Assessing Survey Methods for Greenlip Abalone in South Australia

R. McGarvey

FRDC Project No. 2001/076

SARDI Aquatic Sciences Publication No. RD01/0147-2

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Non Technical Summary

2001/076 Assessing Survey Methods for Greenlip Abalone in South Australia

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NON TECHNICAL SUMMARY:

The aim of this project was to develop and field test a method of research diver survey for estimating absolute greenlip abalone density. Previous Australasian survey designs have sought only relative measures of abalone abundance. However, the ability to directly measure the total harvestable biomass, combining survey absolute numbers with length frequencies and length-weight in any given area, would add very substantially to the power of advice provided to managers setting a yearly (absolute biomass) quota.

A method was sought to achieve six survey-design objectives: (1) Measure absolute abalone density in each survey stratum; (2) be unbiased; (3) quantify confidence intervals; (4) quantify degree of aggregation (clustering); (5) provide a spatially representative sample; (6) permit stratification. Supplementary objectives were (7) that managers can choose areas where abalone density is to be measured; (8) that the survey design can be improved over time; (9) that it provide length-frequency samples; and (10) that the spatial distribution and mean size of abalone can be mapped.

Three candidate survey methods were evaluated. The point-nearest-neighbour distance method was rejected because it was biased in clustered populations, underestimating abalone density in field trials by 10-40%, and because searches over unknown area proved overly time consuming to implement underwater. The two remaining survey methods were tested in collaboration with commercial fishers in 'fish-down' experiments: (1) 20-minute timed-swims currently used in South Australia, and (2) a leaded-line transect method developed under this project.

The basic component of the leaded-line survey design is a transect 100 m long by 1 m wide. This is the sample area over which bottom is searched by each diver for abalone. The transects are pre-designated by deploying a visible stiff leaded rope line onto the bottom from the boat. Divers in pairs swim on either side of the leaded line, counting all abalone within 1 m of the line. Length frequencies are also obtained by one or both divers measuring all abalone that are also counted in the transect. In all leaded-line surveys, a boundary is drawn (in GIS) designating the survey region inside which density is to be estimated.

Survey regions can be partitioned into strata. Stratifying survey regions into subregions of high and low abalone abundance will generally improve survey precision. Stratum boundaries can be drawn based on boat-based sounder and video habitat mapping, or by using the density maps interpolated from previous leaded-line surveys, or by using spatially resolved commercial data, CPUE or GPS-recorded diver tracks.

Confidence intervals on mean absolute abundance were obtained using a two-level bootstrap to model the two levels of the sampling hierarchy, leaded-line locations in each study region, and the two transects (sides of the line) searched at each leaded-line location.

Leaded-lines are placed semi-systematically (uniformly) inside each survey region or stratum. GIS is an essential tool. Maps of survey region boundaries and leaded line

positions, along with coastlines, depth contours, and available habitat mapping, are provided to research diver teams before each survey, including the transect GPS start and end points.

GIS tools were also used to map leaded-line survey outputs. Maps of abalone density and mean length clearly showed areas of high and low density. Mapping of abalone distribution achieves three goals: (1) improved survey precision in future years by improved stratification; (2) detecting spatial contraction (or expansion) in the population, and (3) supporting environmental and ecosystem management of abalone fishery habitat. Leaded-line surveys measure spatial variation over three spatial scales: (i) abalone clustering is quantified by 2-m quadrat counts along leaded lines; (ii) variation in abundance and mean size is quantified across each survey region from the averages at leaded-line locations; and (iii) differences in density and other population measures among reefs along the coastline are quantified by comparing survey estimates from whole survey regions.

Four fish-down experiments were run to test the performance of timed swims and leaded lines. Fishers removed a measured number of greenlip abalone from each survey region. Surveys by both tested designs estimated total (legal) population number before and after abalone harvest. The survey method was successful when it predicted the actual number removed within the survey-estimated confidence interval. Timed swims yielded poor agreement with numbers removed for two experiments. Leaded lines yielded good agreement with numbers removed for three of four fish-down experiments, and performed much better than timed swims in the fourth.

When taken as an input to abalone stock assessment models, absolute numbers estimated from survey will anchor the model parameter estimates, providing the quantity most difficult to infer, namely absolute population size.

Clustering is important for abalone sustainability because fertilisation occurs in the water column. Tighter clusters of males and females produce more fertilised gametes. The quantification and direct measurement of clustering, using 2-m quadrats along each leaded-line, give managers a means to measure the extent to which fishers targeting abalone aggregations might compromise reproduction by reducing fertilisation rate.

Thus, the leaded-line design achieves all 6 objectives, and 4 sub-objectives, above.

OUTCOMES ACHIEVED

1. A survey design was developed and tested which measures absolute greenlip abalone density inside bounded survey regions, with confidence intervals.
2. Combined with length frequencies and length-weight, these surveys give managers estimates of harvestable biomass in any designated area.
3. The survey design can be improved over time, by stratification or the adoption of new measurement technologies.
4. Maps of abalone density and size were produced. These quantify spatial contraction or expansion of abalone populations, serve as the basis for fine-scale spatial management, and supplement environmental monitoring in exploited abalone habitat.

KEYWORDS: abalone; diver survey design, transect, point-distance methods, absolute density; clustering; habitat mapping; abalone density mapping; mean size mapping

Acknowledgments

The South Australian abalone industry provided in-kind support for this work and commercial abalone divers collaborated in the fish-down experiments used to test survey methods. Karen Byth provided critical statistical advice and data analysis of the point-nearest neighbour methods, and identified the underestimation bias therein. Cameron Dixon, Rob Day and Sylvain Huchette provided data and extensive discussion for the analysis of the point

nearest neighbour approach, which they carried out in field studies with a collaborative project investigating density dependence in abalone growth and mortality, now published (McGarvey et al. 2005; J. Shellfish Res 24: 393-399). The leaded-line diver survey protocol was developed through frequent discussions among members of the South Australian abalone research team, led by Steve Mayfield. Advice and input incorporated into the sample protocol came from Karen Byth, Thor Saunders, Steve Mayfield, Brian Foureur, Peter Preece, Alan Jones, Kate Rodda, and Scoresby Shepherd. The habitat mapping methods borrowed heavily from the Tasmanian (TAFI) program led by Alan Jordon who provided Visual Basic software (Seabed Mapper). Miles Lawler visited for three days and showed us the Tasmanian habitat mapping approach, including the use of Seabed Mapper boat-based software (which John Feenstra modified for use in South Australia). Bob Delaine measured abalone lengths harvested during the Waterloo Bay fish-down. The field component of habitat mapping was carried out by Michael Brickhill, Brian Davies, Dave Fleer, Dave Miller and Michael Clark. Abalone processors weighed all abalone and kept them in bags, permitting bag-specific harvest information from Waterloo Bay. Manuscript comments were provided by Scoresby Shepherd, Jason Tanner (Chapter 1), Cameron Dixon (Chapters 3 and 7), and Steve Mayfield. All ArcView maps were generated by Michael Brickhill and John Feenstra using ArcView 8.0. Data analysis and most figures were done by the PI in S-Plus v. 6.

Background

Abalone, worldwide, exhibit a higher risk of stock collapse than other exploited marine organisms. In addition, catch rates provide relatively little information about abundance. Thus abalone is a resource for which the sustainability risks are high but where catches are the least informative for stock assessment. Fishery-independent surveys therefore provide an important and, frequently, the principal means of monitoring resource status globally. Diver surveys are used regularly in Australia and New Zealand, where abalone stocks have been exploited for the most part sustainably, with relatively few collapses by comparison to North American, South American and South African stocks. However, more recently abalone quotas have been lowered in several Australian states. This project aims to identify and rigorously field test a range of possible survey methods for assessing greenlip abalone in South Australia.

A major FRDC initiative (Gorfine Project No. 1999/116) to develop a national model for abalone stock assessment is now completed. Length-frequency and survey measures of abundance are principal model inputs. Survey outputs will provide an important input to this or any stock assessment model developed for use in South Australian greenlip abalone.

Survey methods currently employed in Australasia include (1) timed swim (New Zealand and South Australia), fixed line transects (Tasmania, New South Wales), and fixed radial transects (Victoria). A major problem with these approaches is that being relative measures of abundance, it is sometimes difficult to control for variations in daily visibility, diver search ability, current speed and swell, and other unknown factors, with these problems greatest for the timed swim. A considerable body of work has been published about abalone survey design, but as concluded in review by Macarthur Agribusiness (1999, FRDC Project No. 98/170, p. 86), improving the precision of fishery-independent surveys remains a high priority. In South Australia, an external research review by Andrew (1996) indicated that current survey methods were not sufficient for quantifying trends in the population.

The spatial distribution of abalone on the bottom (how aggregated, and how cryptic) is a principal determinant in selecting from a range of candidate survey designs. Three previous FRDC abalone stock (Nash 88/94), survey (Gorfine et al. 93/100) and movement (Gorfine et al. 95/165) assessment projects investigated blacklip abalone (*Haliotis rubra*). The spatial distributions of greenlip (*Haliotis laevigata*) differ from blacklip. This project will address survey design for greenlip abalone, which the South Australian industry has identified as a high research priority.

Early abalone surveys employed the timed swim, where divers count all the abalone they encounter while swimming along the bottom for either 10 or 15 minutes. Nash (1995 for FRDC 88/94), Gorfine et al. (1997; 1995 for FRDC 93/100), Hart et al. (1997) and Hart and Gorfine (1997) found unacceptable levels of variation in counts from the timed swim (using depletion methods similar to those proposed here) and showed transects to yield lower variance. Line or radial transects were adopted in most Australian states though timed swim was continued, with preliminary investigations of newer survey designs, in South Australia.

One of the critical features of abalone distribution, that they tend to aggregate, especially during periods of spawning, has posed additional obstacles to accurate and precise measurement (Gorfine et al. 1998 for FRDC 95/165). Aggregation is necessary for fertilisation during spawning and is thus a critical aspect of population sustainability. One potential cause for the higher risk of stock collapse in abalone, analysed by Dowling et al (2004a; 2004b; Dowling 2002), is that fishers target aggregations to optimise catch rate. However, in doing so, they target that component of the population needed for successful reproduction. Thus fishing has a relatively greater impact on the reproductive rate of an abalone subpopulation than it does for mobile species such as fish that can re-aggregate almost immediately. It would therefore be advantageous for stock assessment to develop a survey method that quantified not only abalone biomass but also the degree of aggregation ('clustering') of abalone on the bottom. This would provide an additional indicator for monitoring abalone population fertilisation success, therefore recruitment potential, and hence sustainability. Moreover, quantifying clustering ensures more accurate survey estimates of abundance.

Because of high spatial clustering in abalone distribution, due to both aggregation behaviour and large spatial differences in benthic habitat, survey transects in NSW and Victoria are fixed in location. Divers monitor the same transects yearly. In Victoria, radial transects emanate from fixed points. These fixed survey transect locations are kept confidential from commercial and recreational operators. A substantial improvement over timed swim, diver counts along fixed transects are the currently accepted abalone survey design in Australia, having been adopted and implemented in Victoria and New South Wales, and having been further developed and trialed recently (FRDC 2001/074) in Tasmania. In New Zealand modifications of the timed swim have been continued, primarily to maintain time series continuity with previous survey methods.

However, six disadvantages of the fixed-transect method have more recently become apparent:

1. The area searched by divers for abalone is not precisely measured or controlled.
2. Because abundance is measured only at fixed locations, the mean density in any given (even overall surrounding) area remains undetermined. In other words, because an area is

not defined by a fixed location, no specific area that fixed transects are presumed to representatively sample is defined.
3. Insofar as the counts would vary if different fixed locations were chosen, the abundance measures obtained from fixed transects are relative rather than absolute.
4. With sampling locations fixed, managers and fishery management committees cannot specify, in each year, which sub-areas of exploitation they may choose to monitor.
5. Because the counts from fixed transects are a relative measure, the survey design cannot be modified from year to year. To keep the counts from previous years directly comparable, i.e. to keep the time series unbroken, the survey diver protocol for a relative measure of abundance cannot change.
6. The clustering of abalone cannot generally be quantified with current sampling protocols, and a measure of clustering is not currently provided by abalone survey in Australasia.

To date, a measure of temporal change in relative abundance was the principal survey indicator sought, since absolute density could not easily be measured. However, with the advent of new technology, notably (1) differential and now non-distorted GPS signals, (2) new methods to map benthic habitats more precisely, and (3) GIS software to store and process spatial information, absolute survey measures of density may potentially be achieved inside specific abalone harvest areas that managers would designate. Absolute density (as abalone per m^2) is a measure that is independent of the survey method used. If, in future, improved methods to measure or calculate absolute density are developed, the survey time series remains unbroken.

Model estimates are subject to high uncertainty for abalone, because they rely on fitting to length samples. Growth can be highly variable in abalone over quite short spatial scales, making length frequencies difficult to interpret, in particular, for quantifying fishing mortality, from which total biomass is inferred. If a direct absolute measure of abalone density were obtained from survey and used as model input, even in a subset of important management areas, the accuracy of abalone models and associated estimates of biomass would improve substantially. Moreover, rigorously quantified sample variances on absolute density estimates from diver surveys make possible well-formulated model likelihoods, improving measures of stock biomass uncertainty on the basis of which TAC management decisions are ideally set.

The goals of a survey for South Australian greenlip are thus six-fold:
1. Measure absolute density in each survey stratum.
2. Minimise bias.
3. Quantify sample variation.
4. Quantify degree of aggregation (clustering).

Satisfy requirements of rigorous survey design:

5. randomisation
6. stratification.

Optional, but desirable objectives for the survey design developed are:

7. Allow managers to designate specific locations for assessment.
8. Permit flexibility to change the survey protocol over time to improve precision and incorporate newly developing technologies.
9. Measure abalone lengths.
10. Measure spatial information on abalone density.

The choice of survey design to be adopted need not be constrained to be consistent with that used in previous years. We will, however, test the previous South Australian survey method of timed swims to assess the extent of agreement, and if possible, derive a conversion relationship between historical (timed-swim) survey time series and the measure of absolute density developed in this project.

The statistical literature of spatial statistics, primarily developed for application to benthic ecology and forest management, offers three methods to choose from: quadrats, transects, and point-distance methods.

Point-distance methods have not previously been field tested for either species of abalone. In this project we propose to field test point nearest neighbour along with abalone survey methods currently employed including line or radial transects, and the timed swim used to date in South Australia.

Important in future abalone surveys will be habitat maps. These permit stratification, and thus improve the survey efficiency and estimate precision of any survey method. We had intended to use aerial photography, employed by Andrew and O'Neill (2000) for mapping abalone survey habitat in NSW. However, greenlip occur at generally greater depths than blacklip. A new subproject was therefore implemented to undertake habitat mapping at 3 of the 4 fish down experimental study sites, at Taylor Island and Tiparra Reef. Mapping has already been undertaken at Waterloo Bay (Shepherd and Partington 1995; Shepherd and Womersley 1981).

Stock assessment models for abalone are size-based, requiring length-frequency samples and growth as fundamental inputs. Length sampling is therefore a necessary measured output of abalone survey.

Addendum 1: Links to Tasmanian FRDC abalone Project 2001/074

In July 2001, a new project was begun to address Tasmanian abalone (TasFRAB) research objectives. It is important that our current proposed project not duplicate, and where possible, collaborate, to extend these research outcomes to other states, notably South Australia. Three of the four objectives of the Tasmanian Project 2001/074 are to improve the interpretation of catch and effort data or links of data with modelling.

The only area of common interest in the two proposals concerns the fourth Tasmanian objective, of assessing methods for fishery-independent surveys. The Tasmanian Project 2001/074 will assess a wide range of survey design approaches, seeking specifically relative measures of abundance. It will primarily involve blacklip abalone. This South Australian project is devoted to greenlip.

The principal difference between this project and the Tasmanian one is that we seek a survey design yielding a measure of abalone abundance that is absolute. For the National Abalone Model (FRDC Project 1999/116), no data input could be more informative than a measure of absolute total numbers, as this is the estimated *output* of most current stock assessment models. By 'knowing the answer' of true population size, it remains for model inference only to make population length-structures self-consistent with the survey measures of absolute abundance. Measures of absolute abundance would dominate model inferences by, in effect, anchoring the model outputs to the true levels of stock density. Even if these inputs are available only from a subset of the populations/areas under management focus, the accuracy of model outputs will be substantially increased.

Even in the absence of a model, a survey estimate of absolute density (in numbers) combined with length-frequency samples, allows a direct estimate of harvestable-size biomass in surveyed strata. This is not possible with relative measures of abundance. Thus, quotas could be sensibly set without need for a model, chosen as some percentage of the total harvestable biomass.

Moreover, while relative measures of abundance are only informative in a long time series, a single survey estimate of biomass provides direct information for quota setting (the biomass available to harvest) in any area chosen. The areas of management focus can be shifted and surveys placed in any desired region, in any given year. Spatial management of abalone will require this higher resolution (both temporal and spatial) of abalone biomass information.

Measuring the extent of spatial clustering of abalone may allow managers to quantify the risk that densities are too low to yield satisfactory levels of gamete fertilisation in the water column. Thus, measuring clustering can potentially contribute a new and independent indicator for sustainability. Given the hypothesis that abalone is subject to collapse because fishers target aggregations, and that it is precisely these aggregations that provide most fertilised gametes, measuring the extent of clustering before and after fishing and before and after spawning will allow researchers to monitor this sustainability indicator.

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Need

In 1998, industry peak bodies, PIRSA, FRDC and the SA FRAB specified five-year research priority needs for wild-stock abalone fisheries in, “South Australian Fisheries and Aquaculture Five Year Research and Development Strategy”. Priority item 3 (after illegal harvesting and resources sharing) was “Stock assessment method: Accurate assessment is vital to the management and maintenance of a viable industry. Appropriate, cost-effective techniques are required to supply the data needed to effectively manage the fishery”.

The "Review of the South Australian Abalone Research and Management Plan" by N. Andrew (1996) under Review and Recommendation for surveys stated, "Fishery independent surveys of output managed fisheries, such as the South Australian abalone fishery, provide key information on the abundance and size-structure of populations being exploited. The present surveys do not represent a sufficient basis for quantifying trends in the fishery."

The "Wild Abalone Fisheries Research and Development Needs Review" (FRDC Project No. 98/170) by Macarthur Agribusiness (1999, p. 86) wrote that "The Review Team is of the view that fishery independent surveys are essential to effective resource monitoring across all fisheries", but that "Preliminary results show that current surveys may lack the precision to detect the changes nominated in the management plan." They therefore suggested that, "Research aimed at improving precision, or identifying alternative performance indicators is therefore required if this management technique [fishery-independent surveys] is to be applied."

Thus, the need in South Australian abalone resource stock assessment, is to develop and implement a stock assessment monitoring sampling protocol. The survey protocol should be the most cost effective for purposes of stock assessment and management as possible.

In addition, the statistical methods for analysing that data need to be determined, coded, and made readily available for yearly stock assessment.

Objectives

1. To field test the precision and practical applicability of diver survey methods for greenlip abalone.
2. To present for industry approval, survey protocol specifications for adoption in South Australian abalone assessment.

CHAPTER 1. Habitat Mapping for Abalone Survey Stratification

R. McGarvey, M.J. Brickhill and J.E. Feenstra

1.1. Introduction

The principal obstacle to precise estimates of absolute abalone abundance using diver surveys is the high degree of spatial variation in abalone density. Abalone are usually found in localised distributions because they (1) inhabit specific sub-areas of temperate reef habitat and (2) tend to aggregate into clusters within those habitats. This chapter describes methods of mapping the habitat to address the first cause of non-uniform abalone distribution. High spatial variation is why abalone surveys in Victoria and New South Wales use fixed transect locations to where research divers return and survey yearly. However, fixed transects mean no overall measure of density is obtained, because being fixed, the samples are not random or systematic in any specific study region. Thus, the measure of abundance obtained is a relative measure only. The alternative strategy, is to gather detailed information about the habitat in regions of management interest, and focus survey effort in those areas where abalone are, or could be, abundant, potentially permitting a measure of absolute abalone density.
Reef areas occupied by abalone comprise only a small percentage of the coastal zone. Broad-scale mapping prior to survey permits the survey area to be stratified by habitat type, notably to identify areas of habitable bottom for abalone. Concentrating diver survey effort on reef habitat where abalone occur will increase the precision of the resulting survey estimates of absolute abalone density. In a stratified survey design, the mean abalone density in each stratum (obtained by diver survey) is multiplied by the stratum area, given by habitat mapping, to give total abalone numbers. Thus, the first stage in the development of a survey design that can precisely estimate absolute abalone density is stratification.

In all Australian abalone fisheries, catch and effort totals by commercial divers are reported by statistical block, i.e. sub-areas that spatially partition the coastal zone. In South Australia, catch and effort are spatially sub-divided into 190 blocks. These blocks will, in most cases, be used as the highest level of stratification permitting a seamless integration of survey data with catch and effort data in any future stock assessment model. Thus, the specific aim in a longer-term habitat mapping program would usually be to sub-divide catch and effort reporting blocks by habitat type.

In this FRDC project, abalone diver survey methods were tested with fish-down experiments, two in the South Australian Western Zone and two in the Central Zone. One of the two Western Zone fish-down sites is in Waterloo Bay whose habitats have previously been mapped (Shepherd and Womersley 1981). The three remaining fish-down sites are located within Spencer Gulf: one Western Zone site at Taylor Island and two Central Zone sites at Tiparra Reef (Figure 1.1). Thus, habitat maps were generated in this project for the three Spencer Gulf fish-down sites. At Taylor Island (Chapter 3), the habitat map will be used for stratification. At Tiparra Reef, the broad-scale maps are used to locate two specific areas of high abalone abundance chosen as study regions for fish-down experiments.

