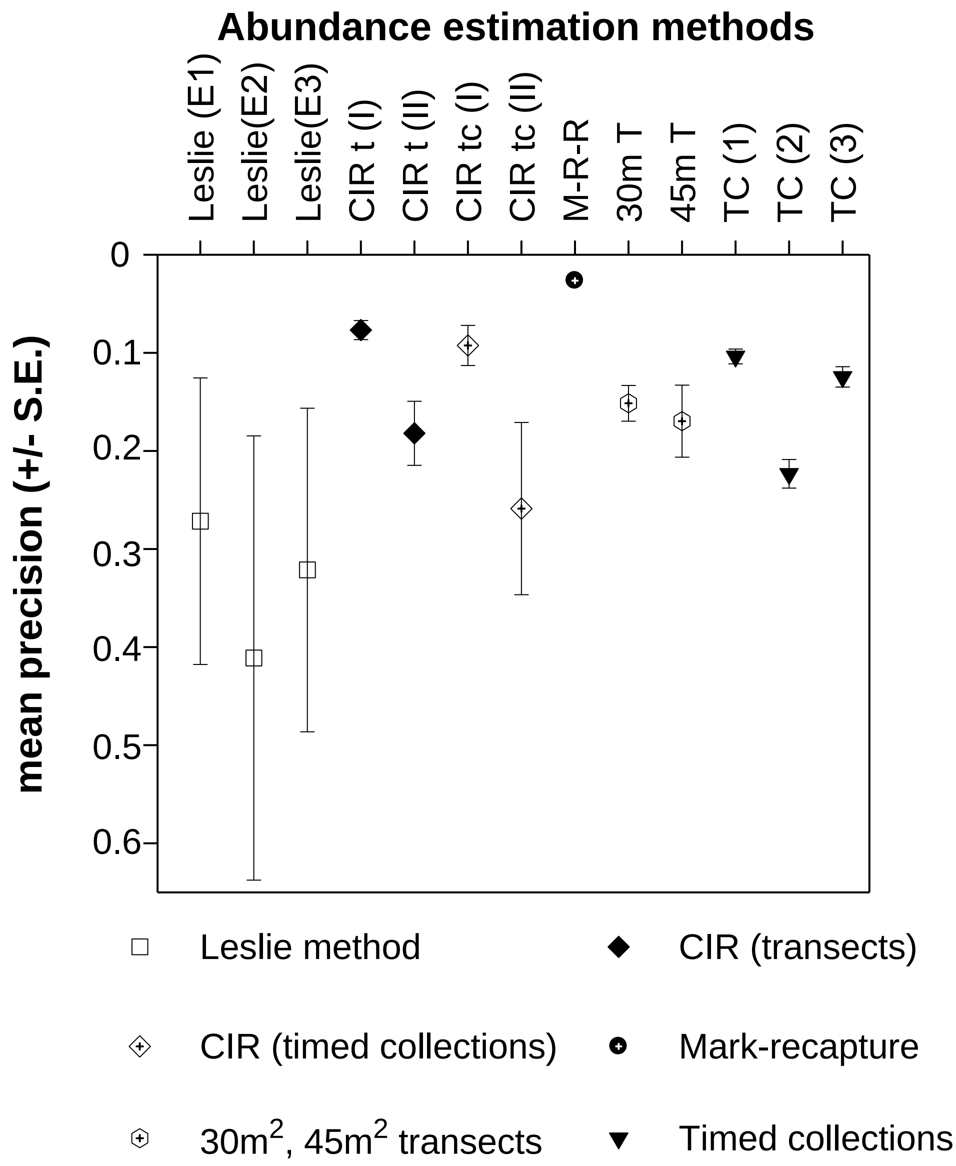


Fig. 2. Comparison of mean precision (± SE) of all methods. Descriptions of methods and their variations are same as Fig. 1.

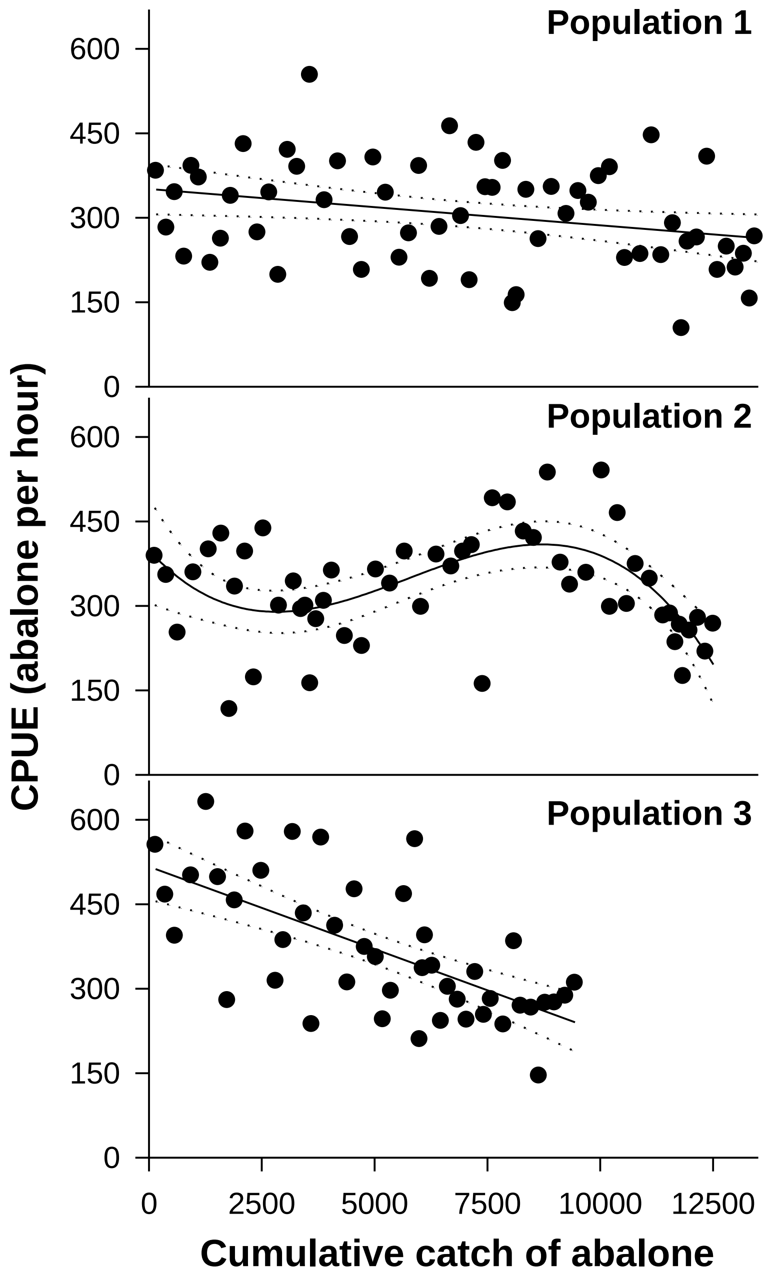


Fig. 3. Comparison of Leslie plots from three adjacent populations of *Haliotis rubra*. Similar proportions of the estimated total abundance of pre-recruits were removed in each population (see Table 1). Dotted lines represent 95% confidence limits.

Table 1
Mark-recapture history for experimental populations of *Haliotis rubra*

	Entire Plot	Population 1	Population 2	Population 3
# tagged	5527	1837	2264	1426
# recaptured	2510	822	1020	668
Proportion recaptured	0.45	0.45	0.45	0.47

Table 2

Calculation table to obtain estimates of total population and 95% confidence limits using data from the diver survey methods. To illustrate the technique, an estimate of population in the entire plot using the 30m^2 transect data is shown.

Definition of symbols:

Pop Population of *Haliotis rubra* in 5 hectares
Srat Each population was divided into several strata, the boundaries identified by latitudinal and longitudinal coordinates.
W_i proportion of the total area in the *ith* strata
N_i number of possible sampling units that can fit into the *ith* strata
n_i number of samples taken in the *ith* strata
$\bar{x}_i$ mean density of abalone in the *ith* strata
s_i^2 variance of mean density in the *ith* strata
X total population estimate
N total number of possible sampling units that can be fitted into the entire plot
$s^2(\bar{x}_{strat})$ variance of overall stratified mean density
$s\ (\bar{x}_{strat})$ standard deviation of overall stratified mean density