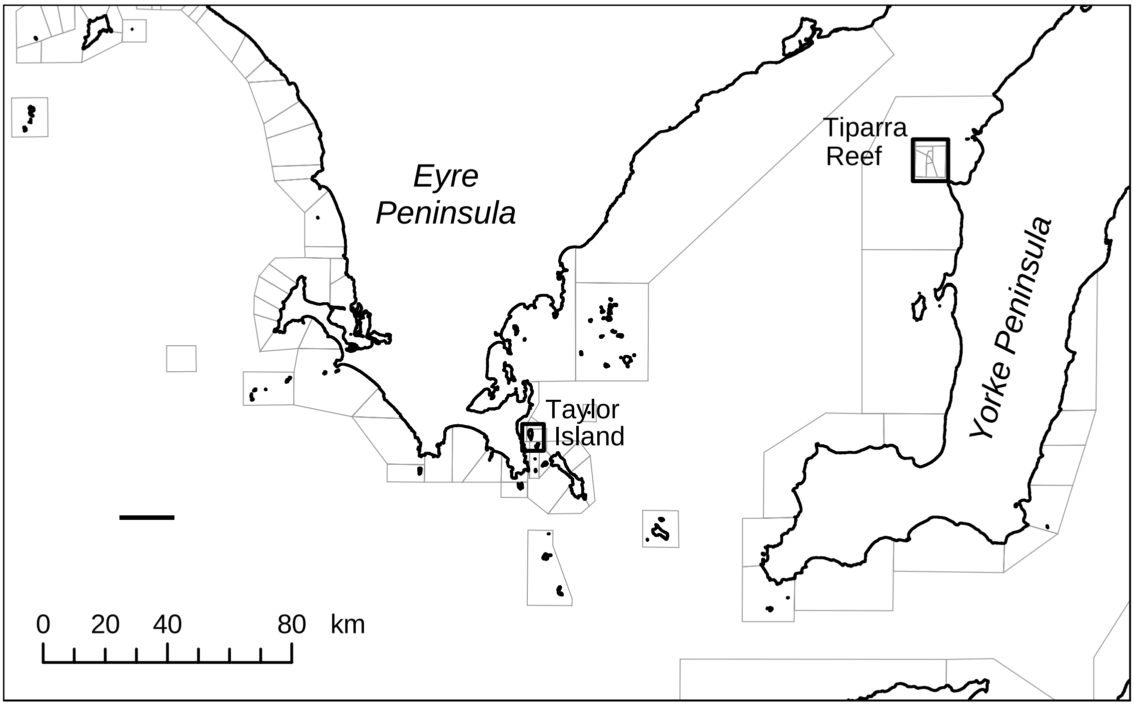


Figure 1.1. Map of Western Zone and Central Zone greenlip abalone harvest catch and effort reporting areas: Spencer Gulf, Eyre Peninsula and Yorke Peninsula, with locations of two study sites at Tiparra Reef and Taylor Island.

1.2. Methods

The habitat mapping method employed for this project was adapted from the mapping protocol previously developed by the habitat mapping group at the Tasmanian Aquaculture and Fisheries Institute (TAFI) for the purpose of mapping the Bruny bioregion in south-eastern Tasmania (Barrett et al. 2001). Advice and software were provided by Alan Jordon, leader of TAFI's habitat mapping group. Miles Lawler, a member of the Tasmanian mapping group's field team, assisted us in implementing a trial version of the habitat mapping system during a visit to SARDI Aquatic Sciences in January 2002.

The on-board benthic habitat mapping system employed for this project continually gathered four information streams while travelling along pre-determined transects over the coastal areas to be mapped. A fifth, video, was deployed along selected locations.

1. GPS latitude-longitude positions were recorded every two seconds. Differential GPS accurate to ±2 m was used when available.
2. Depth to the nearest 0.1 m was recorded every two seconds.
3. The time and date were recorded every two seconds.
4. The person responsible for entering the choice of habitat type into the Seabed Mapper software (called the 'habitat mapper') continually visually monitored the colour sounder, whose changing colour display indicates changes of substrate type and relative extent of plant cover. We did not attempt to record the colour sounder display.
5. Video of the benthos, from a camera suspended approximately 1 m off the bottom with cable feed back to the boat, was displayed on board and recorded for specific time intervals often 5-10 minutes, and at some locations for much longer intervals, when identification of specific species of benthic flora, or further confirmation of the

colour sounder's display were sought, or for detailed mapping. The video also recorded observations of individual abalone.

Details about the instrumentation and information flows are presented in Appendix 1.1.

The time and date were used principally to correct for the tidal variations in depth. The other four streams were used for habitat mapping. Information flows are illustrated below in Figure 1.2.

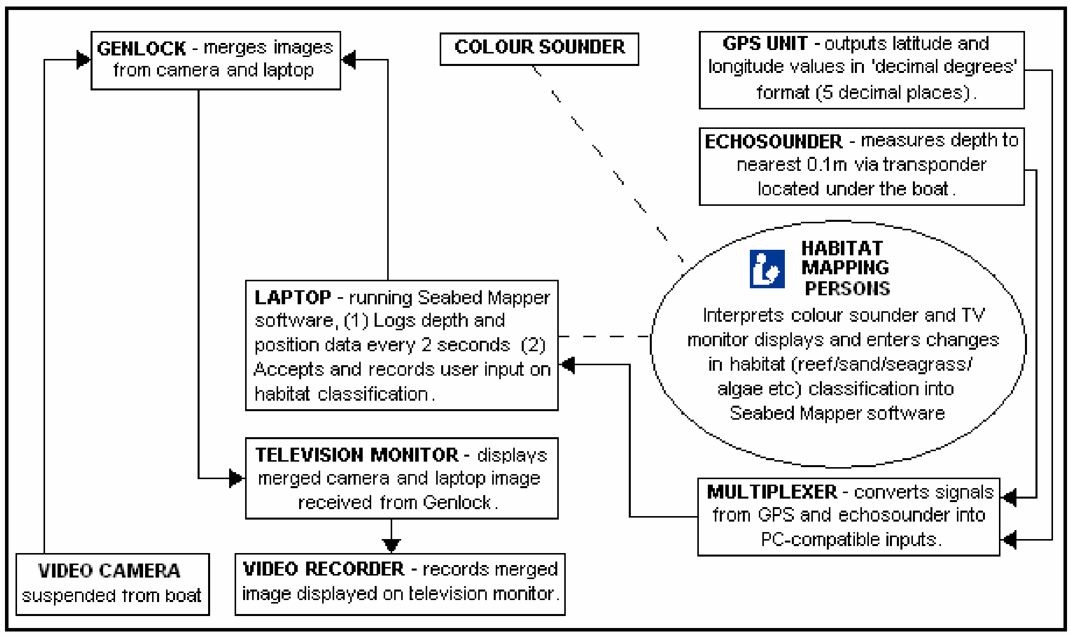


Figure 1.2. Information flow diagram illustrating links among the instruments and the person acting as habitat mapper.

Decisions regarding habitat classification were made in the field by the 'habitat mapper', who operated the laptop computer on board the research vessel as it progressed along pre-determined transects. The principal role of the habitat mapper was to identify points along transects where the habitat type changed. Decisions were made in the first instance by visual evaluation of the colour sounder because:

1. the colour sounder gave a relatively reliable indication of changes in both bottom substrate and in the quantity of plant cover at each point in time and
2. the boat could travel at a speed of up to 15 knots and still return reliable readings on the colour sounder.

Maximum speed when video was being recorded was 1-2 knots.

Repeated classifications at selected points provide a method for assessing the reliability of the habitat classifications assigned. To obtain experimental repetition, therefore, we sought to obtain multiple habitat mapping choices at a number of points in each habitat map. At Tiparra, transects were laid out in a cross-hatch grid directed both E-W and N-S. Broad-scale transects on Tiparra were spaced 500 m apart. By tracing a grid, at each point where E-W and N-S transects intersect, two (essentially) independent measures (i.e. habitat classifications) were obtained. Visual inspection of the resulting maps revealed discrepancies between E-W and N-S transects at intersections points.

At Taylor Island, because of the rapid change in depth and reef structure with distance offshore, the transects were all run perpendicular and as close as possible along the shoreline. As a grid of transects was not appropriate, repetition was achieved by repeating the survey on two separate days.

An important component in the habitat mapping system is the Seabed Mapper software. Written and provided to us by the Tasmanian habitat mapping group, it served two purposes: (1) record the GPS position and depth signals, (2) to accept keyboard input from the habitat mapper who entered changes in the designated habitat type whenever they were identified on the colour sounder or video. Typically, moving along a transect at approximately 15 knots, when the colour sounder indicated a change, the video was lowered and the same bottom re-traced to visually evaluate and interpret the change in the colour sounder's signal. Video footage was reviewed in the laboratory to confirm or adjust habitat boundaries and classifications recorded in the field. The GPS and echo-sounder depth instruments were connected to a laptop computer through a serial port connection (via the multiplexer which combines the two signals into one PC input channel).
The version of the Seabed Mapper Visual Basic software program provided by TAFI was modified to simultaneously display both the video image and the Seabed Mapper laptop user interface on the video channel. This allowed real-time continuous display and recording (on regular VCR tape) of video image of the bottom, the user's choice of habitat classification (substrate and vegetation), GPS latitude-longitude, depth, and time.

ArcView habitat maps were constructed with a minimum of three layers: substrate type, vegetation, and depth. Points were manually connected at a scale of between 1:1,000 and 1:2,500 to generate polygons enclosing areas of similar habitat type. Polygon boundaries reflecting interfaces between different habitat types as identified in the field were later confirmed by review of video footage.

Depth values recorded in the field were adjusted for tidal variation to provide a corrected water depth at mean sea level. The prediction datum specifies the difference between mean sea level and the chart datum level, the latter defined as the level below which the tide never or rarely falls. The tidal depth corrections were based on tide tables and formula specified by the Australian Hydrographic Service (2001):

$$\text{Corrected Depth} = (\textit{measured echosounder depth}) - \Delta h + (\textit{prediction datum})$$

where

$$\Delta h = h_1 + \frac{(h_2 - h_1)}{2}\left\{\cos\left[\pi\left(\frac{t - t_1}{t_2 - t_1} + 1\right)\right] + 1\right\}$$

and

t = recorded time and date of depth observation
h_1 = height of tide (high or low) preceding the depth record being corrected
h_2 = height of tide (high or low) following the depth record being corrected
t_1 = time of tide (high or low) preceding the depth record being corrected
t_2 = time of tide (high or low) following the depth record being corrected.

Prediction datums employed were 0.85 m for Tiparra and 0.76 m for Taylor Island. If these are omitted from the corrected depth formula above, the depths given would correspond with standard depth soundings on navigational charts which give depth relative to chart datum rather than mean sea level.

Depth contours for habitat maps were generated from the tidally corrected depth measurements using a Triangular Irregular Network (TIN) algorithm in the 3D Analyst extension of ArcView 8. The TIN algorithm transforms irregularly spaced data points into a continuous surface of Delaunay triangles, with recorded depth points as the corners of these triangles (Burrough and McDonnell 1998; Barrett et al. 2001). Contours were constructed in 3D Analyst by interpolation along the edges of this triangular network.

On Tiparra Reef, in addition to broad-scale mapping along transects spaced 500 m apart, a more detailed mapping protocol was undertaken inside two smaller areas, of 500 m x 500 m and 500 m x 1000 m where video was used continuously. In these Detail Areas #1 and #2 (Figure 1.8), gridded transects were spaced 100 m apart (Figures 1.9 and 1.10), with E-W transects being 50 m apart in the easterly half of Detail Area #1 (Figure 1.10). The video camera was suspended over the side as the boat motored slowly or (for N-S transects only) drifted with relatively strong tidal currents. The continuous use of video in a closely spaced grid of transects allowed (1) habitat maps on a spatial scale sufficiently small for random or systematic selection of locations for diver survey transects that will be used in fish-down surveys (Chapters 3 and 4), and (2) individual abalone sightings.

The illustrated point locations of abalone sightings in maps of the two Detail Areas (Figures 1.9 and 1.10) indicate observations of from 1 to 3 abalone in the recorded video image. ArcView does not display all of these sighting positions when they are overlapping.

1.3. Results

1.3.1. Taylor Island

Taylor Island (34°52’S, 136°0’E) is located 15 km south east of Port Lincoln within block 19C of the South Australian abalone fishery’s Western Zone (Figure 1.3).

Mapping was done only on the eastern shore of Taylor Island where most abalone fishing occurs. Habitats at Taylor Island were classified into three categories: reef, sand and seagrass. The seagrass category was in turn broken down into three sub-categories based on coverage density (Table 1.1). Dense beds of the seagrass *Posidonia sinuosa* could be readily distinguished on the Koden colour sounder.

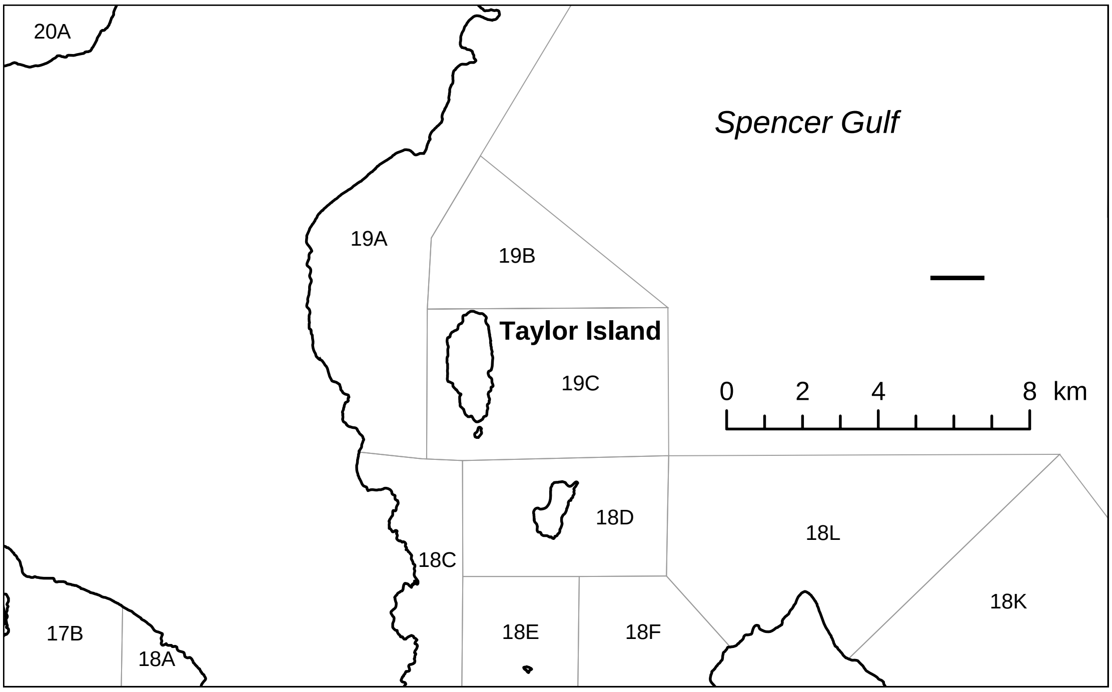


Figure 1.3: Map showing location of Taylor Island statistical-reporting block (i.e. 'map code') 19C of the South Australian abalone fishery's Western Zone

Table 1.1. Definitions of substrate types and habitat classifications applied at Taylor Island in this study.

Reef
High-relief coastal reef The classification of high-relief reef was applied when the depth of rock substrate changed rapidly on the sounder and required upward hauling of the camera. High-relief reef represented steep submerged cliffs adjacent to the coastline at Taylor Island, where depth variation exceeded 1.0 m over approximately a boat length (7 m).
Isolated patchy reef. This classification was applied for small areas of reef such as boulders, outcrops and 'bommies' rising up from surrounding sand.
Unconsolidated Substrate
Sand This classification was applied to large areas of apparently unconsolidated (non-rocky) substrate which did not emit a second echo on either the colour sounder or echo sounder.
Vegetated Unconsolidated Substrate
Seagrass The seagrass classification was applied at three scales depending upon the density of coverage. The 'sparse' label was applied in cases where seagrass covered 0-25% of the video field of view and the substrate beneath seagrass (primarily sand) was easily visible. The 'intermediate' scale label was applied in cases where seagrass covered 25-75% of the field of view and the 'dense' scale label was applied in cases where seagrass covered >75% of the field of view of the video image. Species labels applied: *Posidonia sinuosa, Zostera tasmanica* and *Amphibolis antarctica.*

The island consists of a granite basement rock overlain with a limestone (calcarenite) cap. The eastern side of the island drops off in a steep face that continues into the sea. This steeply dropping rock slope meets sand at depths of about 5 m in the northern extremity of the eastern shore, dropping to deeper depths of about 20 m at the southern end of Taylor Island (Figure 1.4). Boulders are scattered intermittently along the rock-sand interface. Sandy bottom east of the rocky slope is colonised by *Posidonia sinuosa* seagrass. Along much of the eastern shore, greenlip abalone inhabit a strip of flat limestone at the base of the steep rock slope, with high densities common at the rock-sand interface. This reef area (regarded locally as prime abalone habitat) widens to several hundred metres at the southern tip of Taylor Island (Figure 1.4).

A sand beach partitions the eastern shoreline into northern and southern halves (Figure 1.4). The subtidal algal assemblage on the descending limestone reef was dominated by *Ecklonia radiata*, *Cystophora monilifera* and *Seirococcus axillaris* south of the sand beach (where water movement was greater) and *Cystophora monilifera*, *Cystophora subfarcinata* and *Sargassum* spp. on the northern half of Taylor Island's eastern shore. The gradual change in vegetation supported the existence of a weak gradient of decreasing water movement from south to north (Shepherd and Womersley 1981, Shepherd et al. 1992), following the direction of the approaching swell from the south. The seagrass community to the immediate east of the narrow (yet discontinuous) sand strip delineating the rock-sand interface was dominated by *Posidonia sinuosa*.

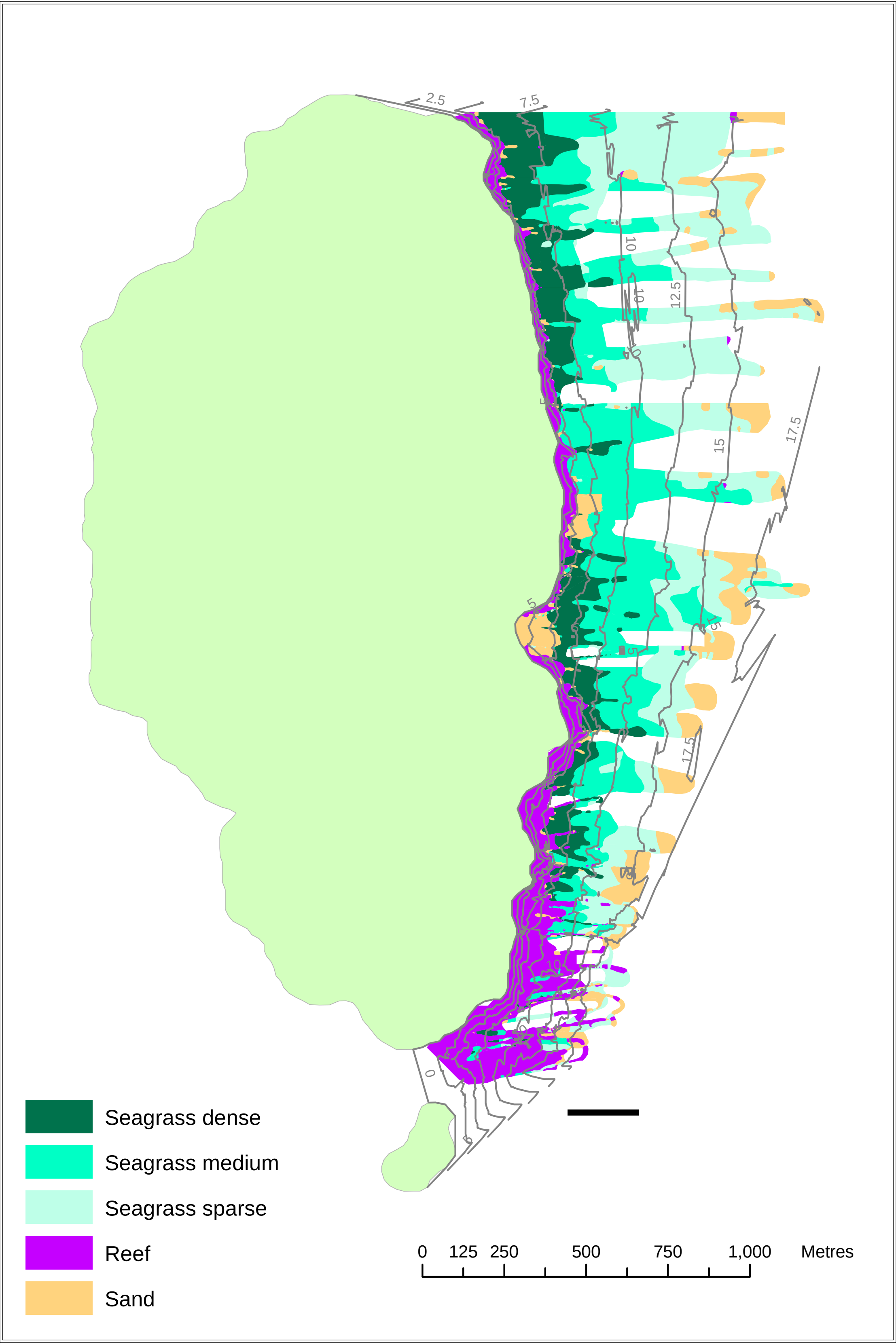


Figure 1.4. Map illustrating benthic habitat classifications off the eastern coastline of Taylor Island. Based on data collected on 4/9/2002 and 24/9/2002.

1.3.2. Tiparra Reef

Tiparra Reef (34°3'S 137°23'E) is a large limestone reef complex covering an area of approximately 50 km^2 in Tiparra Bay, 15 km west of Port Hughes within the boundaries of blocks 21A-G of the South Australian abalone fishery's Central Zone (Figure 1.5). The reef complex is shallow, with most of the fishable zone in 5 to 14 m of water. Currently nearly all of the greenlip abalone quota from the Central Zone is taken at Tiparra (Mayfield and Ward 2003).

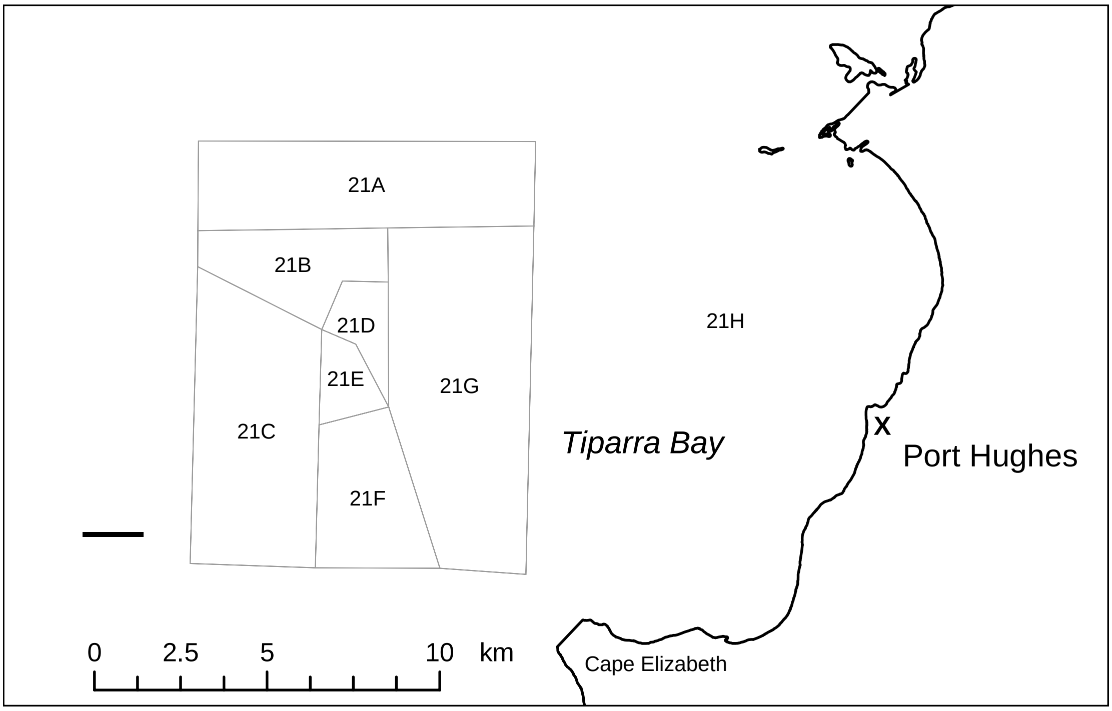


Figure 1.5: Map showing location of the Tiparra Reef complex within reporting blocks 21A-G of the SA abalone fishery's Central Zone.