Pop	Strat	W_i	N_i	n_i	$\bar{x}_i$	s^2_i	$\frac{W_h^2\ s_i^2}{n_i}$	$\bar{x}_i\ N_i$
1	A	0.167	833	8	17.63	31.696	0.11006	14687.5
	B	0.167	833	8	17.38	127.982	0.44438	14479.2
2	A	0.083	417	11	8.45	27.272	0.01722	3522.73
	B	0.083	417	10	11.5	94.722	0.06578	4791.67
	C	0.083	417	10	9.2	103.511	0.07188	3833.32
	D	0.083	417	11	19.91	602.89	0.38061	8295.45
3	A	0.083	417	11	4.72	16.618	0.01049	1969.7
	B	0.083	417	10	6.7	55.567	0.03859	2791.67
	C	0.083	417	11	13.09	147.091	0.09286	5454.54
	D	0.083	417	10	20	137	0.09514	8333.33

Total population estimate $X = \sum \bar{x}_i\ N_i = 68159$

Variance of stratified mean $s^2(\bar{x}_{strat}) = \sum \frac{W_i^2\ s_i^2}{n_i} = 1.32701$

95% confidence limits for pop. $= X \pm t_{0.05}\ N\ s(\bar{x}_{strat}) = \pm 11289$

Table 3
Categories by which relative accuracy of each method is assessed. A is classified accurate, B is moderately accurate, C is inaccurate

Experiment	Categories of accuracy A	B	C	Explanatory notes
Entire Plot	61343 - 74975	47711 - 88607	any value outside the range of B	The 30m^2 transect estimated the number harvested for the entire plot to within 9% of the true value. Thus, 'true' populaiton size was defined as that estiamted by the 30m^2 transect, ie 68159. Categories A and B were defined as any value within (± 10%) and (± 30%) respectively, of 68159.
Population 1	nil	20417 - 37917	as above	Neither diver survey method accurately estimated (within 15%) number harvested from Population 1 (see Table 1 of Hart et al. 1995), hence no category A could be defined. Category B was defined as (± 30%) of the 'true' population size, as measured by the 30m^2 transect.
Population 2	nil	14311 - 26571	as above	As in Population 1
Population 3	19057 - 24025	28393 - 15289	as above	Estimates of number harvested from both diver survey methods were within 15% of the true value (Table 1, Hart et al. 1995), however the timed collection unit assumming 100m^2 area swept per 10 mins, TC(A), was closest. Thus Categories A and B were defined as (± 10%) and (± 30%) respectively, of the 'true' population size, as measured by TC(A).

Table 4

Comparison of accuracy of the abundance estimation methods for each population. Categories (A - accurate; B - moderately accurate; C - inaccurate) are fully defined in the methods section. EP - entire plot; P1 - Population 1; P2 - Population 2; P3 - Population 3. Descriptions of methods and their variations as in Figure 1.

		Population						Population			
Method		**EP**	**P1**	**P2**	**P3**	Method		**EP**	**P1**	**P2**	**P3**
Leslie	*E1*	C	C	C	B	30m^2 transect		A	B	B	B
estimator	*E2*	B	B	C	C	45m^2 transect		B	B	B	B
	E3	C	C	C	C	Timed	*TC1*	B	C	B	A
CIR (transects)		A	B	B	B	Collections	*TC2*	C	B	C	C
CIR (collections)		B	B	C	A		*TC3*	B	C	B	B
						Mark - recapture		B	B	C	A

Table 5

Comparison of proportions of post-recruits (abalone ≥ 10cm) from CIR point (*P*) and CIR ratio *(R)* estimators of $\hat{p}_j$ before and after fishing. Results are given for the 30m^2 transect and the 10 minute collection. $\Delta p = p_1 - p_2$ = change in proportion of post-recruits between before and after harvesting.

Population		30 m^2 transect			Timed collection		
		before	after	Δp	before	after	Δp
EP	*P*	0.54	0.36	0.18 ⇔	0.59	0.45	0.14 ⇔
	R	0.52	0.35	0.17 ⇔	0.57	0.43	0.14 ⇔
P1	*P*	0.55	0.39	0.16 ⇔	0.59	0.41	0.18 ⇔
	R	0.53	0.38	0.15 ⇔	0.59	0.41	0.18 ⇔
P2	*P*	0.45	0.28	0.17 ⇔	0.49	0.40	0.09 ⇔
	R	0.49	0.3	0.19 ⇔	0.46	0.37	0.09 ⇔
P3	*P*	0.62	0.43	0.19 ⇔	0.63	0.49	0.14 ⇔
	R	0.60	0.41	0.18 ⇔	0.65	0.52	0.13 ⇔

Table 6

Results of tests of the assumption of equal catchability (= slope of Leslie regression) between tagged and untagged abalone.

Experiment	Result	p
Entire plot	t = -0.31;	ns
Population 1	t = 0.06;	ns
Population 2	t = 0.02;	ns
Population 3	t = -6.23	***

Table 7
A comparative evaluation of various methods for estimating abalone abundance. A full description of ratings is given in the methods section

Method	Index			Rating			Data Requirements			Overall rating
	Absolute	Relative	Standardisation required	Accuracy	Precision	Robustness	Before surveys	Catch / effort	After surveys	
Leslie E1		✓		P	P	F		25		F-
E2		✓	✓	F	P	F		25		F
E3		✓	✓	P	P	F		25		F-
CIR I	✓			G	G	G	13	25	13	G-
(transects) II	✓			G	F	G	13	25	13	F+
CIR (timed I	✓			F	G	F	8	25	8	F
collections) II	✓			F	P	F	8	25	8	P+
Mark - Recapture	✓			F	E	G	11	25		G
30 m^2 transect	✓			G	F	G	13			G
45m^2 transect	✓			G	F	G	7			G
Timed TC1		✓		F	F	F	8			F+
Collections TC2		✓	✓	P	P	P	8			P+
TC3		✓	✓	F	F	F	8			F+

Rating Scale: E - Excellent, G - Good, F - Fair, P - Poor

A Field Technique for Estimating Abalone Abundance

M. P. Callan, A. M. Hart and D. Forbes

June 1995

VFRI Technical Report

Introduction

In determining the most appropriate technique to establish population parameters of a sedentary, demersal species such as abalone, it's pattern of distribution and the amount of information required must be considered and balanced against the physical and logistical limitations imposed by working underwater (Shepherd 1985). The free-range search technique (Kenchington 1978) where the diver searches freely over the bottom, is the most efficient in locating the maximum number of individuals in a given time, because divers use their knowledge of the species' habitat to direct their searching and so maximise the use of time underwater. The limitation of this method is that it allows only relative estimates of the density to be derived from such data unless the power and the efficiency of the diver are known. Until 1992 this method (10 minute collections) was used by the abalone stock monitoring program at the Victorian Fisheries Research Institute (VFRI). Since then a sampling strategy which incorporated 30m^2 transects radiating from a fixed point (hence the term radial transects) has been adopted as the preferred method. It enables an absolute estimate of density and Gorfine and Forbes (in press) have found it to be highly efficient for large scale surveys. Furthermore transects have been effectively utilised to assess abalone abundance in NSW (Andrew and Underwood 1992).

This report describes the radial transect method used by the VFRI's abalone stock monitoring program and discusses the techniques by which different reef habitats are surveyed under varying environmental conditions.

Method

Site selection

Initial selection of areas where sites may be located is based on catch data, accessibility under a range of weather conditions and an underwater site inspection. Reef codes on dockets returned by abalone divers, in compliance with the Abalone Quota Management System (AQMS), enables the identification of reefs from which daily catches were taken. These reefs are visited by a VFRI survey team, aboard a research vessel equipped with a colour monitor sounder which is used to obtain a visual impression of the substrate. The resolution of the picture produced by the sounder is such that potential abalone habitat may be discerned. A dive is then carried out to confirm that the area is inhabited by a population of abalone. The aspect and exposure of the site to prevailing weather and swell conditions are noted. Having satisfied the three afore-mentioned criteria, a latitude and longitude from a global positioning system (GPS) are recorded. This allows the survey team to return the same site during subsequent years' surveys.

At present, eighty-five sites are visited annually (Figure 1). Thirty in the Eastern Zone, largely in the vicinity of Mallacoota; 18 in the Western Zone, with 6 at Port Fairy and 12 at Portland; and 37 in the Central Zone:

Apollo Bay	7
Port Phillip Bay	5
Nepean to Cape Schanck	4
Bushrangers Bay to West Head	8
Phillip Island	4
Wilson's Promontory	9

Construction of transect lines

As a site is approached, the equipment system from which the transect lines are swum is assembled (Figure 2). The system consists of a 25 mm diameter, nylon shot-line clipped to 20 kg lead weight and held vertically by a polyform buoy. A stainless steel ring has been spliced into the shot-line about 1 m above the weight. Two 35 m swim-lines of 25 mm diameter silver rope are attached to the ring using swivel clips. The swim-lines are marked at 5, 15 and 20 m intervals from the lead weight. Nylon rope is used for all the lines because of its ability to float which reduces the likelihood of snags and tangles. Once assembled all lines are trailed from the stern of the vessel. Tangles are eliminated and the lines kept separated by securing one of the swim-lines to one side of the stern and the second swim-line and shot-line to the other. When the vessel is on-site the lines are untied and the weight dropped over the side. The vessel is then anchored so that the stern lies close to the shot-line buoy.