Habitats at Tiparra Reef were classified at two levels: substrate and vegetation. Substrate was partitioned into four categories: sand/rubble, low-relief reef, medium-relief reef and high-relief reef. Vegetation also had four categories: bare, seagrass, mixed (seagrass and algae) and algae. Vegetation categories (seagrass, mixed and algae) were in turn broken down into three sub-categories based on extent of plant cover (Table 1.2).

On the broad scale, substrate and vegetation show the same strong association of algae on rock and seagrass on sand (Figures 1.6-1.8). The major species of seagrass encountered at Tiparra Reef were *Posidonia sinuosa*, *Amphibolis antarctica* (~6-8 m) and *Amphibolis griffithii* (~8-10 m). Densities ranged from almost 100% coverage in the north-eastern corner of the reef area to less than 25% across much of the western and southern areas. Other notable marine plant species observed included various *Cystophora* spp., *Sargassum* spp., *Osmundaria prolifera* and other large, fleshy and foliose red algae. The latter, constituents of abalone diet, were found on exposed reef areas in the north-west sector (notably including the 'West Bottom' abalone fishing ground) of Tiparra Reef.

The southern half of the original Tiparra study area did not give evidence of favourable abalone habitat (Figure 1.6). Much of it was seagrass or bare sand (Figure 1.7), and the video indicated a generally less dense and less diverse vegetation at greater distances southward from the reef complex centred around the lighthouse (Figure 1.8). After running E-W transects, we elected not to complete the N-S transects of the survey grid in this southern half because this area was not of interest for abalone fishery management or survey design, and the scale of variation was large so that the fine scale spatial resolution obtainable by repeating the same area with N-S transects was not deemed cost-effective.

Areas of rock/algae and sand/seagrass were generally consistently identified on both N-S and E-W transects, providing repeated measures of those classifications at the intersection points. Areas with some inconsistency of N-S with E-W transects include the curved N-S transect in the northern reaches of block 2F (Figure 1.6 and 1.7, second N-S transect from the east), the upper north-west corner (Figure 1.8), and some of the grid in the centre of Tiparra (Figure 1.6, block 21C) with sand indicated in N-S transects and low or medium relief reef running E-W. These indicate areas of less reliable habitat classification and taken overall, indicate the general level of classification precision. Tiparra reef is flat, and sand is common in depressions of the limestone substrate, making classifications generally less distinct than for many reef habitats.

Table 1.2. Definitions of substrate types and habitat classifications applied at Tiparra Reef in this study.

Substrate
High-relief reef The classification of high-relief reef was applied when the depth of rock substrate changed rapidly on the sounder and required upward haulage of the camera. High-relief reef represented steep submerged cliffs following edges of reef platforms adjacent to the lighthouse at Tiparra Reef and included areas where depth variation exceeded 1.0 m over approximately a boat length (7 m).
Medium-relief reef. The classification of medium-relief reef was applied for areas where depth variation of rock substrate changed by 0.4-1.0 m over approximately over a boat length (7 m).
Low-relief reef The classification of low-relief reef was applied for areas of rock substrate that were almost flat but displayed some minor variation in depth (<0.4 m) over approximately a boat length (7 m). **Sand and rubble.** This classification was applied for areas across which small consolidated reef components such as boulders, stones, pebbles and gravel were exposed above otherwise unconsolidated (non-rocky) substrate (sand).
Vegetation
Seagrass Seagrass classification was applied at three scales depending upon the density of coverage. The ‘sparse' label was applied in cases where seagrass covered 0-25% of the video field of view and the substrate beneath foliage (primarily sand and rubble) was easily visible. The ‘intermediate' scale label was applied where seagrass covered 25-75% of the field of view and the 'dense' scale label was applied in cases where seagrass covered >75% of the field of view of the video image. Species present: *Posidonia sinuosa, Amphibolis griffithii and Amphibolis antarctica.*
Macroalgae Macroalgae classification was applied at the same three scales of coverage (0-25%, 25-75% and >75%) as for seagrass. While seagrass species were dominant on sand and rubble and areas of reef in which sand had collected and formed sufficiently thick layers, macroalgae colonised reef areas and isolated patches of sand and rubble where there was sufficient exposed reef elements. Species present: *Ecklonia radiata*, *Sargassum* spp., *Osmundaria*, *Scaberia, Cystophora monilifera, Seirococcus axillaris, Caulerpa,* miscellaneous reds and pink corallines.
Mixed Mixed classification was also applied at the same three scales (0-25%, 25-75% and >75%) as for seagrass and macroalgae. There were several areas where seagrass and macroalgal species co-colonised areas of substrate in which there were sufficient sand layers and exposed reef elements to support rhizomes and holdfasts respectively.

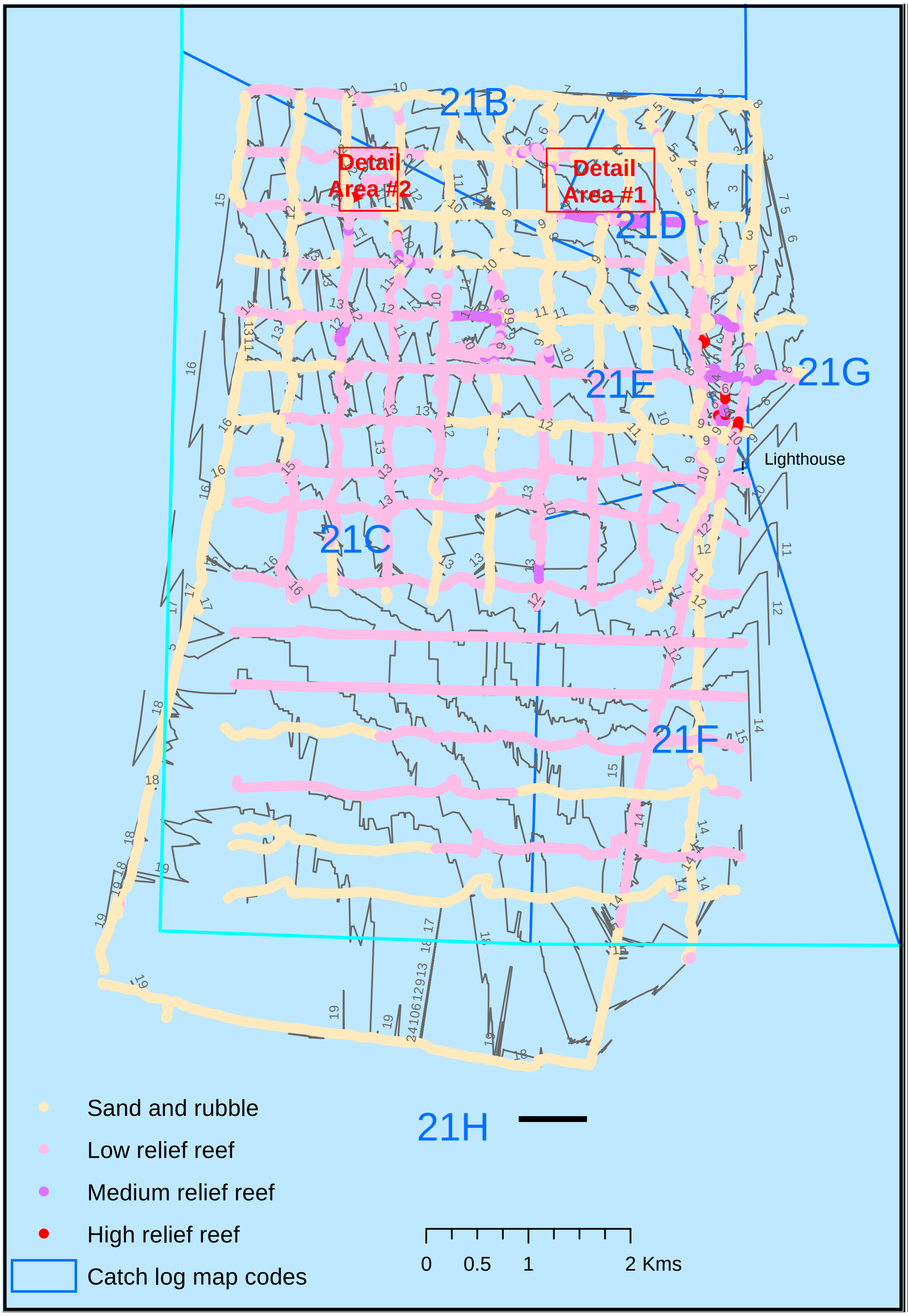


Figure 1.6. Tiparra Reef complex: bottom substrate type.

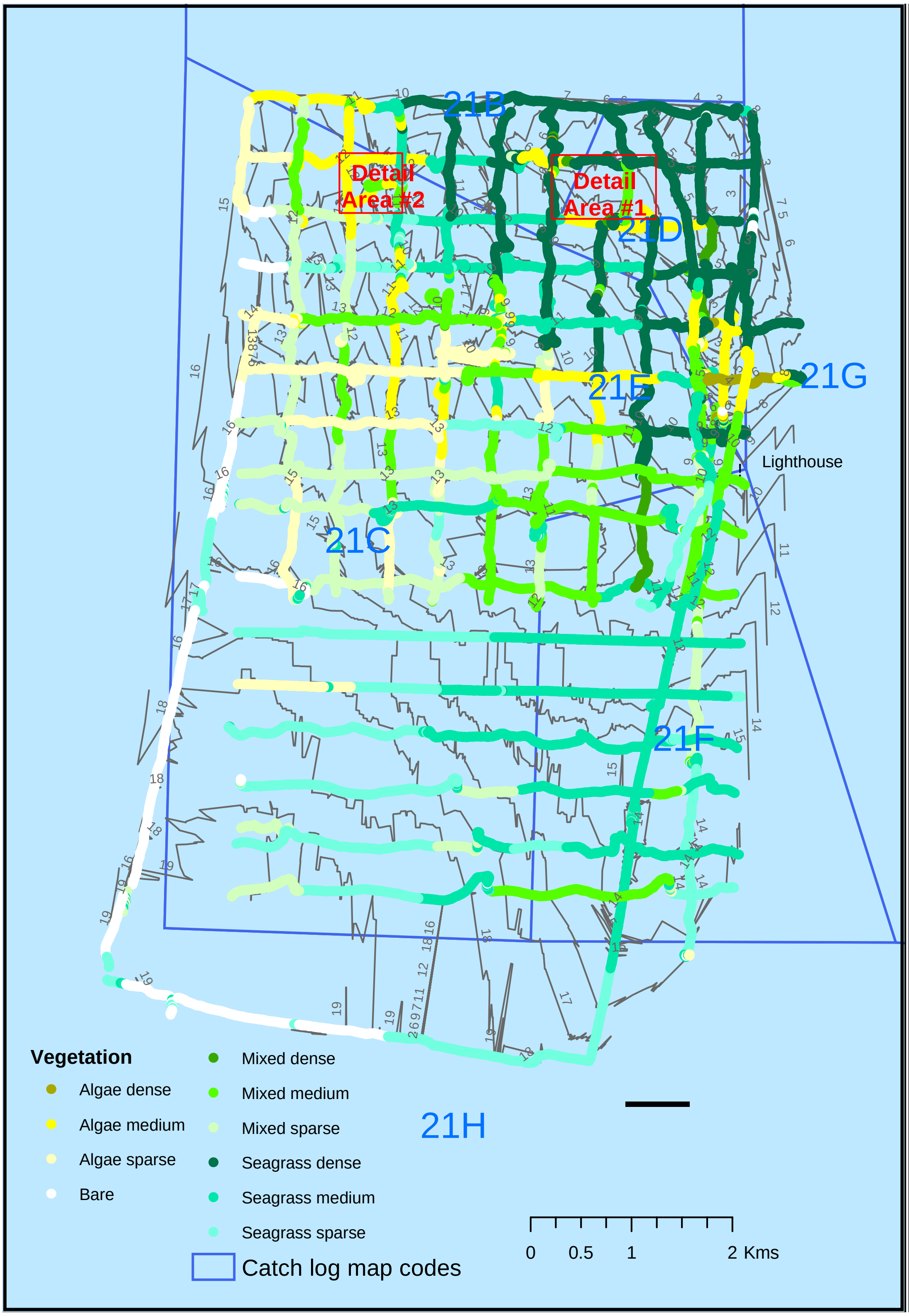
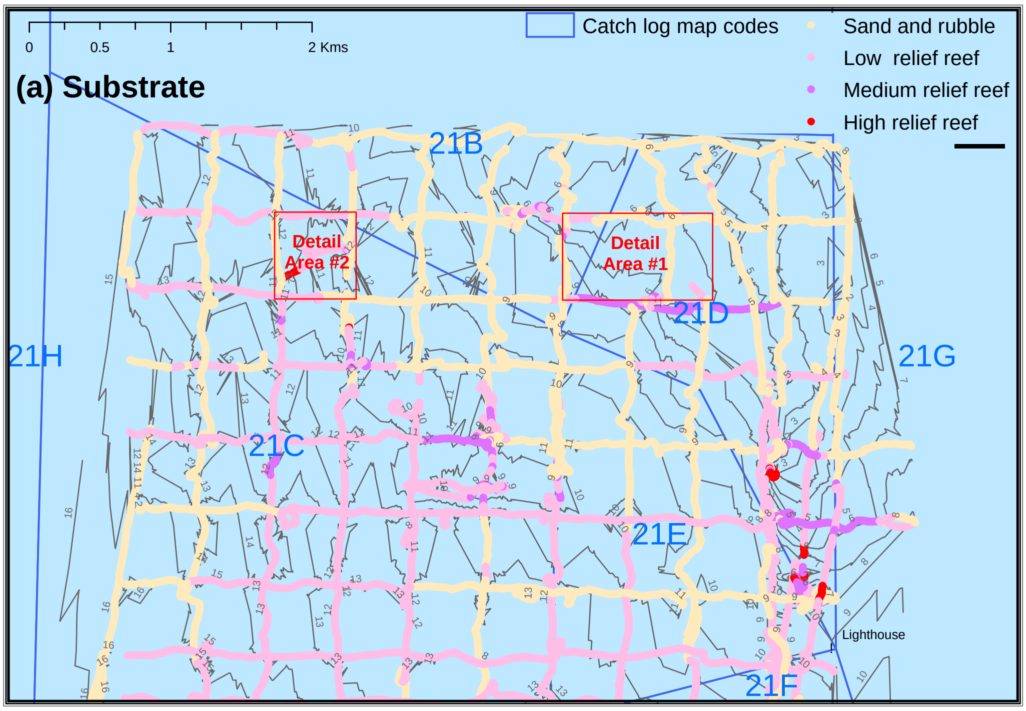


Figure 1.7. Tiparra Reef complex: algal and seagrass vegetation cover.



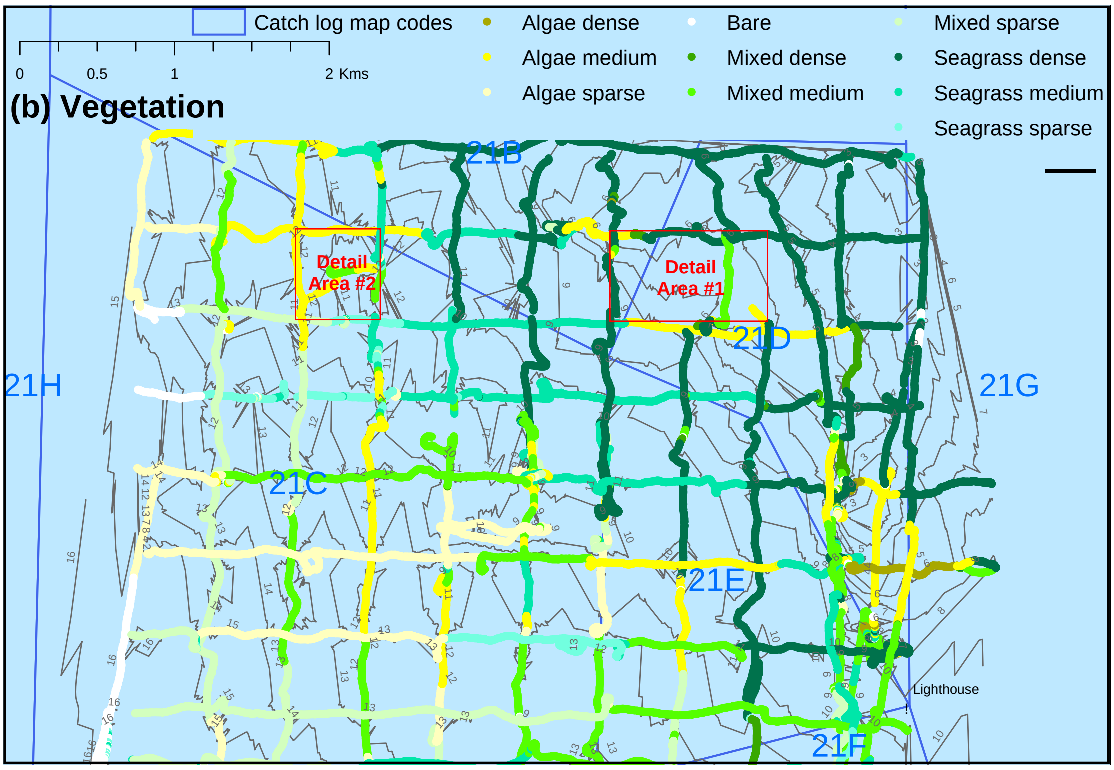


Figure 1.8. Northern half of Tiparra reef: (a) substrate and (b) vegetation.

Counts of abalone in video transects over Detail Areas #1 and #2 indicated areas where abalone were abundant. The abalone numbers sighted varied substantially among habitat types and were sufficiently high to provide meaningful statistics of spatial distribution: 212 sightings (of 1, 2 or 3 abalone per sighting) in Detail Area #2, 68 in the western half of Detail Area #1 and only 2 in the eastern half of Detail Area #1. The well-known spatial association of (1) algae with rocky (i.e. reef) substrate, and (2) much higher densities of abalone in rock/algae areas was evident. Abalone were not observed in seagrass beds. These spatial correlations serve to confirm the ability of boat-based video to make coarse-level identifications of abalone habitat.

Detail Area #1 was traversed by the rocky drop-off in depth (known as the 'reef edge'), shown as more closely spaced depth contours (Figure 1.9) running northwest from the Tiparra lighthouse (Figure 1.8). This is an important feature for abalone fishers and abalone sightings on the video occurred frequently along and above this reef edge. Seagrass beds to the northeast and southwest of this reef edge were thick and abalone-free. The occurrence of abalone only along the northwest stretch of the reef edge in Detail Area #1 (Figure 1.9) was not explainable with observed habitat classifications, i.e. it is not known why there were relatively few abalone along the middle and southern stretches of the reef edge.

Detail Area #2 (Figure 1.10) is predominantly abalone habitat with small patches of sand/seagrass. Algae/reef complex covers most of this 500 x 500 m square area. Abalone sightings were numerous (= 212) (Figure 1.10). This area is known to commercial abalone divers as 'West Bottom', and has historically been an area of high abalone production.

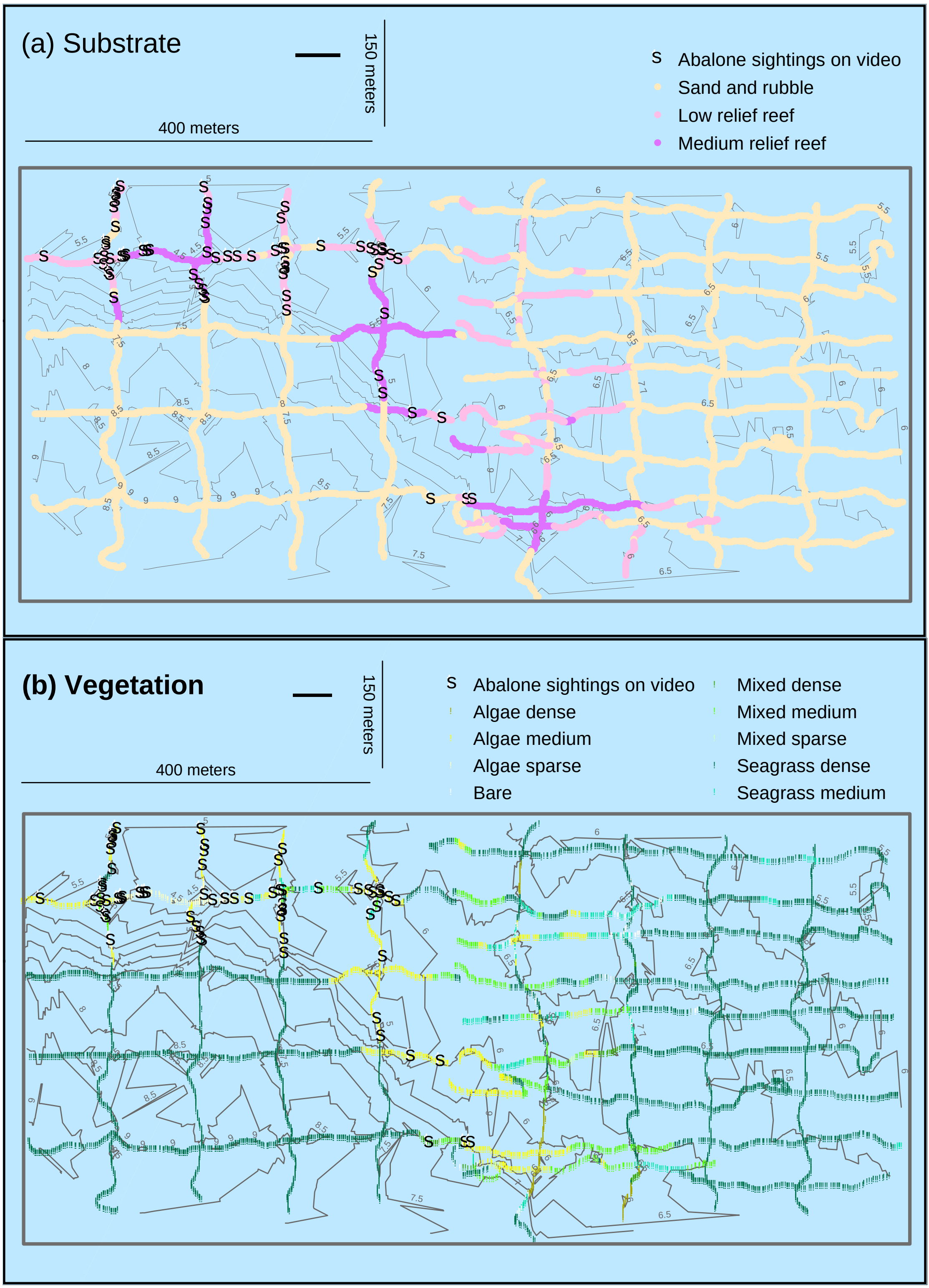


Figure 1.9. Detail Area #1: (a) substrate and (b) vegetation.