Diver deployment

Two divers gear up and are connected to SSBA. All equipment complies with the occupational diving standard AS2299. Each diver carries three numbered, open-mouthed, catch-bags and a small lift bag clipped to a stainless steel ring; an abalone blade or iron, used for prising the abalone off the substrate and a combination gauge which houses a compass and small slate on which 3 random bearings are written. The first diver descends the shot-line to the weight. Here the catch bags are either clipped to the ring on the shot-line or tied to the swim-line. The catch-bag numbered 1 is detached and the underwater compass set to the assigned bearing. If visibility allows some feature on the bottom is selected as a visual reference for the heading. The swim-line is then tucked under the diver's armpit, and from the 5m mark all abalone larger than 50 mm, within a strip 1 m wide are collected. Estimation of 1 m should be made from the armpit under which the swim-line runs to a point somewhere on the divers prising arm. When an aggregation of abalone is encountered the diver removes a 1m wide swathe in the assigned direction. The compass is checked periodically over the 30 m transect length.

At the end of the first collection the diver secures the catch-bag mouth with a shock-cord draw string and uses the swim-line to return to the lead weight. The first catch-bag is clipped back on to the ring, the second catch-bag removed, and the compass reset to begin the next transect. At about this time, the second diver enters the water and starts his transect collections. On completing three transects, the first diver unclips or unties his catch-bags from the weighted end of the swim-line and reties them to the free end. The lift bag is inflated and the bags carried to the surface. The diver may drag some point of the swim-line back to the vessel or the swim line may be snared with a small grapnel from the vessel and the abalone sample hauled aboard the vessel. The third diver then enters the water and completes three transect collections. The total bottom time for each dive is usually between 30 and 60 minutes, depending on abalone abundance.

On board the vessel, length measurements of the abalone from each of the divers 3 transects are recorded to the nearest mm using a vernier caliper. The abalone are transferred to another catch-bag after being measured and taken back to the bottom to be replaced or lowered to the bottom to be replaced by a diver already in the water.

The vessels anchor is weighed and the shot-line buoy is retrieved with a boat hook. All lines are coiled on the deck and the vessel heads to the next site.

Discussion

Effect of environmental variables

Ideally for diver efficiency and therefore accuracy of the transects, conditions of little or no swell/surge, no current, good visibility and open bottom are desirable. However, such days are rarely encountered and the diver must often contend with one or more of these variables.

<u>Swell/surge</u>

Swell produces a surge on the bottom which pulls a diver towards it as it approaches, and pushes the diver in the direction it moves as it passes. The diver experiences a backwards and forwards or side to side displacement depending on his orientation to the swell. The regularity of displacement depends on the swell frequency, while its intensity depends on the size of the swell. For example, if the swell is approaching in sets, the diver will only be moved across the bottom during the sets, while the rate at which he moves and the distance moved will be determined by the size of the swell in the sets.

Swell/surge not only affects a divers ability to maintain a transect bearing but can also interfere with prising abalone off the substrate (“chipping”) and transfer to the catch-bag. Obviously it is best to survey sites in the absence of swells but reliable results can be obtained in small swells and when moderate swells (1-1.5m) are in sets.

The depth of water at a site will determine the size of swells that can be worked because the effects of swell stand to be lessen with increasing depth.

Light surge should not appreciably affect the efficiency of a diver and can in fact aid swimming if a transect has the same or reciprocal bearing as the swell. In any swell/surge it is wise to take visual references using bottom features while working along a transect. This facilitates re-orientation on a transect position and bearing if a diver is displaced. When a diver feels moderate surge approaching it is best to cease activity and secure the current position. After the swell has passed the diver can resume activity. In this way, position on the transect is maintained and the ability to cleanly chip and bag abalone is not compromised. The number of abalone chipped before being bagged should be reduced in swelly conditions to minimise losses.

It is possible to work bigger swells and heavier surge (particularly when it occurs in sets) using the techniques described above, however it is not recommended. Judgements of swell conditions should be made to ensure the reliability of the data collected and safety of the divers. Particular attention should be paid to middle ear equalisation, when sampling in shallow areas affected by moderate to large swells, to avoid middle and inner ear barotrauma.