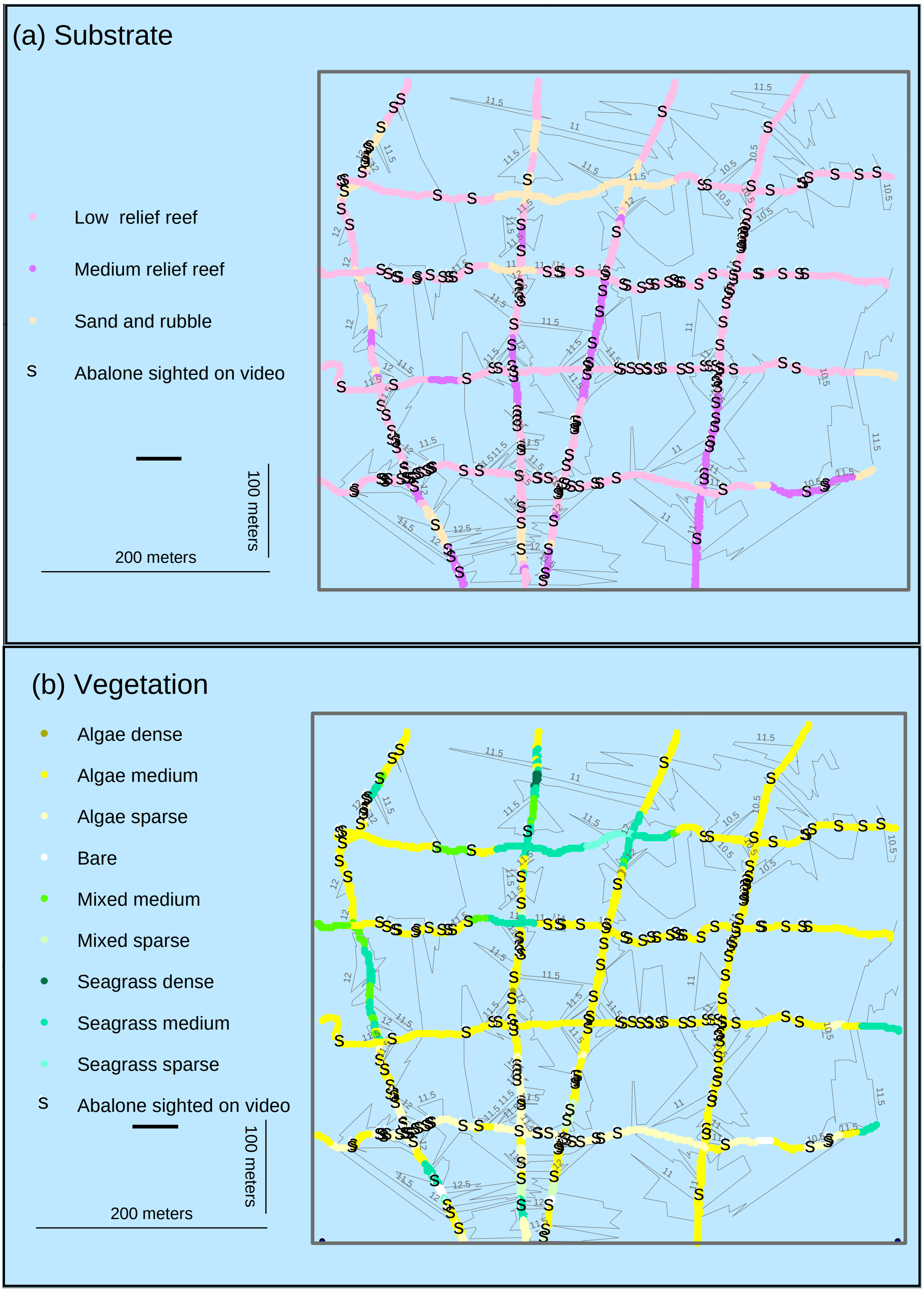


Figure 1.10. Detail Area #2 (West Bottom): (a) substrate and (b) vegetation.

1.4. Discussion

The work undertaken here suggests that habitat mapping for stratification in abalone survey design is feasible. The methods above (developed, or adapted, notably from TAFI) provide evidence of being able to differentiate the broadest scale of habitat classification. Specifically, these methods (1) differentiate broad-scale bottom types, such as seagrass and reef, (2) map depth accurately, (3) allow boundaries to be drawn for survey stratification, (4) estimate the areas of each stratum, and (5) produce the underlying maps onto which survey transects can be drawn in a GIS package such as ArcView (see Chapters 3, 4 and 6).

It is not clear yet that colour sounder combined with intermittent video can distinguish more detailed habitat sub-categories and, in particular, uniquely identify the specific sub-areas of reef bottom where abalone are found in harvestable numbers.

Research and commercial divers can often visually identify the specific areas of ‘good abalone bottom’ while swimming over the reef. Incorporating this knowledge into the ArcView maps with boat-based information (and the associated broad-scale maps) will be a cumulative learning process. The divers will play an essential role here in three ways: In areas where they have dived previously, they give verbal advice about where on a patch of reef abalone are known to occur in significant densities. Secondly, and more rigorously for an on-going program of abalone habitat mapping, the specific habitat observed on each survey transect can be regularly recorded relative to the start and finish GPS positions of each transect. Third, when 2-m quadrat counts are recorded along each transect, these provide direct and reliable information on abalone density over short spatial scales. Thus, we can continue to update and refine the initial habitat maps obtained from the boat using research divers’ transect habitat classifications. After several years of this, in combination with the diver survey measures of abalone density, there may be sufficient information to undertake cluster or principal components (i.e. linear) analysis of the measured quantities that would give probabilities of observing significant quantities of abalone, i.e. to differentiate ‘good abalone bottom’ based on environmental variables that can be measured from the boat. For many species, including greenlip and blacklip, the depth, substrate type (for greenlip, often relatively flat rock), and distance from productive seagrass with epiphytic red algae growing in its canopy are essential factors in identifying likely abalone habitat. Other features of ‘good abalone bottom’ remain to be identified and quantified. Moreover, patches of optimal abalone habitat can shift over time, due to sand or vegetation movement, for example.

In the medium term, the objective is to map a select set of specific fishing grounds where abalone are harvested year after year, or possibly, where they once were harvested over a number of years. Thus, we do not require a generalisable method. Rather, at each location of designated management interest we will make use of whatever information is available to get a detailed map of the bottom, and to identify the areas of important abalone habitat.

Future improvements in technology will doubtless increase the resolution and detail of habitat mapping. Side-scan sonar technology, with a spatial resolution of 10-cm, is currently available but not yet fully implemented in South Australia. A series of sonar frequencies are reflected off the vegetation and substrate, and produce, as output, a highly detailed map of ‘textures’, each texture identifying a bottom type as differentiated by the multiple reflected frequencies after post-processing by a linear analysis (principal components, or more sophisticated approaches). Thus, this high-resolution empirical classification must be combined with video or diver-based ground-truthing to identify what habitat each of the textures represents. Currently the side scan system costs about $5000/day to run. As costs decline, and technical improvements continue, this will become feasible over the specific stretches of abalone bottom of management interest.

Side-scan methods will integrate naturally with the video and diver mapping approaches already implemented in this project. The two primary features of side-scan technology, that it (1) covers all the area within a designated site, and (2) differentiates very fine-scale differences in habitat type, complement the boat and diver-based information which (1) cover a relatively small fraction of the area, with (2) relatively coarse classifications but (3) provide direct ground-truthing in a rigorous and systematic protocol.

In the two 'Detail' areas, video was deployed over essentially all transects covered. This permitted the identification of individual abalone in the video footage. It is clear that divers would have found abalone that the video missed, and we could not in this deployment estimate the area of bottom swept in the video field of view. Therefore a survey measure of absolute density from the video was not achieved. However, the rough relative measure of abalone abundance, obtained as a matter of course from the same video imagery used to map habitats is of great value in the principal objective of identifying abalone habitat. On Tiparra Reef, where conditions are relatively favourable for video owing to the relatively flat topography, 212 abalone were sighted in Detail Area #2, compared with only 2 in the easterly of the two 500 x 500 m squares in Detail Area #1, allowing us to identify Detail Area #2 as an area of abalone habitat. Thus, abalone counts on video provide a useful and relatively inexpensive tool for identifying the areas of abalone habitat. High abalone densities on video sightings were strongly confirmed by diver survey and fish-down harvest (Chapter 4).

The increase in both precision and spatial resolution of classification in the two Detail Areas (Figures 1.9 and 1.10) is substantial. This was obtained at higher cost: (1) transects were much closer together (spaced 50 or 100 m); (2) video was run continuously; and (3) travel speed was 1-2 knots versus 10-15. Thus, as expected, much higher habitat map detail was achieved with much greater boat-times allocated.

In the future, the use of video may be extended to directly measure abalone density. Because abalone (like many herbivores) are often partially or fully hidden from above, it is probable that the counts from video will always be lower than those obtained by experienced research divers covering the same transect. Nevertheless, the ability to get broad-scale relative measures of abalone density from boat-based video is attractive because it would allow coverage of much larger areas than divers who are limited by dive times. Moreover, it would allow rapid and less expensive survey in areas where divers can go only for short times, notably waters deeper than 20 m. Ideally, any broad-scale boat-based surveys would be run in conjunction with diver transects permitting estimation of the amount of undercounting that the boat-based video incurs. Thus, a combination of (1) the broad-scale but lower quality information about abalone density that video provides, with (2) the higher quality more spatially localised information from divers, can allow abalone density estimates over much broader areas than with divers alone.

We believe that mapping abalone habitats for survey stratification will prove to be a valuable step in obtaining estimates of absolute abalone density of sufficient precision to be useful for stock assessment and resource management. For this reason, the habitat mapping and boat-based video components were implemented in this project. It is increasingly recognised that spatially explicit management of abalone fisheries is needed (Worthington and Andrew 1998; Prince et al. 1998) . To this end, it would be fruitful to further develop this habitat mapping capability for abalone survey stratification, fishery habitat mapping, and environmental management of exploited abalone habitats.

1.5. Acknowledgements

We thank the following people for their valuable assistance in habitat mapping and system development: TAFI habitat mapping group (Miles Lawler, Alan Jordan, Vanessa Halley); Vladan Blagojevic from MorphVision (Sydney) for technical assistance and support for the MorphCam video camera; Neil Sandercock from PIRSA Spatial Information Services for advice with ArcView GIS; Stephen Chamberlain and Peter Stevenson (commercial abalone divers based in Port Hughes) for information about Tiparra and specifically regarding choice of detailed areas for video surveying at Tiparra Reef; Brian Davies, David Miller, David Fleer and Michael Clark for providing field supervision and for driving the FRV 'Odyssey'; Robert Driessen from DataVision GIS Pty Ltd for assistance in Visual Basic programming of Seabed Mapper. Steve Mayfield, Brian Foureur, and the abalone research program provided essential field services and support.

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Appendix 1.1.

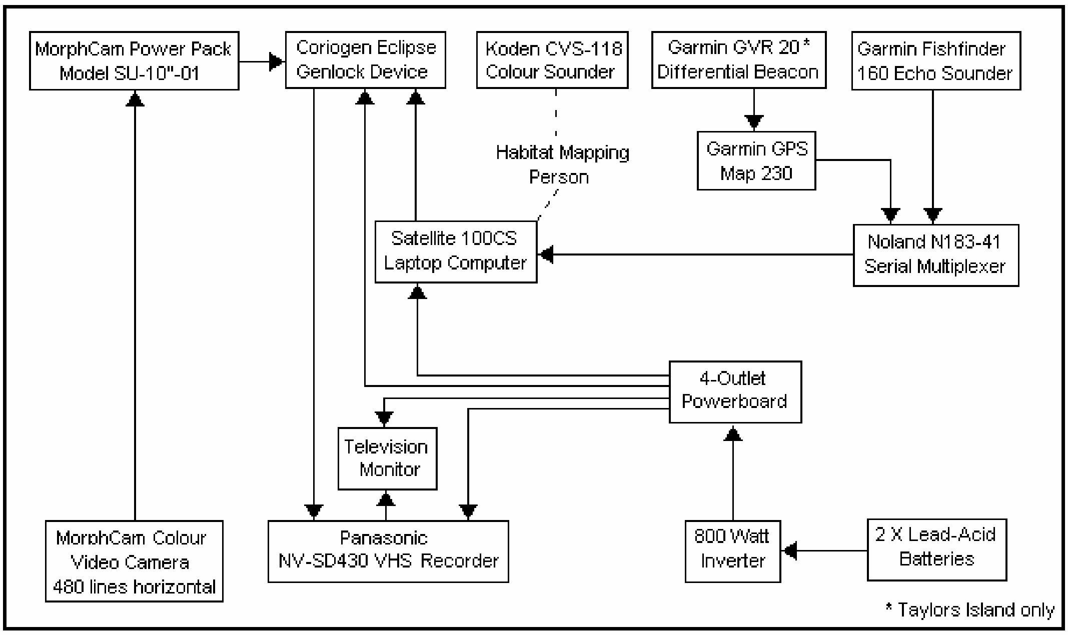

Figure A1.1. Information flow diagram illustrating electric and digital signal processing instrumentation.

CHAPTER 2. Field trials and Simulations of Point-Nearest-Neighbour Distance Methods for Estimating Abalone Density

Richard McGarvey, Karen Byth, Cameron D. Dixon, Robert W. Day, and John E. Feenstra

2.0 Abstract

We investigated evidence for bias in estimates of abalone density from the point-nearest-neighbour (PNN) diver survey method wherein divers measure distances from random points to abalone and between abalone. Field and simulation tests of the PNN survey method were undertaken. In two plots of a lightly exploited abalone population in South Australia at Tiparra Reef, all the greenlip abalone (*Haliotis laevigata*) present were enumerated by divers, providing the true density in both study regions. Clustering of abalone was visually evident and quantified by a Hopkins test. The study areas were gridded into 1-m^2 quadrats. Divers measured distances from randomly selected grid points to the nearest abalone, and from that nearest abalone to its nearest neighbour. Inter-abalone distances from every fifth tagged abalone were also measured. Two PNN estimator formulas, of Byth (1982) and Diggle (1975), were used to estimate abalone density. The resulting estimates from both PNN estimators were biased, underestimating true (enumerated) density by 18-29% and 18-55% in the two sites respectively. The Byth estimator showed less underestimation. Clustering of abalone is the likely primary cause of density underestimation in the two study areas. Simulated PNN surveys in clustered populations quantified both overestimation and underestimation bias. Randomly interspersed individuals reduced density underestimation, and centrally (rather than uniformly) distributed clusters worsened it. Because the spatial distributions of abalone and other invertebrates are often clustered, this strong bias is problematic for the use of point-nearest-neighbour as a survey method for estimating density in these populations. This work is now published in Shellfish Research (McGarvey et al. 2005).

2.1. Introduction

Point-distance methods have been often proposed for use in forestry to estimate the density of stands of trees (see Diggle 1983; Upton and Fingleton 1986), though their use in forestry practice is not widespread. Abalone are currently surveyed by divers using a range of fishery-independent techniques (McShane 1995; Hart and Gorfine 1997; Hart et al. 1997). Officer et al. (2001b) advocated the use of point-nearest neighbour (PNN) distance methods for abalone survey designed to estimate population density.

High spatial variation characterises the distributions of abalone on the bottom, notably high levels of clustering (Shepherd and Partington 1995; Officer et al. 2001a). For this reason, abalone diver surveys have predominantly used fixed sample locations (Gorfine et al. 1997; Hart et al. 1997), rather than random or systematic transects. Fixing transect locations reduces imprecision of the yearly abundance measure caused by spatial variation, but it leaves all but the fixed locations unsampled, and thus provides only a relative measure of abalone abundance.

The point-distance methods tested in this study were designed to measure absolute abalone density. This requires a clear boundary defining the study region of marine benthic habitat inside which mean abalone density is to be estimated. At two bounded study sites, a point-nearest-neighbour (PNN) distance-based diver survey design was tested. Comparing PNN estimates of density with the true density from direct counts (enumeration) of all abalone in these two sites provided a direct test of survey estimate accuracy, permitting a field test of the PNN method. A second stage of testing the PNN method for use in abalone diver survey was undertaken using simulation.

Simulations were run to investigate potential causes for the underestimation observed in the field estimates of abalone density at the two study sites. The principal result was that the PNN methods, using density estimators of Diggle (1977) and Byth (1982), underestimated abalone density for realistic combinations of cluster size and radius.

The accuracy of PNN density estimates were tested for three spatial patterns of clustering in simulated populations: (1) uniform circular clustering, (2) the occurrence of loners scattered among uniform clusters, and (3) a central (bivariate normal) distribution of abalone within each cluster characterised by highest densities in the middle and lower densities around the edges of each cluster. Spatial properties (1) and (3) induce bias in estimates of density using PNN. Only for random distributions or clusters of two or three abalone were PNN estimates accurate.

Spatial patterns of clustering typify many communities of benthic invertebrates, casting doubt on the reliability of point-distance methods for estimating density in these populations.

2.2. Methods

2.2.1. Field Measurement

During March 2002, 308 greenlip abalone were tagged at two sites on Tiparra Reef, South Australia (Dixon and Day, in press). The two sites selected, 10 m apart, were similar in depth (3 m), size range of non-cryptic abalone present, and habitat. At both sites, areas of continuous low-relief scalloped limestone were interspersed with boulders supporting macroalgae, with some sandy areas and small patches of seagrass. The corners of each site were marked with weights. The first site, S1, was 34 m x 14 m in size, and the second site, S2, was 14 m x 12 m. Ropes were used to sub-divide each site into 1-m^2 quadrats, where the intersections of these ropes marked grid-point locations. Points were randomly selected from the grid, excluding the site boundaries.

Divers moved systematically through both sites, tagging every abalone found and recording the quadrat in which it was tagged. At S2, every abalone was tagged, while at the larger S1 site divers systematically tagged every third abalone encountered. The number of tagged abalone provides a complete enumeration (a census) of the total number of abalone present at S2 and approximately one-third of the total number of abalone present, ±2 abalone, at S1. The distance to the nearest neighbour of every 5^{th} abalone tagged (every 15^{th} and 5^{th} abalone found at sites S1 and S2, respectively) was measured to provide a systematic (thus effectively random) sample of nearest-neighbour distances.

PNN distance sampling was also undertaken at both sites. At randomly selected grid points, divers searched in a circle around each point, and measured the distance to the nearest abalone from the grid point. They then measured the distance from this abalone to its nearest neighbour, providing a second sample of nearest-neighbour distances. Distances were measured from and to the centre of each abalone shell using a tape measure. Distance samples of 22 to 30 were measured (Table 2.1).

By recording the quadrat and the order in which abalone were tagged, numbers inside each 1-m^2 quadrat were inferred to an accuracy of ±2. As only every third abalone encountered was tagged at S1, every third abalone tagged at site S2 was used for quantifying numbers per quadrat. For example, in quadrats where only one abalone was tagged, the inferred allowable number per quadrat was 1 and 5, and in quadrats where two abalone were tagged, between 4 and 8, etc.

Table 2.1. Sample sizes, as numbers of point-to-abalone and abalone-to-abalone distances measured at the two study sites.

Distance measurement	Mathematical symbol	Site S1	Site S2
Grid point to nearest abalone (*x*)	n_x	25	30
From abalone nearest to a grid point to its nearest neighbour (y^g)	n_{y^g}	25	30
From every 5th abalone tagged to its nearest neighbour (y^5)	n_{y^5}	22	22

2.2.2. Quantifying Abalone Clustering

To investigate the effects of clustering on density estimates, we first quantified the extent of clustering inside the two study regions. The Hopkins (1954) test was used to quantify deviations from complete spatial randomness of the measured abalone distributions based on point-neighbour and nearest-neighbour measurements. The Hopkins test statistic, H_F , is written $H_F = \sum_{i=1}^{n_x} x_i^2 \Big/ \sum_{j=1}^{n_y} y_j^2$, where $\{x_i, i = 1...n_x\}$ = distances from randomly sampled grid points to the nearest abalone, and y_j $\{y_i, i = 1...n_y\}$ = distances from abalone to their nearest neighbours. The sample sizes of these distance measurements are denoted n_x and n_y (Table 2.1). This notation will be employed in all that follows. When the *x*- and *y*-distances are randomly (and thus independently) sampled, the Hopkins statistic under complete spatial randomness follows an *F*-distribution, namely $F_{2n_x, 2n_y}$. Diggle et al. (1976) and Byth and Ripley (1980) have shown that H_F is sensitive and generally superior to other tests for detecting clustering. The principal objection to the Hopkins statistic has been that obtaining a random sample of abalone for *y*-distances (abalone-to-abalone) was impractical, generally requiring complete enumeration (Hines and Hines 1979; Diggle 1983, p.39; Upton and

Fingleton 1985, p. 61). In the present study, random nearest neighbour *y*-distances were measured for every 5th abalone tagged (denoted $\{y_i^5\}$ below).

2.2.3. Abalone Density Estimation

Complete enumeration of greenlip abalone numbers in the two field populations permitted a direct field test of the point-nearest-neighbour method for abalone survey estimates of density.

Two PNN estimator formulas of density were applied to the data sets of *x*- and *y*- distance measurements from the two sites. The first estimator, call it γ^{*-1}, was proposed by Diggle (1975) and was used in the PNN simulations of Officer et al. (2001b): $\gamma^{*-1} = m \Big/ \pi\sqrt{\sum_{i=1}^{m} x_i^2 \cdot \sum_{i=1}^{m} y_i^2}$. This can be generalised to differing numbers of point-abalone (n_x) and abalone-abalone distance measurements (n_y) as $\gamma^{*-1} = \left[\frac{\pi}{n_x}\sum_{i=1}^{n_x} x_i^2 \cdot \frac{\pi}{n_y}\sum_{j=1}^{n_y} y_j^2\right]^{-\frac{1}{2}}$.