<u>Currents</u>

The current that may be experienced at a survey site is typically generated by tide. Therefore its intensity and resultant effects on a diver swimming along transects will be determined by the stage of the tide. Surveying during slack water, the period of no tidal movement between the end of the flood and start of the ebb flow or vice versa, avoids the influence of tidal currents but is not always possible. When it is necessary to dive in tidal current an assessment of its strength should be assessed against the diver's ability to swim reliable transects. However, seldom would current prohibit the successful sampling of a site.

The effects of current depend on transects orientation. A transect bearing across current will tend to be skewed in the direction of the current. This can be minimised by staying close to and maintaining a firm grip on the bottom. Swimming a transect into the current increases the workload on a diver but combined with the chance of better visibility may improve the search. Conversely transects with the current aid the swim but a firm grip should be kept on the swim-line to ensure a proper search of the transect.

On completion of the transects, a diver should head towards the vessel's anchor, with the catch-bags if possible, and ascend via the anchor line. This facilitates getting both diver and catch-bags out of the water efficiently.

Visibility

The visibility at a site is influenced by its proximity to inputs such as rivers and creeks, and prevailing environmental conditions. Sites located close to inputs are more likely to have reduced visibility more often, while wind, waves and swells, can stir-up the bottom to suspend sediments and other particulates. It is difficult to accurately assess marginal visibility until in the water. Anything less than 1m horizontal visibility should be avoided.

Reduced visibility hinders the detection of abalone, particularly the smaller cryptic individuals and can lead to disorientation. Under these conditions, transect swim time should be increased to ensure adequate search time, and the compass heading should be checked more frequently as visual, topographic, reference points are difficult to discern. Close attention should be paid to position of the swim-line, especially when finishing a transect, because losing the line makes finding the weight difficult.

Bottom type

Although abalone habitat, actual reef topography varies from site to site and includes low-lying platform reef, bommies, boulders, cobbles and rubble. The bottom reef form or topography affects transect collections in two ways. Firstly, it affects swim-time because it is easier to perform transect collections over relatively flat, open ground than rugged relief reef forms such as bommies, gutters and drop-offs where the diver must swim up and down. Secondly the topography should also determine search time. For example boulder reef provides far more habitat for abalone than flat, open reef.

In general, search and swim time should be adjusted depending on the bottom type so that sufficient time is spent in locating abalone on the transect.

Seaweed

Many sites are located on reefs covered in seaweeds that are attached to the rocky bottom by a holdfast and grow into a branched, ribbon or streamer type thallus which may be up to 3m long (such as the kelps *Phyllospora comosa*, *Macrocystis angustifolia* and *Ecklonia radiata*). Stands of kelps increase the time taken to sample a transect because they impede swimming by creating a physical barrier that the diver must swim through, and cause delays in sampling whilst attending to the inevitable snags. Additionally, kelps can obstruct the diver’s vision and consequently increase the search time.

The manner and extent to which a diver is impeded varies with the density of the seaweed but the way to overcome these problems is essentially the same. By staying close to the bottom a diver only has to contend with single stalks (stipes) growing from the holdfast rather then the entire branched thallus. This removes much of the barrier as well as reducing the chance of snags and visual obstruction. A diver can use the stipes to provide secure handholds for contending with surge and a dragging himself along the transect.

Effect of diver

Effect of diver

During an experiment to assess several methods of estimating abalone stock abundance, radial transects were timed. The divers who carried out these transects had varying degrees of experience in surveying abalone reefs. This can be illustrated by comparing the range of times that each diver spent sampling transects and the time period during which the highest counts were made. For example, most of Diver 1's (the most experienced diver) transects were completed in 3 to 9 minutes whereas Diver 4 (the least experienced diver) spent as long as 27 minutes on some transects. Similarly Diver 1 had counted 30 or more abalone in 3 to 9 minutes on several occasions whereas diver 4 had not counted more than 30 abalone until at least 13 minutes and more often 18 minutes had elapsed.

The results confirmed that Diver 1 was more experienced in transect-based sampling of abalone than was Diver 4. It is reasonable to assume that, because of this additional experience, Diver 1 was more familiar with the abalone habitat and therefore better able to cope with environmental variables previously described. Consequently, Diver 1 spent less time sampling transects than did divers with less experience..

Least squares regressions were performed on the experimental data and comparison of the slopes of the equations showed that they were not significantly different among divers. Although individual divers differ in the manner in which they perform transect collections, these differences of approach have a much more limited effect on the number of abalone sampled than they do on samples collected during the free-range searches.