Byth (1982) proposed the *E** estimator: $E^* = m^2 \Big/ \left\{\left(2\sum_{i=1}^{m} x_i\right)\cdot\left(2\sum_{i=1}^{m} y_i\right)\right\}$. This formula assumes equal samples of X and Y. If the number of *x* and *y* measurements differ, this can be generalised as $E^* = \dfrac{1}{\left\{\left(\frac{2}{n_x}\sum_{i=1}^{n_x} x_i\right)\cdot\left(\frac{2}{n_y}\sum_{i=1}^{n_y} y_i\right)\right\}}$; in terms of the means of X and Y, this can be written $E^* = \dfrac{1}{4\bar{x}\,\bar{y}}$.

Because the abalone-to-abalone nearest neighbour (*y*) distances were sampled twice, once from each abalone found closest to each grid point, denoted $\{y_i^g\}$, and again, for every 5th abalone tagged, denoted $\{y_i^5\}$, two PNN estimates of density were obtained at each site and by each estimator.

Total survey estimation error, including both bias and sample variance, is quantified by the root mean square error (*RMSE*), the sum over the two experiments of the squared difference of each survey estimate from the true value of abalone population number in each experimental study region known by enumeration. We will, in general, be interested in quantifying the percentage (i.e. standardised) *RMSE* (Diggle 1977), written $\sqrt{\left(\frac{\hat{\gamma}(S_1)-\lambda(S_1)}{\lambda(S_1)}\right)^2 + \left(\frac{\hat{\gamma}(S_2)-\lambda(S_2)}{\lambda(S_2)}\right)^2}$, where $\lambda(S_1)$ and $\lambda(S_2)$ are the true (enumerated) population numbers at the two study sites and $\hat{\gamma}$ (using either γ^{*-1} or *E**) is the PNN-estimated density at each site.

2.2.4. Bootstrap Confidence Ranges

To generate confidence ranges for probable estimates of abalone density under the observed PNN data sets at the two sites, we used a standard bootstrap, resampling with replacement from the sets of x and y distance measurements.

For y^5, where field sampling was of every 5th tagged abalone, these y-distances (abalone-to-abalone) were sampled independently of the x- distances, so the bootstrap resamples for y were resampled separately from the x's. For regular PNN, where y_i^g and x_i are a pair of distance measurements taken at the same sampled grid point, i, we randomly resampled only once for each grid point thus randomly selecting a single observed pair of (x_i, y_i^g) distance measurements.

Each bootstrap iteration used the resampled set of x- and y-distance values and generated a PNN estimate of mean density. At each study site, for both estimators, and for both y_i^g and y^5 inter-abalone distance data sets, 3000 bootstrap replicates were run. The resulting distributions of bootstrap estimates of mean density were plotted as kernel density curves, visually illustrating the estimated probable range for abalone density given the observed variability in the two data sets.

2.2.5. Simulations of Point-Nearest-Neighbour Sampling

Three plausible causes, three patterns of abalone clustering, were proposed for the underestimation bias observed in the field trials. To test these three hypotheses, computer simulations of point-nearest-neighbour sampling were constructed. Each spatial point pattern of abalone was investigated for bias under PNN by comparing the PNN-simulation-estimated value for density with the true (known simulated) value.

We first examined complete spatial randomness (no clustering) to serve as a baseline for comparison. Three clustering patterns were tested. (1) We first tested PNN with uniformly distributed circular clustered populations. In each scenario tested, we fixed (controlled for) the number of abalone within each cluster and the radius of cluster size around randomly chosen points at the centre of each cluster. The simulated abalone were distributed uniformly inside each circle so designated. Holding the total number of abalone in the study region fixed at 270, we inversely varied the number of abalone per cluster and number of clusters. Clustering scenarios simulated were 135 clusters of 2 abalone per cluster, 90 clusters of 3 per cluster, etc., up to 3 clusters of 90 abalone. (2) Second, we added loners or individual abalone to the otherwise uniformly clustered populations. (3) Third, we removed the loners, and modified the distributions of simulated abalone within each cluster to be bivariate normal rather than uniform. To compare uniform with normal clusters, given that 95% of the abalone around the bivariate normal cluster centre will lie inside a circle of radius twice times the standard deviation, we choose normal cluster standard deviations for testing which are half those of the radii tested for uniform circular clusters. Programming was done in S-PLUS using S+SpatialStats v. 1.5.

The procedure in each iteration of simulated PNN sampling was as follows: A bounded study region of 15 m x 18 m, inside which abalone density was to be estimated, was defined inside an overall simulated population area of 21 m x 24 m. Cluster centres were placed randomly inside the population area and individual abalone were distributed around each cluster centre until the ‘true’ simulated number of 270 abalone inside the study region was reached. This assured a simulated density of exactly 1.0 abalone m^{-2} inside the study region. Second, 25 simulated PNN sample points ($n_x = n_y = 25$) were randomly selected without replacement from the 1-m grid, excluding the outer boundary. Distances to the nearest-neighbour abalone from each selected grid point were calculated. Third, a random sample of 25 abalone were selected and distances to their nearest neighbours, which could be abalone outside the study region, were calculated. Fourth, simulated PNN density estimates were obtained from resampled distance data sets using both estimators, γ^{*-1} and E^*.

Mean densities from 200 simulated PNN iterations were calculated for each scenario and these were compared with the true simulation density of 1.0 abalone m^{-2} to assess the evidence for bias.

2.3. Results

2.3.1. Field Measurement

At S1, 210 abalone were enumerated yielding a mean density of 1.25 abalone per m^2. At S2, with 294 abalone enumerated, the mean density was 0.62 abalone per m^2.

At S2, where every abalone was tagged, the number of abalone in each 1-m^2 quadrat was recorded (Figure 2.1). This map of the distribution of abalone across the smaller study region shows clear evidence of a non-random distribution, including clustering. Abalone tended to aggregate at the base of low limestone ledges that crossed from diagonally from left to right.

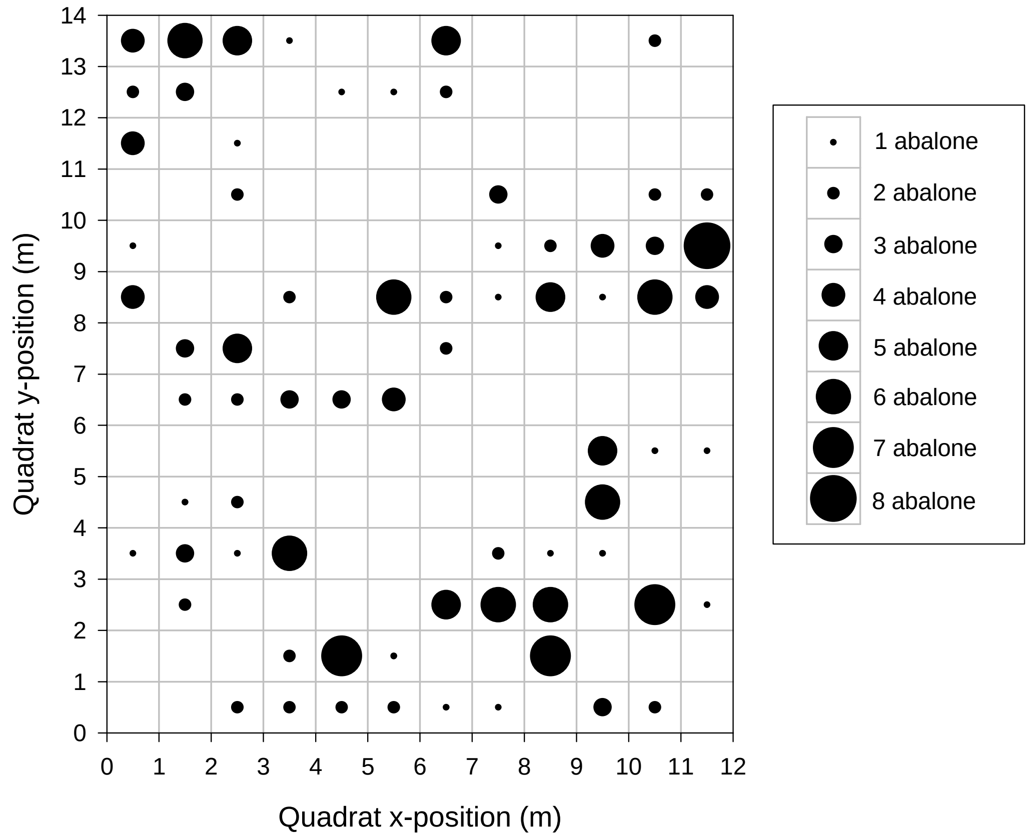

Figure 2.1. Bubbleplot showing number of abalone found in each 1-m^2 quadrat of study region S2.

At site S1, 88% of clusters (i.e. 1-m^2 areas) in which abalone were tagged contained less than 5 abalone, compared to 71% of clusters at S2 (Figure 2.2). However, at S1 larger cluster sizes were evident, with up to 20 abalone found in a single 1-m^2 area, compared to a maximum of 11 in a 1-m^2 quadrat at S2.

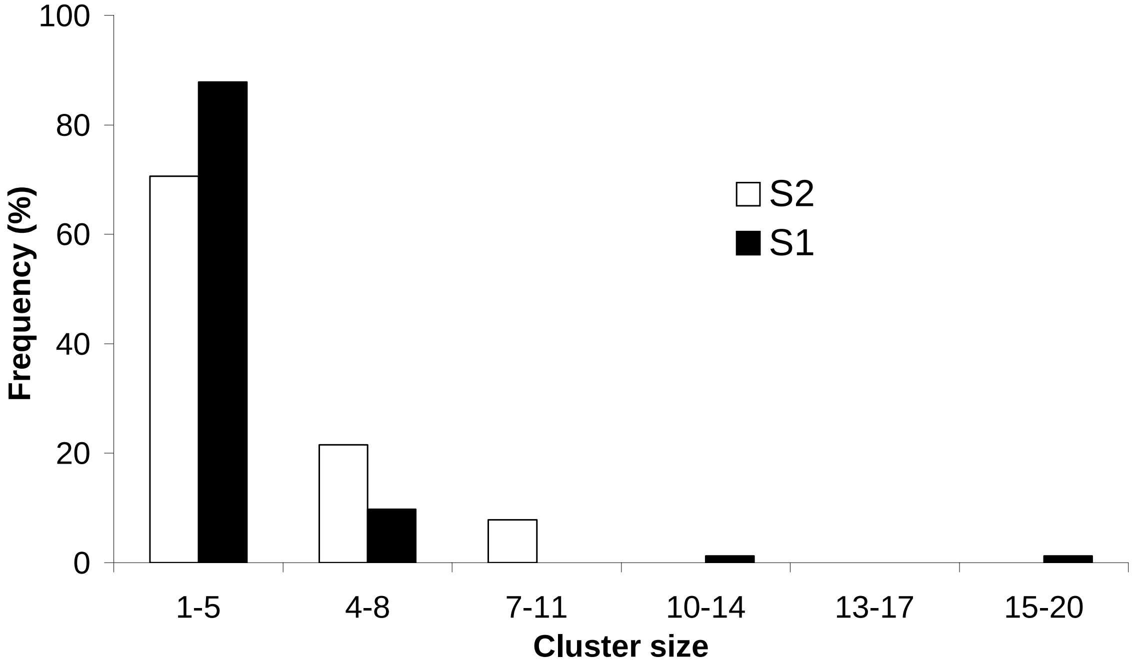

Figure 2.2. Percentage frequency of cluster sizes (±2), quantified as numbers of tagged abalone within 1-m^2 quadrat areas at sites S1 and S2.

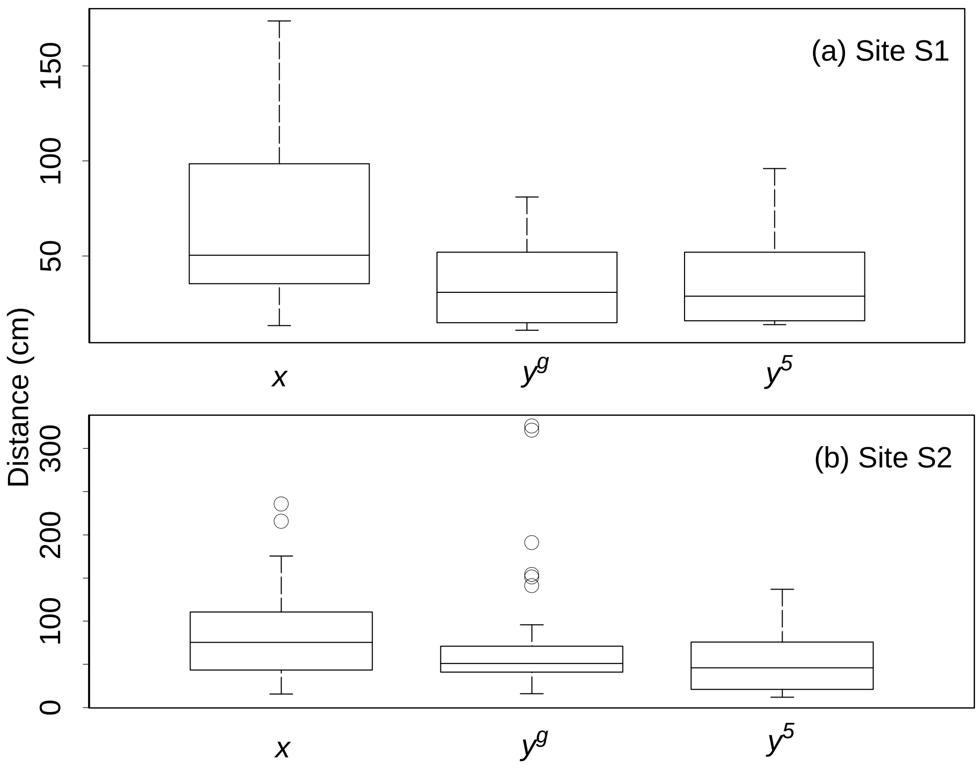

Figure 2.3. Boxplots of measured distances at the two study sites: x = distances from grid points to nearest abalone; y^g = distances to their nearest neighbours from abalone that lie nearest sampled grid points, and y^5 = distances from every 5th tagged abalone to their nearest neighbours.

Loners at site S2, shown as circle outliers, are evident in Figure 2.3. No outlier distance measurements were observed at S1 (Figure 2.3a). At S2, two outliers of long distance between grid points and abalone were observed (x circle markers in Figure 2.3b), and six high-distance measurements between PNN-sampled abalone (circle outliers above y^g in Figure 2.3b) and their nearest neighbours. Thus, at S2, the nearest abalone were sometimes farther than the distance to the randomly selected grid point, indicating that they were loners.

2.3.2. *Tests for Clustering*

The Hopkins tests confirmed that the abalone distributions were clustered at both study sites. At S1, the Hopkins test gave a value of H_F = 3.69; under the $F_{50,46}$ test, the assumption of complete spatial randomness is therefore rejected with α = 0.00001 > Pr($F_{50,46}$ > 3.69) probability. Because the abalone-to-abalone distances must be independent of the point-abalone distances, only y^5-values were used in the Hopkins tests. At study site S2, a Hopkins statistic of H_F = 2.28 implied less strong evidence of clustering, with Pr($F_{60,44}$ > 2.28) = 0.002. At S2, divers reported more medium-sized clusters but also a significant number of loners, the latter acting strongly to reduce the Hopkins statistic.

2.3.3. *Estimation of Abalone Density*

The point-nearest-neighbour estimates at both sites underestimated the true density (Table 2.2). The PNN estimates were lower than the true enumerated densities for all 8 combinations of estimator (γ^{*-1} and E*), abalone-to-abalone data set (y^g and y^5) and site (S1 or S2). Underestimation bias was greater at the S2 site, varying from 18% to 55%, while at S1, PNN estimates were about 18%-29% lower than the true value.

Table 2.2. True enumerated population density (abalone per m^2) inside the two field study regions, and PNN estimates of density using estimators of Diggle (1975) and Byth (1982), and using either y^g or y^5 inter-abalone distance samples. Also shown in parentheses are the percentage biases, (estimated–true)/true*100.

Method	Population density		Standardised RMSE
	Site S1	Site S2	
True abalone population density (by complete enumeration)	1.25	0.62	
<u>PNN Method</u>			
Diggle γ^{*-1} estimator			
using y^g	0.95 (-24%)	0.28 (-55%)	51%
using y^5	0.89 (-29%)	0.45 (-27%)	39%
Byth E*estimator			
using y^g	1.02 (-18%)	0.35 (-44%)	40%
using y^5	0.97 (-22%)	0.51 (-18%)	29%

The E^* estimator of Byth (1982) performed better than the γ^{*-1} estimator of Diggle (1977) for all 4 pairs of estimates, underestimating by less and thus yielding a smaller standardised RMSE for all comparable combinations of site and *y*-data set. The largest underestimates were observed at site S2 using the y^g inter-abalone distances (Table 2.2). Figure 2.3b suggested that loners selected under the PNN protocol (rather than having been randomly chosen—outliers were not observed above y^5 in Figure 2.3b), gave rise to inter-abalone distances larger than the average in the S2 study region, in turn causing much larger density underestimation when the PNN y^g-distances rather than randomly sampled (y^5) inter-abalone distances were used.

2.3.4. Bootstrap Confidence Ranges

The right-skewed shape of all four bootstrap distributions (Figure 2.4) reflects the lognormal-like tendency to extend probable density estimates upward, thereby tending to reduce underestimation bias. Accordingly, both Byth and Diggle estimators gave bootstrap density means that were about 0.04 abalone m^{-2} higher than the estimated (raw data) PNN estimates.

At site S2, the y^5 inter-abalone distances gave much better estimates than y^g, for both Diggle and Byth estimators. This was not observed at S1.

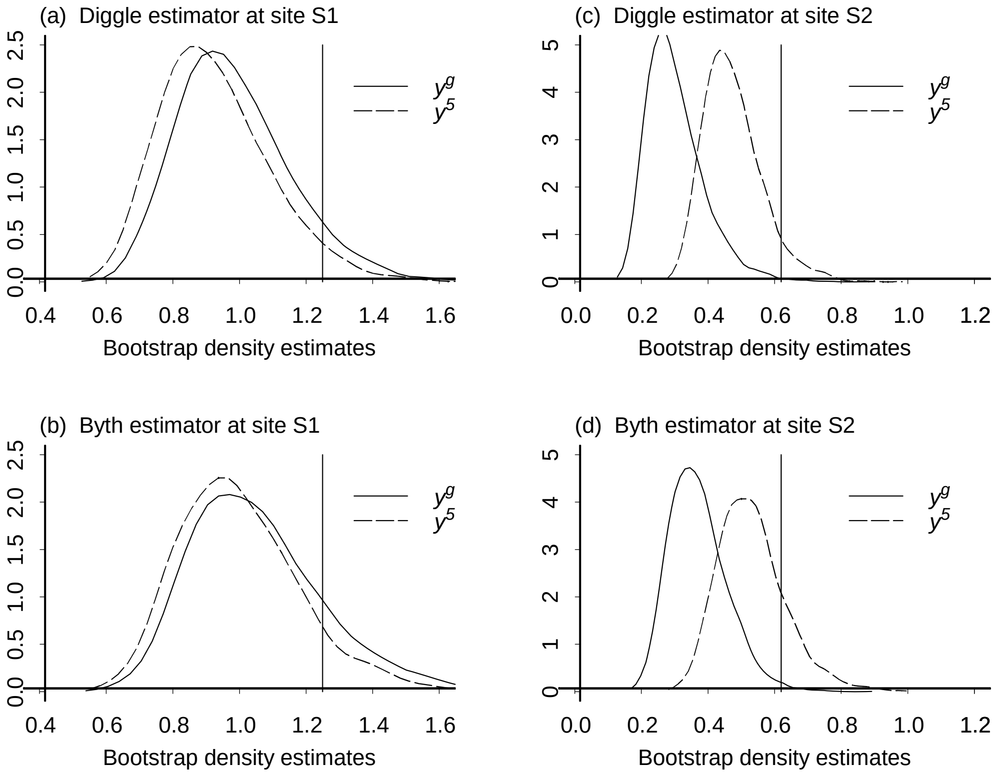

Figure 2.4. Distributions of estimated mean densities from 3000 bootstrap resamples. These kernel density plots of PNN bootstrap estimates are shown for eight cases: Diggle and Byth PNN estimators, at both sites, and using both inter-abalone distance data sets, namely y^g and y^5. Vertical lines show the true (enumerated) density in each study region.

The superior performance of the y^5 data set at site S2 reflects a known drawback of the basic PNN sampling protocol, namely that even applied to completely random distributions, a density-underestimation bias is induced in the PNN estimates obtained using y^g distances (Besag and Gleaves 1973). Inside the circle of radius x_i around each grid point, i, no abalone will be found, because, by definition, x_i is the distance from the grid point to the nearest abalone. Thus, the overall density in the immediate neighbourhood of the nearest abalone to a random grid point will be lower, on average, than around a randomly chosen abalone because in the portion of this neighbourhood that lies towards the grid point, there are no abalone neighbours. For this reason, in the simulations to follow, we used only the random sample of inter-abalone distances, i.e. used only y^5 and not y^g.

2.3.5. Simulations of Point-Nearest-Neighbour Sampling

Simulations were undertaken to assess the impact of clustering on the accuracy of PNN density estimates. Simulated populations of clustered abalone locations were generated, and random abalone distances were measured to simulate PNN survey sampling. Three forms of spatial clustering were examined, (1) uniform circular clusters, (2) uniform circular clusters interspersed with random loners, and (3) circular bivariate normally-distributed rather than uniformly distributed abalone within each cluster. All simulated populations had a true mean density of 1.0 abalone m^{-2}, shown as a dotted line in simulation output graphs of estimated density (Figures 2.5-2.7).

2.3.5.1. Uniform Circular Clustering

The simulation outcome for uniform circular abalone clusters (Figure 2.5) shows that clustering can result in both overestimation and underestimation, depending on the radius of the cluster. Most tested combinations of cluster radius and number of abalone per cluster show relatively high levels of bias, overestimating or underestimating true abalone density. Unbiased estimates were only obtained for small numbers of (2-3) abalone in each cluster, when cluster radius is 1 or 2 m.

PNN substantially overestimated density when cluster radius was 0.5 m and 0.33 m (Figure 2.5). This outcome was consistent for both Byth and Diggle estimators. We are not aware of previous work finding overestimation bias as a potential outcome of PNN estimators in density in clustered populations.

For larger simulated clusters (radius 1.0 m or 2.0 m), density was underestimated (Figure 2.5). However, at smaller cluster sizes (≤9 abalone per cluster), the bias is relatively small. Above 9 abalone per cluster, the underestimation bias was worse for larger clusters of 2 m radius than for those of 1 m.

For all simulations, the Diggle estimator yielded lower values than Byth. With underestimation being more common, both in our simulations and field trials above and in the literature, Byth has generally yielded estimates closer to true than Diggle. However, for the case of uniform clusters of radius 0.33 and 0.5, where both estimators overestimate the true density, Byth is more overestimation biased.

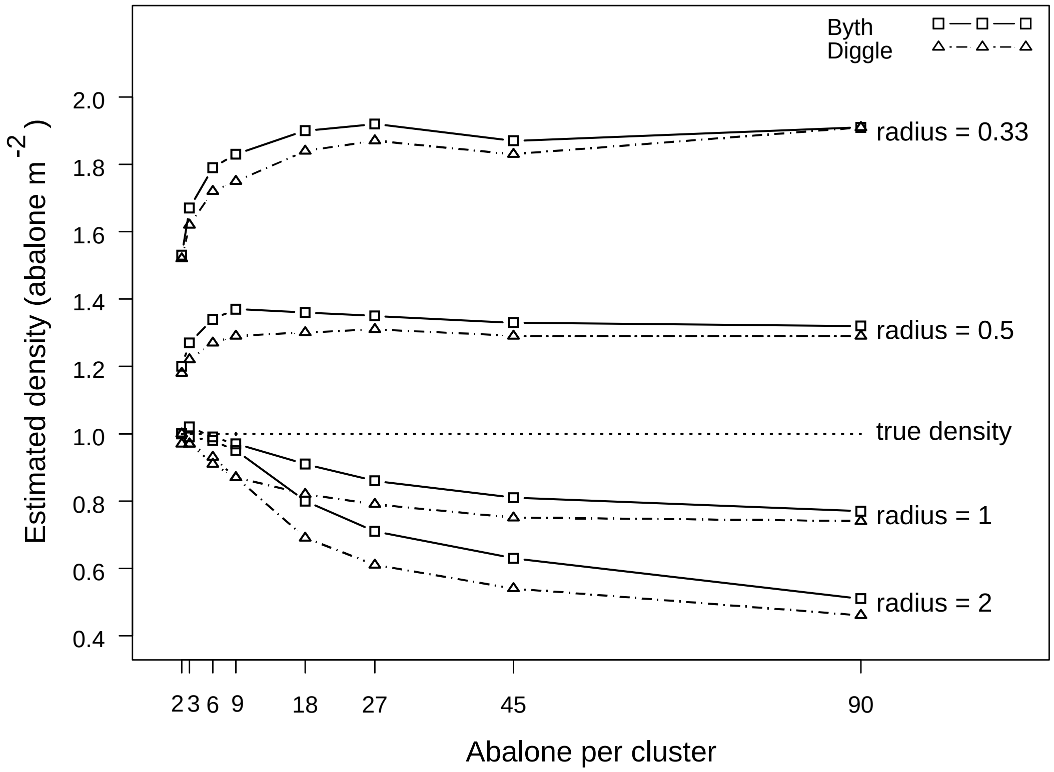

Figure 2.5. Estimates of abalone density using PNN for simulated populations of circular uniformly distributed abalone clusters of radii (in m) shown. True density for all simulated populations was 1.0 abalone per m^{-2}. PNN estimators of Byth and Diggle were used.

2.3.5.2. Loners

The second set of simulations investigated the effect of adding interspersed individual abalone among uniform circular clusters (Figure 2.6). As the number of loners in the study region rose from 0 to 25, thus 0% to nearly 10% of total population size, the levels of underestimation bias in abalone density was noticeably reduced for clusters of 27 or more abalone. This is consistent with the result (Byth 1982; Diggle 1977) that for complete spatially random populations, PNN does provide a largely unbiased estimator. We presented only the Byth estimator outcomes in Figures 2.6 and 2.7 for clarity.

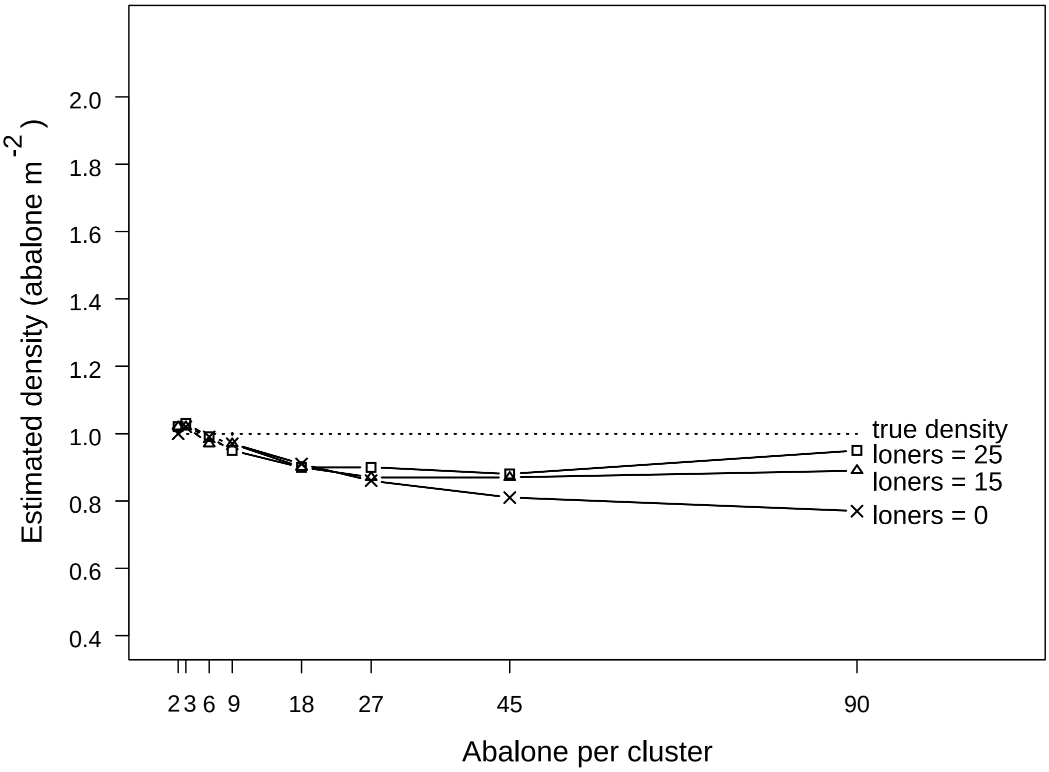

Figure 2.6. PNN-simulation density estimates for ‘loners’, that is individual abalone randomly interspersed among circular uniform abalone clusters. The number of loners in each population tested is indicated, while keeping the total simulated population fixed at 270 abalone. In other respects, this is the uniform circular case of radius = 1.0, using only the Byth estimator in this figure. The loners = 0 plot, identical to that shown for uniform clusters of radius = 1.0 (Byth) in Figure 2.5, is shown for comparison.

2.3.5.3. Normally Distributed Clusters

Abalone density was also overestimated or underestimated when abalone were normally distributed. The pattern of overestimation bias for very tight clusters, observed for uniform circular abalone clusters (radius = 0.33 and radius = 0.5 in Figures 2.5 and 2.7), was repeated for bivariate normally distributed clusters of similar cluster diameter (sd = 0.165 and sd = 0.25, Figure 2.7). The extent of overestimation was, however, considerably greater for uniform clusters with these radii (0.33 and 0.5 m), by comparison to the bivariate normal clusters with standard deviations of half their radius (Figure 2.7). Changing the simulated distribution of abalone around tight clusters from uniform to bivariate normal thus reduced the extent by which density was overestimated.

For less tight clusters (radius = 1 and sd = 0.5, Figure 2.7), both uniform and normal clusters resulted in underestimation rather than overestimation of abalone density. Normally distributed abalone clusters resulted in lower estimates of density, and thus greater (underestimation) bias than uniformly distributed clusters.

The widest clusters tested of radius = 2 m and sd = 1 m (Figure 2.7) showed nearly identical outcomes for normally and uniformly clustered abalone populations. However, overall, these widest-diameter clusters resulted in the greater underestimation bias, notably for large clusters of 18 or more abalone per cluster.

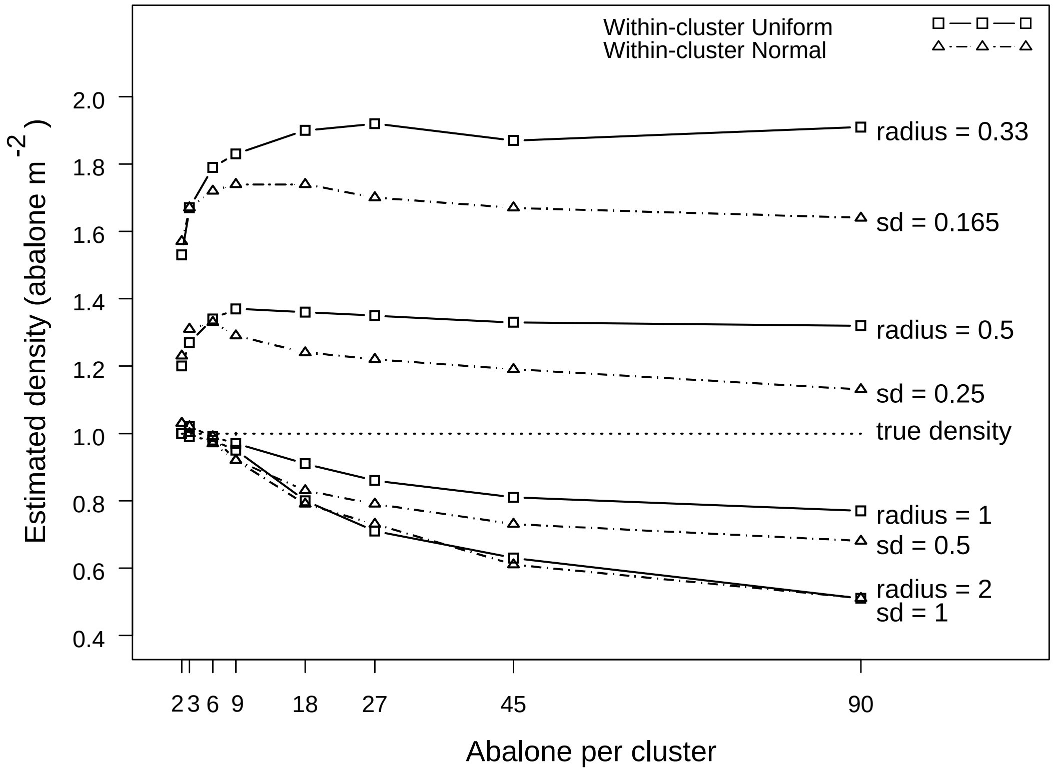

Figure 2.7. PNN-simulation density estimates for normally-distributed clusters. The four comparable plots from uniform circular clusters (radius = 0.33, 0.5, 1.0 and 2.0 m, also presented in Figure 2.5) are shown along with the plots for normally-distributed clusters with standard deviations (sd) of half the same size, 0.165, 0.25, 0.5 and 1 m. Byth estimator results only are shown.

2.4. Discussion

Thus, a wide range of simulated and observed patterns of spatial clustering in abalone populations induce bias in estimates of density based on the distances between abalone and random points and between abalone and nearest neighbours. Because the spatial distributions of real populations of marine invertebrates (and of most biological organisms) are rarely random and are usually clustered, estimates of density based on distance methods using PNN measurements will often be biased.

Two of the three spatial patterns of abalone distribution (uniform and bivariate normal clusters) that we simulated induced underestimation bias for patterns exhibiting the amount of aggregation present in the sampled abalone populations. Underestimates of abalone density were obtained for normally-distributed clusters, above about 3 abalone per cluster when the Diggle estimation formula was used, and above 6 abalone per cluster when the Byth estimator was used. Byth yielded less underestimation than Diggle for all cases simulated which showed underestimation bias. Byth (1982) showed that bias underestimation of these orders of magnitude (20-50%) was expected theoretically with compound Poisson processes. Such processes assume numbers per cluster to be Poisson, and the spatial distribution of clusters to also be Poisson. Here we fixed the number of abalone per cluster in each simulation case examined in order to control for that feature of clustering.

Our simulation results do not implicate loners as a potential source of bias. Rather, loners appear to ameliorate underestimation bias, presumably by yielding a spatial distribution of abalone which is more nearly uniformly random.

Unexpectedly, uniform circular clusters with very tight radii, of 0.33 m and 0.5 m, overestimated density substantially. Overestimation was observed in simulated populations of extremely high within-cluster density which are not typical of field populations of greenlip abalone. The field populations clumped along limestone ridges, showing more complex clustering patterns than the radially symmetric clusters we simulated, but it was visually evident in Figure 2.1 that the approximation spread of these clusters was greater than or equal to 1 m, i.e. greater than one quadrat. Thus, underestimation, rather than overestimation, is generally expected in greenlip populations, based on these field and simulation outcomes.

The finding of large bias in the presence of clustering differs from the outcome observed by Officer et al. (2001b) in simulation studies. They reported roughly unbiased density estimates from PNN simulations run in a population of measured blacklip abalone locations. This difference apparently results from their choice of definition for the true density with which simulation PNN estimates were compared. A more likely choice of definition for the true simulation density of abalone would have taken the count of abalone and the surface area from within the same bounded region. When this latter definition for true density is employed, the result would be roughly consistent with what we have found here, namely underestimation by about 10-30%.

In field survey practice, it is rarely feasible to obtain a complete enumeration, as we have done in these two relatively small study regions and, therefore, a true random sample of nearest neighbour distances is not usually obtainable. This induces yet another source of underestimation bias which was evident in our field measurements of y^5 yielding better estimates than y^g at site S2. For this reason, Besag and Gleaves (1973) proposed the 'T-square' design modification that restricts the search for nearest neighbours to the half plane lying away from the grid point in order that the inter-abalone distances are not affected by this source of underestimation bias resulting from the known absence of abalone between the grid point and its nearest neighbour. In abalone surveys underwater, the additional step of somehow drawing the T-square line perpendicular to the line between the grid point and the nearest neighbour, to one side of which the search must be restricted, can be difficult or impossible, further adding to the impracticality of PNN for abalone survey.

In addition to significant underestimation bias in the presence of moderate clustering, the obstacles to practical implementation of point-nearest neighbour methods underwater are formidable. In separate trials of point-nearest neighbour in unmapped habitat at Avoid Bay, it took two divers 41 and 60 minutes respectively to find the nearest abalone to a drop point and also three successive nearest neighbours, where the distances apart ranged from 3 to 5 m. Thus, rarely more than one or two points can be searched and sampled in a single dive, limiting sample sizes to not more than 8 points searched in a day by each designated pair of abalone research divers using the point-nearest-neighbour method.

Given the two major drawbacks of PNN, bias and excessive search time, in future we will direct our search for new abalone survey methods to those that are, in theory at least, unbiased. Specifically, we examine a survey design where divers count abalone 1 m or less from 100-m transects along of leaded rope lines deployed from the boat at systematic locations inside bounded study regions. Because random or systematic transects are never biased, this provides the opportunity of an unbiased survey design for estimating absolute abalone density in fishery-independent diver surveys.

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CHAPTER 3. Experimental Surveys at Taylor Island: the Leaded-Line Transect Method

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3.1. Introduction

Abalone stocks have collapsed in Canada, the USA, and Mexico and have exhibited a generally higher risk of stock collapse than most marine organisms. In addition, diver harvest rates provide relatively little information about abundance, being highly depensatory (Dowling et al. 2004a; 2004b). Thus abalone is a resource for which the sustainability risks are high but where commercial catch rates are the least informative for stock assessment. Fishery-independent diver surveys therefore provide an important and, frequently, the principal means of monitoring resource status globally.

Currently, the fishery-independent survey designs employed in three countries where abalone fisheries remain, Australia (Shepherd et al. 1985; Gorfine et al. 1997; Hart et al. 1997), New Zealand (Andrew et al. 2000), and South Africa (Tarr et al. 2000), have sought only a relative measure of stock abundance. The reason for this is the highly spatially variable distribution of abalone. Abalone habitat is itself complex, and within that habitat abalone cluster. Thus, it was thought that the sample variances would be unusably wide if these surveys were designed to achieve the more ambitious objective of measuring absolute density.

In this chapter, we present a transect method for measuring absolute abalone density (in numbers per m^2). Trials of this diver survey design for greenlip abalone (*Haliotis laevigata*) undertaken off Taylor Island are reported in this chapter. In Chapter 7 we report on a fish-down experimental test of this method.
In Chapter 2, the first candidate method of abalone survey design tested in this FRDC project, point-nearest neighbour, was found to be highly biased, underestimating greenlip abalone density by 20-40% in the presence of clustering. Most or all abalone populations are clustered to varying degrees. Such a high level of bias in estimates of density means that point-nearest neighbour-distance methods are not suitable for abalone survey. Moreover, field trials of point-nearest-neighbour in relatively dense algae showed that searching a circular area of undetermined size was not feasible, requiring too much time underwater. Therefore, being biased and unfeasible, the point-nearest neighbour distance method for measuring abalone density was rejected and will not be considered further in this report.

The advantages of an unbiased survey estimator are numerous but two features predominate: (1) With unbiased estimators, larger sample sizes will always improve mean closeness of the estimate to true abalone density, and (2) unbiased estimates imply unbiased estimates of confidence interval. Thus, confidence intervals can be estimated that will include the true value to any user-chosen significance, e.g. 95%.

In this chapter, we (i) present the methods and results of the first field tests, at the Taylor Island study region, of the two remaining abalone diver survey designs: (i) timed-swims, which have been used for South Australian greenlip abalone assessment to date, and (ii) a transect-based method developed in this project wherein the search area is designated by a weighted rope deployed from the boat onto the bottom. We refer to it henceforth as the ‘leaded-line (LL) method’. Briefly, pairs of divers search on either side of the leaded rope line, and count abalone lying within 1 m from the line.

All transect (or quadrat) methods are in principal unbiased, being direct diver count measures of density at a representative sample of locations. Being unbiased is a principal reason why transects were chosen as the basis of this leaded-line survey design.

Currently, abalone survey protocols in Australia and New Zealand do not designate a bounded survey study region inside which estimates of abundance are sought. However, absolute abalone density has no fixed meaning except inside a specific bounded study region. With high spatial variability typical of abalone, if this boundary were to change or simply remain undetermined, so also would the estimate of abalone density. Under the leaded-line abalone survey design, a study region boundary will always be drawn and mapped using a GIS package.

Transect samples can be allocated to systematic or random locations. We have chosen to locate leaded-lines systematically, meaning transects are spread evenly (i.e. uniformly) across each study region or survey stratum. In this way, an unbiased estimate of absolute abalone density can be attained. The advantages of a systematic over a random allocation include (1) higher precision by obtaining a more spatially representative coverage of the population inside the study region, and (2) better data input for spatial analysis, such as kriging, by yielding as survey output, an approximately uniform grid of point samples of abalone density across space.

A principal advantage of a leaded rope line on the bottom for designating the transect area is that it affords divers no choice about where to search in their count of abalone. This reduces a major potential source of bias, wherein divers may subconsciously stray towards areas of higher density, or of random variation due to uncertainty about how wide an area was covered, and with timed swims, in the length of area searched. By laying a line prior to divers entering the water, diver-choice bias and uncertainty about the area searched is effectively alleviated.

In this chapter, we also (ii) estimate the proportion of abalone which are of legal size, and statistically test for whether the levels of variation in proportion level exceed expectation based on a random distribution of abalone by size, (iii) stratify the Taylor Island survey region, notably for use in analysing the leaded-line density estimate, and (iv) summarise the current South Australian timed-swim method for estimating mean abalone density, (v) examine within-versus-between leaded-line variation in abalone density, (vi) plot estimated absolute abalone population numbers versus length, and (vii) assess the statistical power of two alternative abalone density estimators based on delta and negative binomial distributions.

The (1) leaded-line survey sampling protocol, and statistical methods of survey data analysis, for (2) leaded lines and (3) timed swims are included in three appendices. A ratio estimate was used to quantify a lower bound for the standard error of the timed swim density estimate; and for a standard error of the estimated proportion of legal-size abalone. Confidence intervals for the leaded-line survey measure of abalone density are obtained using a 2-level bootstrap which mirrors the 2-level leaded-line sampling design.

The ability of both survey methods to estimate change in absolute legal population numbers in a commercial fish-down study region is presented in Chapter 7.

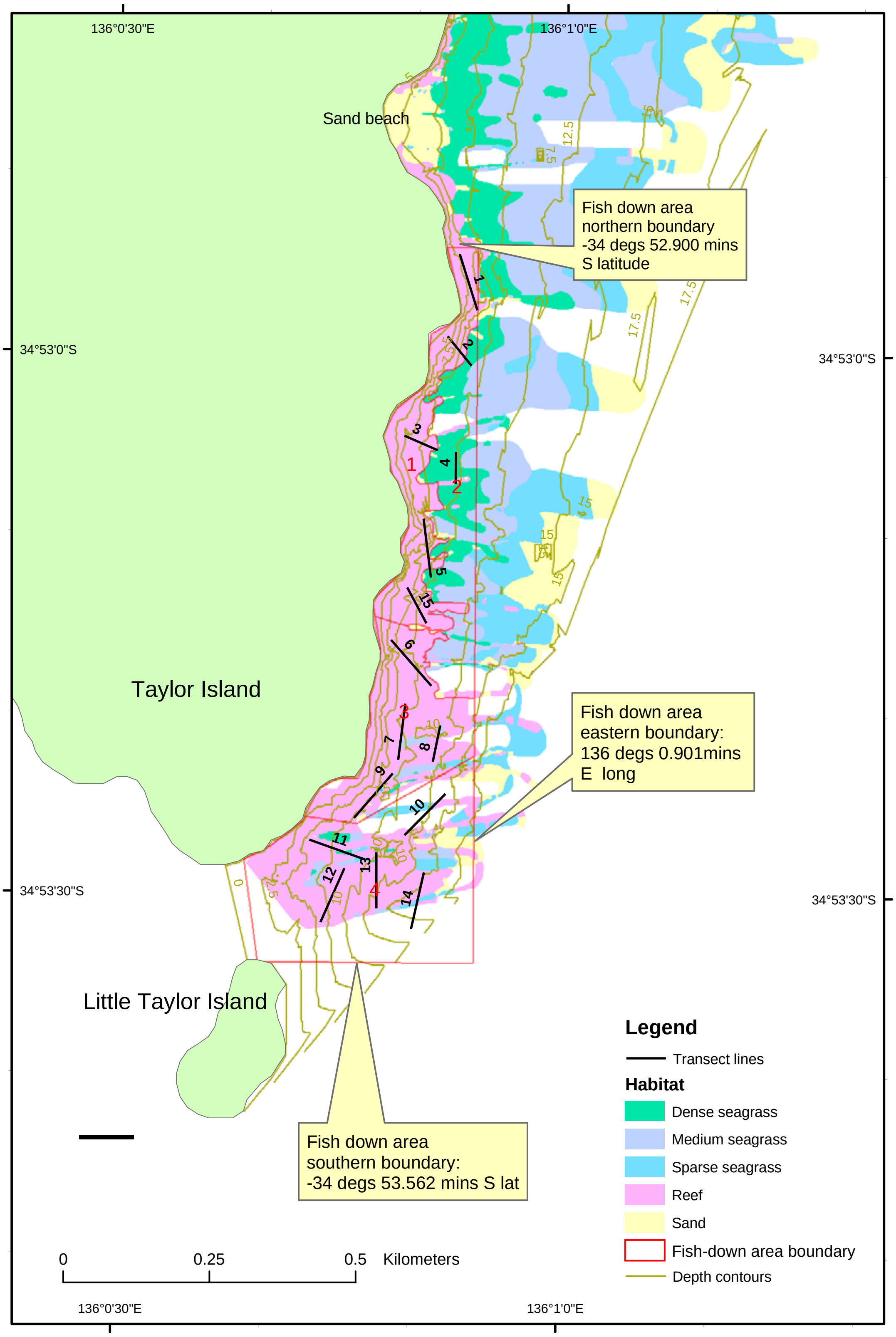

Figure 3.1. Map of study region boundary and transect locations (1-15) for the Taylor Island leaded-line surveys.

3.2. Methods

3.2.1. Study Site

An ArcView map of the Taylor Island habitat and depth contours (Figure 3.1.) was generated using boat-based sounder and video as described in Chapter 1. With advice from commercial and research divers, an area of fished abalone habitat along the south-eastern shore of Taylor Island (Figure 3.1) was selected as the study region for the Taylor Island fish-down experiment. While some fishing occurs north of the sand beach, this northern strip of abalone reef along the eastern shore is only a few metres wide and is thus inappropriate for intensive directed fishing like that of a fish-down experiment with up to 23 Western Zone commercial divers participating.

3.2.2. Leaded-Line (LL) Surveys

The surveys in the Taylor fish-down experiment were the first field trials of the leaded-line diver sampling protocol. In this section we describe the leaded-line method applied at Taylor Island. Details of the leaded-line survey sampling protocol are given in Appendix 3.1.

The locations of the 15 transects (Figure 3.1) were originally distributed systematically to uniformly cover two habitats of the study area, seagrass and reef. For the two leaded-line surveys (pre- and post-fish-down), a map (Figure 3.1) was provided to the research divers as a waterproof laminated sheet, with start and end GPS lat-long positions of all leaded-line transects included on the back. Only one transect was placed in seagrass where few or no abalone were anticipated. In addition, at the request of research divers, transects were shifted eastward out of the deeper water at the southern end of the study region and one of these (LL15, Figure 3.1) was moved up into the 'good bottom' in the central area of the study region. Because of these relocations of transects away from a systematic distribution, the survey study region was post-stratified, to avoid bias, specifically from having just one transect in the seagrass, and from having moved a transect (LL 15) up into the central area of presumed higher density.

Transects were of length both 60 m and 100 m. The standard leaded-line protocol uses only 100-m length transects. The transect length was varied, in the these first trials, because we did not know how long was practically feasible for divers using tank air. However, in the field, divers chose to shorten some 100-m transects to 60 m, and at one transect, divers did run out of air. It may have been that this choice by divers on the day of where to swim 60 m rather than a full 100 m was influenced by prior knowledge of where 'good bottom' was located. Therefore, if some transects were chosen to be 100 m because of presumed higher densities, (probably modest) overestimation bias would result if the longer transects were given proportionally higher weighting in the computed mean.

To obviate this second potential source of bias, in choice of transect distance swum, overall mean density was calculated using an unweighted mean across the set of 15 LL's. Thus, densities at each LL, within each stratum, were treated as independent equally-weighted repeated measures (regardless of transect length).

The two divers swam either side of the leaded-line. One diver recorded counts in every 2-m quadrat along the 1-m wide transect (to the right of the leaded line). Distance marks had been attached to the leaded-line rope every 2 m along its length. The other diver measured the length of every abalone within 1 m of the line. This protocol yields both (1) a length sample and (2) a 2-m spatially resolved measure of abalone density. In addition, a measure of absolute abalone density is obtained from both divers as the total count inside the specified transect search areas of 60 or 100 m^2.

The same set of leaded-line transect start and end coordinates were used for both pre- and post-fish-down surveys. In practice, however, the exact stretch of bottom covered by each physically deployed leaded line cannot be precisely controlled. Being laid out from a boat for each survey, the location of the leaded lines will vary with each deployment due to currents, GPS accuracy, etc., with an uncertainty of about ±5-15 m. Being only 2 m wide, the transect paths for surveys run before and after the fish down would often not overlap.

Details of the method for (1) estimating legal abalone density, (2) stratification, and (3) estimating confidence intervals for the estimate of legal density using the 2-level bootstrap developed in this project are given in Appendix 3.2.

3.2.3. Timed Swim

Timed-swim surveys followed the standard sampling protocol used by South Australian abalone researchers at Taylor Island in previous years. This protocol was first proposed by Shepherd (1985), though no method for estimating confidence interval for the estimate of density has previously been suggested.

Pairs of divers descend and swim in two successive timed swims of 10 minutes each, thus a total of 20 minutes per diver per dive. Divers begin their first 10-minute swim once the first abalone is encountered. They search an area of approximately one metre wide as they swim, actively seeking out higher-density habitat (Shepherd 1985). All counted abalone are measured for shell length using a ‘Shepherd gauge’ (Shepherd 1985).

Details of how these data are analysed, based on the method used to estimate the area covered by each 10-minute timed swim of Shepherd (1985), are presented in Appendix 3.3.

3.2.4. Proportion Legal

For analysis of fish-down results, we are interested mainly in the density of legally harvestable abalone (‘legals’), those whose shell length is greater than the minimum size limit for harvest. This is straightforward for the length-diver leaded line counts and the timed-swim counts which can be restricted to include only the legal-size abalone. However, for leaded-line estimates of legal density which use counts from both divers, notably including the 2-m count diver side for which separated counts of legal size abalone are not possible because lengths were not measured, the proportion legal, either for each leaded line, or overall, must first be estimated in order to estimate legal density.

The expected distribution of observations under the logical null hypothesis of random choice is given by a binomial probability density, like tossing a coin, since there are only two possible outcomes for each observation, namely the abalone is of legal or sublegal size. This null hypothesis assumes simple random sampling for each abalone, regardless of size. Thus, the null hypothesis predicts a standard error in proportion legal given by the binomial probability model. Specifically, given an observed proportion of legal-size abalone, call it

P_{leg}, the binomial standard error is estimated by $SE(P_{leg}) = \sqrt{P_{leg} \cdot (1 - P_{leg}) / n}$, where n is the number of abalone sampled. We tested the null hypothesis that proportion legal varies randomly among leaded-line and timed swim samples.

3.3. Results

3.3.1. Abalone Density

One of the principal obstacles to precisely estimating absolute density (as with all abalone and most fishery-independent surveys) is the high spatial variation, both between and within sample locations. It is therefore informative to quantify and compare within- and between-leaded-line variation in the observed measurements of abalone density.

3.3.1.1. Within-Leaded-Line Variance

Plots of the observed count densities from the two divers, searching either side of the rope, at each leaded line are shown in Figure 3.2.

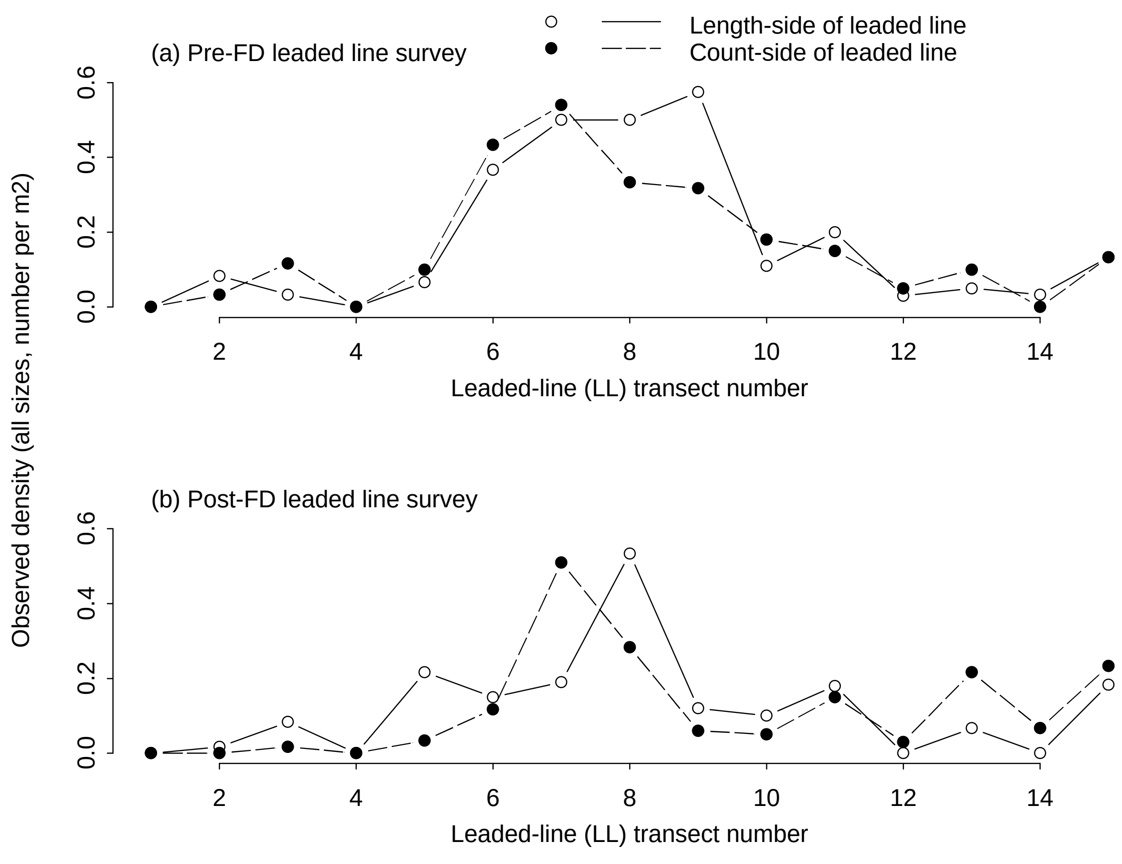

Figure 3.2. Abalone densities (all sizes) from the leaded-line survey diver counts that (a) preceded and (b) followed the fish-down harvesting in the Taylor Island study region. For each survey, 15 leaded line transects were each swum by 2 divers, one measuring lengths and the other recording 2-m quadrat counts.

The general agreement between counts from the two divers at each leaded-line location, shown in Figure 3.2, indicates the self-consistency, and thus quality of the information about abalone density at each sample location. If these two count densities had differed greatly at each leaded line, in other words if the extent of randomness in abalone density counts were high, even within each sample location, the levels of overall variation at each leaded line, and the associated confidence intervals could have potentially been unworkably wide. Thus, these plots give a preliminary qualitative test of the leaded-line survey method.

The plots from the two surveys at Taylor Island suggest that, overall, the two divers tended to get similar counts, i.e. within-leaded-line variation was not excessive. This is a positive outcome insofar as it suggests that a useful measure of density at each leaded-line location can be achieved.

The correlations of count-side versus length-side were both significant ($r = 0.91$, $p = 0.000004$ for the pre-fish-down survey, and $r = 0.59$, $p = 0.01$ for the post-fish-down survey). Thus it appears, based on the example of this first Taylor Island trial of the leaded line protocol, self-consistent measures of abalone density at each leaded line location can be obtained. Thus, the spatial trends in absolute density are self-consistent.

3.3.1.2. Between-Leaded-Line Variance

The mean densities at each leaded-line are shown in Figure 3.3. Averages of densities from the count and length divers (shown in Figure 3.2) were plotted for each leaded line location.

The low- or zero-density leaded lines showed consistently low levels for both pre- and post-fish-down surveys (Figure 3.3). Leaded lines 1 and 4 yielded zeros for both pre- and post-fish-down surveys. Similarly, at leaded-line locations (2, 3, 5, 10-15), diver-measured densities were consistently low for both pre-fish-down and post-fish-down surveys. For these low-density leaded-line locations, the post-fish-down densities were as often higher as lower than the pre-fish-down survey measure (Figure 3.3). These plausibly reflect low levels of fishing at these low-density areas, together with the higher relative uncertainty in the survey estimates that are obtained from low abalone counts of zero to a handful.

For the higher-density locations, a declining trend from before to after the fish down was evident (Figure 3.3). Densities were lower for 3 (LL6, LL7, LL9) and the same for 1 (LL8) of the 4 leaded-line locations (LL6-LL9) that showed relatively higher densities in the pre-fish-down survey (Figure 3.3). Generally lower observed densities following the commercial fish down at these 4 leaded line locations likely reflect fishing concentrated there. It is plausible or likely that fishers located these higher densities (in relatively shallow depths) and targeted them. Most of the overall decline in legal density (Figure 3.3) was observed at these sample locations.

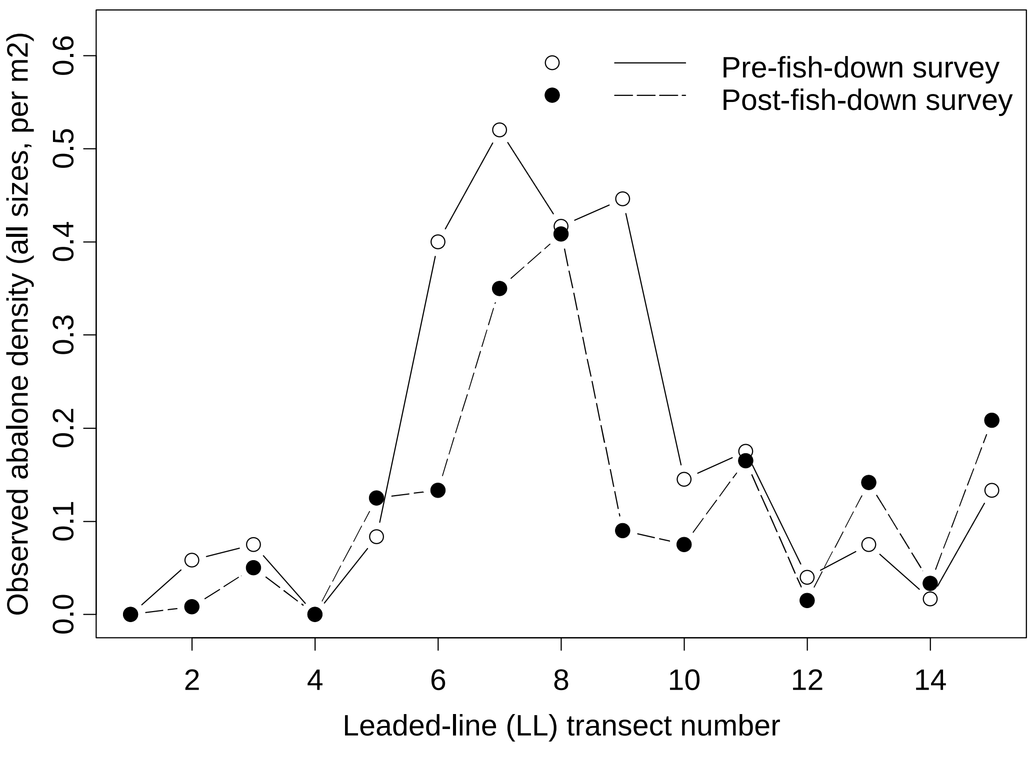

Figure 3.3. Observed densities, by leaded line surveys before and after the fish down, based on diver counts from both sides combined.

3.3.2. Proportion Legal

The proportion of measured abalone that were of legal size varied between surveys and between transects. Specifically, the observed measures of proportion legal varied more, both between surveys and among leaded lines within each survey, than a null-hypothesised binomial probability would have led us to expect. Results are summarised in Table 3.1.

Table 3.1. Proportions legal estimated from length samples by the two survey methods: leaded lines and timed swim.

	Leaded lines			Timed swims		
Survey	Proportion legal (from length sides)	Percent SE (as binomial error)	Percent change in proportion legal	Proportion legal	Percent SE (as binomial error)	Percent change in proportion legal
Pre-fish-down	0.61	3.4%	+16.8%	0.80	3.6%	+7.2%
Post-fish-down	0.71	3.9%		0.85	2.6%	

Both the direction and magnitude of the differences in proportion legal from before to after the fish-down removal of abalone differed from expectation. The direction of change was unexpected because the proportion of legal abalone increased for both timed swim and leaded lines despite the removal of only legal-size animals. Secondly, the extent of increase in proportion legal (17% for leaded lines and 7% for timed swim) is sufficiently greater than the estimated SE that it was unlikely to have occurred under the assumption that the sample of legals or sublegals is binomial and random. The binomial (null-hypothesis) estimated confidence intervals (as SE-CV) were 2.6-3.9%. Thus, the observed levels of variation in proportion legal are substantially greater than expected under a null hypothesis of binomial random variation.

Proportion legal and density are plotted for the 15 leaded-line locations (Figure 3.4). Proportion legal fluctuated substantially, varying from 0.4 to 1 (Figure 3.4a). The binomial SE’s for individual leaded-lines are also shown as error bars. Wide SE’s in proportion legal shown by wide error bars (pre-fish-down, LL numbers 1-5 and 10-15, Figure 3.4a) are expected for the low-count leaded lines, since these necessarily reflect low sample size. However, even for the higher-count leaded lines (pre-fish-down, LL numbers 6-9, Figure 3.4a), high variation in proportion legal is evident. Some error bars for high-density leaded lines do not overlap (e.g. LL7 and LL8), suggesting relatively high spatial variation in proportion legal in the pre-fish-down population. The declining trend from LL6 to LL9 (Figure 3.4a) in this stratum 3 (Figure 3.1) of high density corresponds to a spatial trend in proportion legal, declining north to south, from 0.86 to 0.41 over a distance of about 200 m.

In the post-fish-down survey, the error bars of LL’s 6-9 do overlap more, and appear to vary less (with the exception of LL6). The analysis of Figure 3.3 suggested that most fishing did occur in this stratum. Thus fishing appeared to moderate high variation in proportion legal.

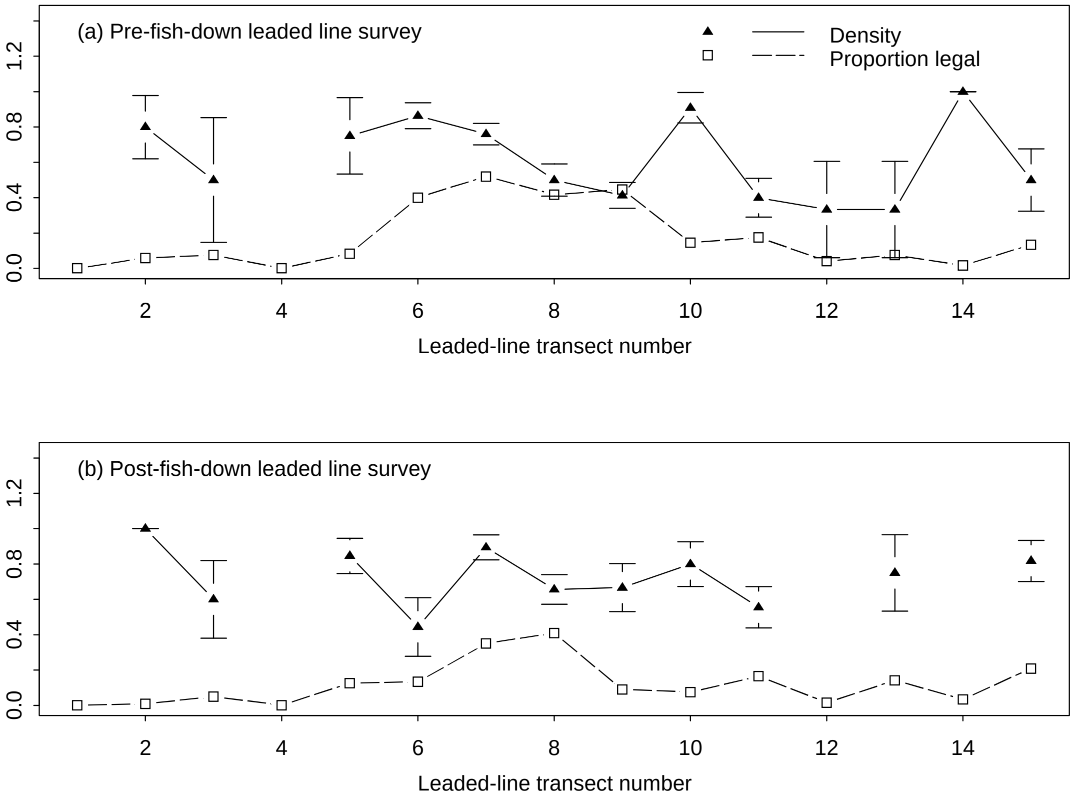

Figure 3.4. The proportion of legal-size abalone and abalone density (all sizes) versus leaded line number for (a) pre- and (b) post-fish-down leaded-line surveys at Taylor Island. The proportion legal measurements come only from the length-diver sides of each leaded line. Densities are those shown in Figure 3.3. Error bars on proportion legal are calculated as independent binomial samples at each leaded line.

Correlation between proportion legal and density can cause or enhance bias in estimates of legal density. Thus, this correlation should be statistically accounted for. The correlation coefficient (r) of proportion legal with (all-sizes) density was calculated considering each leaded line as an independent repeated sample unit. Leaded lines with zero counts were excluded, no meaningful proportion legal being definable. The results were $r = 0.0011$ for the pre-fish-down survey and $r = -0.042$ for the post-fish-down survey. Thus, statistically no correlation whatsoever was observed between density and proportion legal. This is visually evident comparing density and proportion legal in both graphs of Figure 3.4. For the timed swims, the correlation of density with proportion legal was also low, with $r = -0.173$ and $r = 0.134$ for the pre- and post-fish-down surveys respectively.

3.3.3. Length Frequencies

Length frequencies were obtained using both survey methods. For the leaded-line method, only the length diver measured abalone lengths. Higher proportions of legal abalone in the timed swim surveys (Table 3.1) were observed. This may be due to less time spent searching for smaller individuals in the timed swims, or reflect where timed swims were located.

The lines shown on the length-frequency graphs for the two leaded-line surveys (Figures 3.5. and 3.6) are kernel density curves, which are smoothed versions of the 5-mm binned histograms, also shown. The kernel density, programmed in SPlus, generates a length-frequency curve by assigning a normal distribution centred at each length sample point, and summing all these normal probability densities at designated points along the x-axis and connecting them. Thus, this smoothing method is model-free and avoids the jagged randomness typical of binning that characterises histograms, including those shown in Figure 3.5 and 3.6. The kernel-smoothed probability density will be used, rather than or together with binned histograms, when presenting length-frequency distributions in this report.

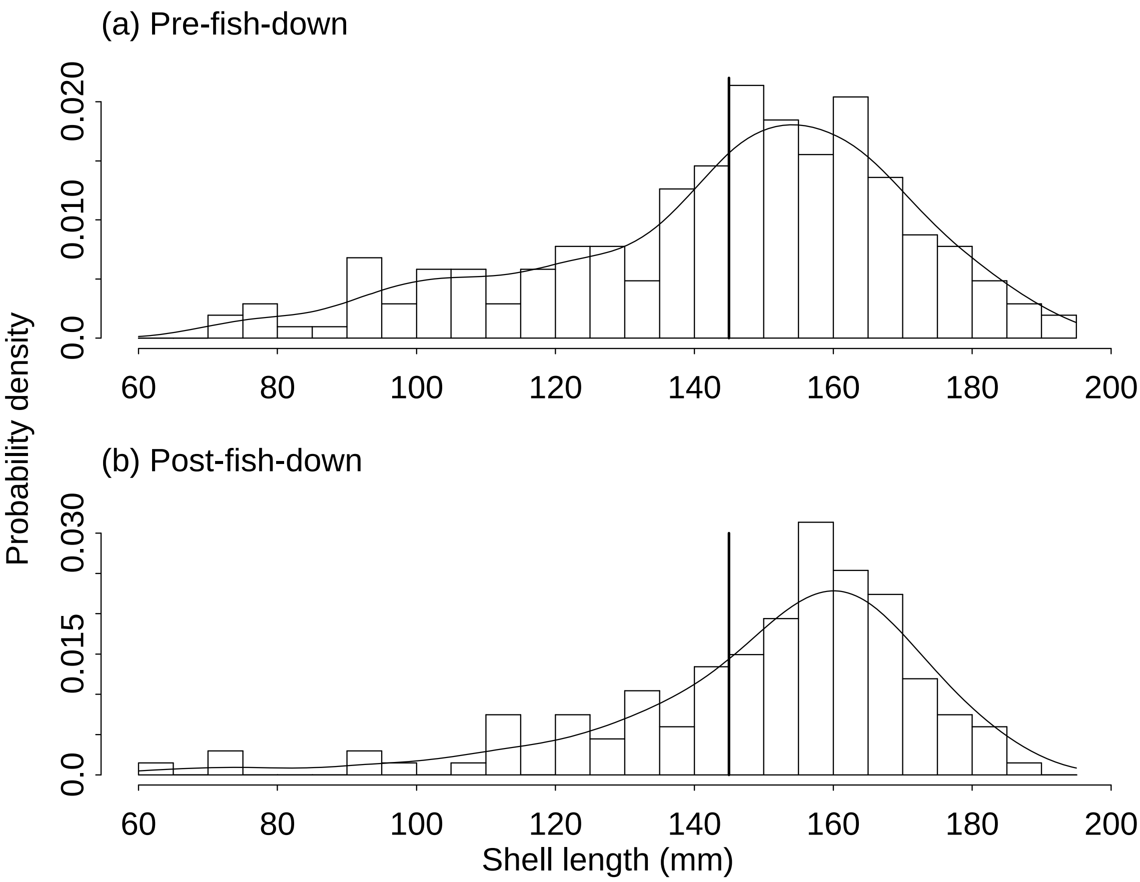

Figure 3.5. Leaded-line length frequencies. Both histogram (bars) and normal-smoothed kernel density (line) of the (a) pre-fish-down (n = 206), and (b) post-fish-down (n = 134) abalone shell lengths measured by the 'length-divers' on the 15 leaded-line transects. Legal minimum length (145 mm for greenlip in this Western management zone) is indicated by a vertical line. The y-axis is given as a probability density per 1 mm of abalone shell length.

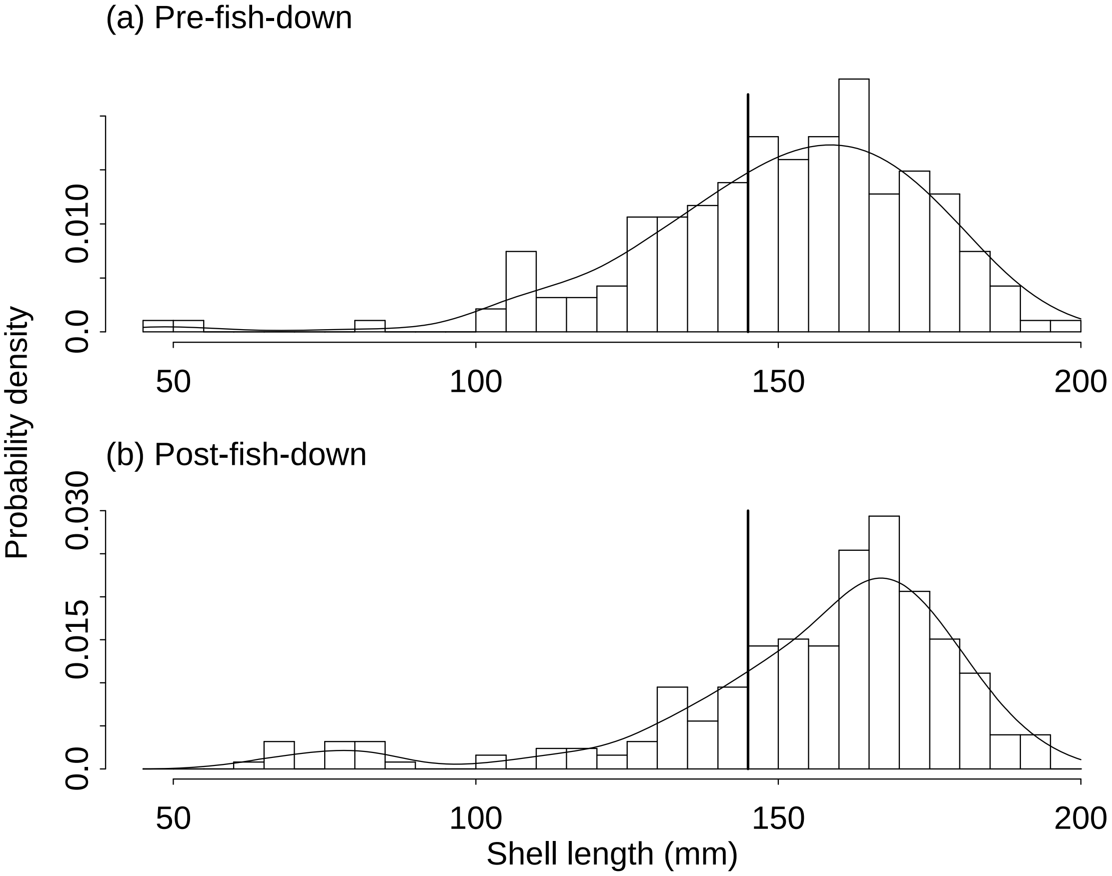

Figure 3.6. Timed-swim length frequencies. Both histogram (bars) and normal smoothed kernel density (line) of the (a) pre-fish-down (n = 200), and (b) post-fish-down (n = 264) abalone shell lengths measured by the timed-swim survey method. A vertical line marks the legal minimum length of 145 mm SL.

3.3.4. Legal Density: Overall

Stratification reduced the estimated overall mean density (Tables 3.2 and 3.3). Stratified means are more accurate because the bias induced by non-uniform (or non-random) placement of leaded-line transects in the study region was thereby reduced or eliminated. A lower overall mean density was expected because the overestimation that would have resulted from moving LL15 from low-density stratum 4 into high-density stratum 3 was obviated by stratification. Very small differences (< 1%) between bootstrap mean (Tables 3.2 and 3.3) and regular (Table 3.2) or stratified mean (Table 3.3) suggest that this bootstrap measure of bias is small. In addition to alleviating bias, stratification provided more precise estimates. The 2-level bootstrap-estimated standard errors on mean density were lower for the stratified than unstratified means (Tables 3.2 and 3.3).

Table 3.2. Leaded-line survey summary statistics: Density for legal-size abalone, unstratified.

Survey	Mean density	2-level bootstrap standard error	SE-CV (as SE over the mean)	Percentage change in mean density from pre- to post-fish-down	Bootstrap mean	Number of bootstrap replicates	Bootstrap measure of 'bias'
Pre-fish-down	0.104	0.029	27.4%	-18.6%	0.105	3000	-0.0086
Post-fish-down	0.085	0.022	26.0%		0.085	3000	0.006

Table 3.3. Leaded-line survey summary statistics: Stratified legal-size density.

Leaded-line survey	Stratified mean density	2-level stratified bootstrap standard error	SE-CV (from 2-level bootstrap)	Percent change in stratified mean density from pre- to post-fish-down	Bootstrap mean	Number of bootstrap replicates	Bootstrap measure of 'bias'
Pre-fish-down	0.081	0.009	11.7%	-17.3%	0.081	3000	0.0018
Post-fish-down	0.067	0.015	22.4%		0.068	3000	-0.0065

Table 3.4. Timed-swim survey summary statistics: Density of legal-size abalone.

Timed-swim survey	Mean density	Standard error	SE-CV	Percent change in mean density from pre- to post-fish-down	Correlation coefficient of density versus proportion legal
Pre-fish-down	0.119	0.011	9.3%	+51.2%	-0.173
Post-fish-down	0.180	0.022	12.4%		0.134

Timed swims showed generally similar standard errors around the estimate of mean legal density by the ratio estimator (0.011 and 0.022 m^{-2}, Table 3.4) to leaded lines (unstratified: 0.029 and 0.022 m^{-2}, Table 3.3; stratified: 0.009 and 0.015 m^{-2}, Table 3.3). This general range of estimated standard error was confirmed by a second statistical method implemented to compute standard error for a timed-swim, namely by a 2-level bootstrap (like that described above for leaded lines, but over the 2 timed-swim sites and 4 10-minute swims at each site). The results of the bootstrap standard error estimates for timed swim legal density (0.013 and 0.022 m^{-2}) were similar to those from the ratio estimator.

As noted above, a number of other additional sources of error that characterise timed-swim estimates, such as diver choice bias, variations in actual area searched, are differing abilities to detect abalone among divers, are not taken into account in these estimates of confidence range based on the ratio estimator and 2-level bootstrap.

While lower bound estimates of timed swim confidence interval are similar to those obtained from leaded-lines, there were large differences in the actual estimates of mean density. The timed-swim density estimate was 47% higher than the stratified leaded-line mean for the pre-fish down and 169% higher than stratified leaded-lines for the post-fish-down surveys.

3.3.5. *Legal Density: By Length*

The length samples (as probability density) were combined with estimates of absolute population size to generate length-frequency distributions of total population numbers by length. Because the numbers under the probability density length-frequency curves in Figures 3.5 and 3.6 sum to 1, total population numbers per mm of abalone length along the x-axis is given by the simple product of the length density curves of Figure 3.5 or 3.6 times the estimate of abalone population number in the Taylor Island study region. Therefore, for any given size range, total abalone numbers are given by the sum under the curve.The resulting length-frequency distributions of absolute population number, comparing before to after the fish-down, were graphed for leaded-line (Figure 3.7) and timed-swim (Figure 3.8) surveys. The leaded lines show a modest decline from before to after the fish down of 17% (Table 3.3), the same magnitude as the SE of these density estimates. The timed swims estimated a 51% increase in density from surveys swum before and after the fish down, evident in the length-frequency curves of Figure 3.8. A 50% rise far exceeds the timed-swim SE (Table 3.4), and therefore suggests inconsistency of the pre- to post-fish-down timed swim measures of abundance. The fish down removed only a small proportion of the total abalone at Taylor Island, around 5%. Detailed assessment of the outcome of the Taylor Island fish-down experiment for the two survey methods is presented in Chapter 7.

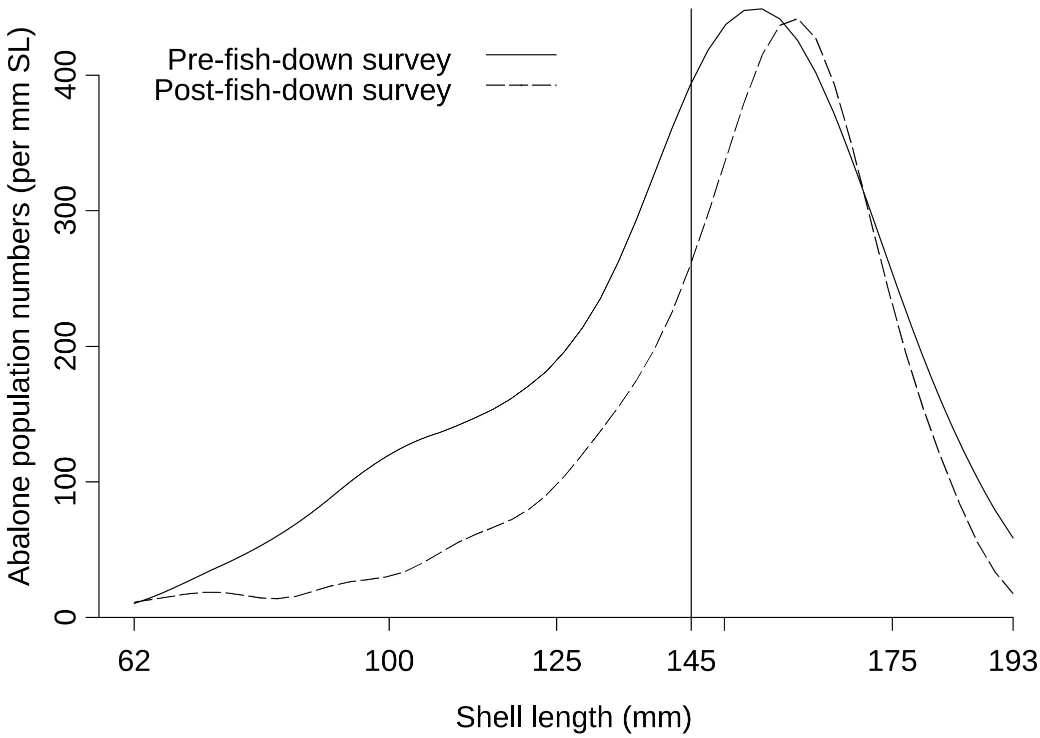

Figure 3.7. Leaded-line length frequencies from pre- and post-fish-down surveys. One of the two divers at each of the 15 leaded-line transects measured abalone lengths. Kernel-smoothed length-frequency densities only shown (i.e. in place of 5 mm histograms). The y-axis values have been rescaled such that the value plotted at each 1-mm SL interval in the two length-frequency plots is the leaded-line estimate of total abalone number inside the Taylor study region in each 1 mm abalone length interval.

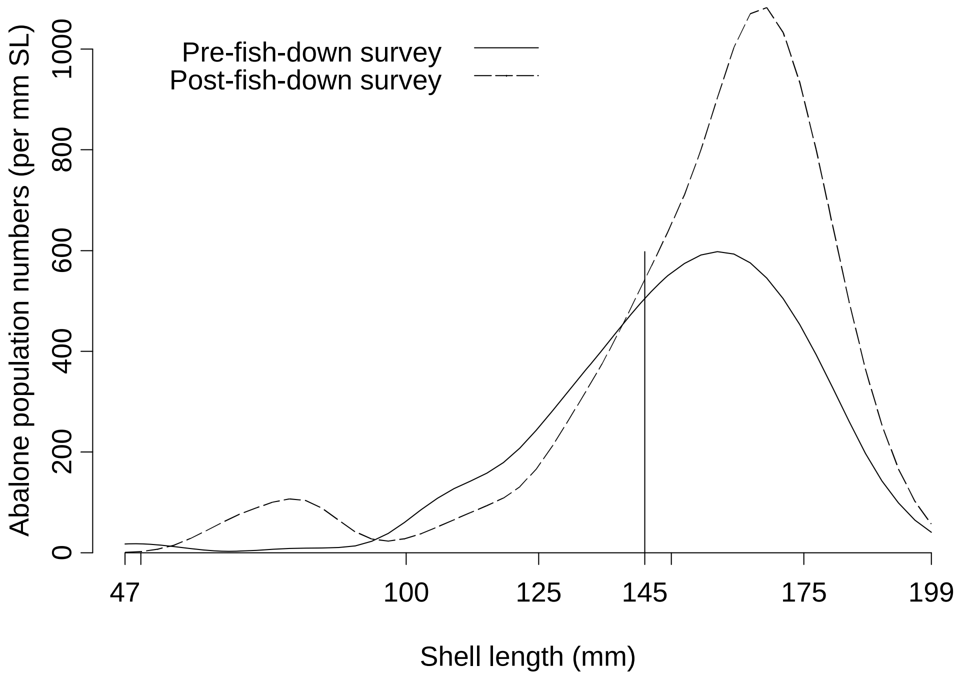

Figure 3.8. Timed-swim length frequencies from pre- and post-fish-down surveys. The y-axis has been rescaled by the measure of absolute density obtained from the timed swims, to yield a measure of absolute abalone number present in each 1-mm SL interval.

3.3.6. Evaluating Delta Distribution and Negative Binomial Estimators for Density

The estimates above used a standard sample (i.e. arithmetic) mean for calculating density from the survey counts. Two other estimators of mean density were examined and tested. These were an estimator based on a delta distribution of observed density values and a second assuming a negative binomial distribution. Both were plausible because the survey count data (1) are skewed to the right with a few scattered high counts that dominate the mean, and (2) contain zero counts. These two properties suggested the need to consider the explicit distribution of observed values in inferring mean density.

The result, however, was that the delta distribution (Pennington 1996), which is lognormal in conjunction with zeros, did not improve the precision. The calculated standard errors of mean density using the delta-distribution estimator (Pennington 1996) were, in fact, larger by 14% for the pre-fish-down counts and 40% higher for the post-fish-down counts than obtained from a density estimator based on the standard arithmetic mean. Moreover, the delta distribution may not be an appropriate description of the distribution of abalone counts insofar as very high values of 4-6 orders of magnitude greater than the lower non-zero values which describe the extreme levels of skewness for which the delta distribution has been shown to yield substantial improvements in precision (Pennington 1996) were not observed and would not likely be observed for abalone transect counts.

The negative binomial is, on the other hand, a very plausibly apt distribution for describing abalone counts. In particular, a negative binomial distribution is expected for counts from quadrats or transects where the mean density varies (as a gamma distribution) over the study region of interest. However, examination of the literature of estimators of mean density based on the negative binomial (Pennington, pers. comm; Johnson, Kotz and Kemp 1992, Chapter 5) shows that the maximum likelihood estimate of the mean is, in fact, identical to the standard arithmetic mean. Thus, in effect, we are already using a negative binomial estimator. Under a two-level bootstrap, the confidence intervals will therefore be identical. Thus, the estimated mean survey density of abalone, and its confidence interval, will be the same whether we use the arithmetic mean or a negative binomial maximum likelihood estimator.

There is a practical statistical programming advantage in using the arithmetic mean. An arithmetic mean is simple enough to be easily incorporated into the 2-level bootstrap algorithm. In that way it allows the estimation of confidence intervals for the multiple levels of sampling between and within leaded lines, and any other complications in the survey sampling protocol (e.g. the 4 timed swim counts) that need to be represented in the estimates of confidence range.

Thus, a standard arithmetic sample mean will be used for all survey density estimates in this report.

3.4. Discussion

3.4.1. Advantages of an Absolute Measure of Abalone Density

Previous Australasian survey designs have sought only relative measures of abalone abundance. The principal objective of the abalone survey design developed in this project was to obtain a measure of absolute abalone density (as numbers per m^2). Advantages of estimating absolute density are five-fold:

1. The ability to directly measure the total harvestable biomass, combining survey absolute numbers with length frequencies and length-weight in any given area, would add substantially to the power of advice provided to managers setting a yearly harvest quota (as absolute biomass, in kg). Total population size is obtained from the survey estimate of absolute abalone density by multiplying by the area (in m^2) of the survey study region. Study region area is calculated by GIS software packages, in which the study region boundaries would previously have been mapped. When survey measures of population number are combined with length-frequency data and with weight-length information, the total harvestable biomass inside any leaded-line survey study region can be estimated directly from survey, without need for model inference and the associated assumptions that models require. Knowing the harvestable abalone biomass leaves only the choice to managers of exploitation rate in order to set a harvest quota.

2. Absolute density is a measure that is independent of the survey method used. If, in future, improved methods to measure or calculate absolute density are developed, or if the survey design is improved or modified, the survey time series remains unbroken, even using new technologies, such as video. Survey protocols measuring relative abundance cannot be changed, because that would render subsequent survey time series inconsistent

with earlier years.

3. When a survey design measures an absolute density rather than a relative measure of abundance, managers are free to designate where surveys are located. Only a single survey is required to provide information useful to managers. With relative measures, a time series over years must be gathered before the measure of abundance becomes informative. By contrast, a single survey measuring absolute abalone density provides information on total population size in any area chosen.

4. A measure of absolute density can be used to compare study regions separated by large distances along the coast, or with published literature, thus, potentially indentifying regions of low absolute density which may signal areas of high sustainability risk.

5. When taken as an input to abalone stock assessment models, absolute numbers estimated from survey will anchor the model parameter estimates, directly measuring the quantity most difficult to infer, namely absolute population size. Usually, a length-frequency of absolute population numbers (e.g. Figure 3.7) is the estimated output from rather than the input to a stock assessment model. The leaded-line survey outcomes thus greatly enhance model input data and will almost certainly improve model accuracy, often substantially.

3.4.2. Systematic or Random Placement of Leaded-Line Transects

Transects can be randomly or systematically located inside the study region. Byth and Ripley (1980) recommended a semi-systematic disposition of transects for distance methods. Cochran (1977, p. 205) commented that sample variances should, in general, be lower for systematic than random survey sample locations. This is because, with a random distribution, sometimes two samples will by random selection fall very close to one another. In that case, we get repeated sampling at that location but therefore an effectively lower overall sample size (that is, fewer primary sample units, which are those at different locations inside the study region).

When spatial variation is high, having more primary units is often the best way to improve survey precision (Pennington and Volstad 1994). Spacing primary units uniformly across the study region maximises the spatial coverage and thus captures by direct observation as much of the spatial variation in abalone density as survey cost and feasibility permit. For the Tiparra leaded-line surveys (Chapter 4), leaded lines were spaced in a symmetric pattern relative to the rectangular shape of the Tiparra study regions. In the Waterloo Bay surveys (Chapter 6), leaded lines were allocated as close as possible to uniform by visual assignment of their locations within an irregular study region boundary.

Thus, a systematic distribution can yield higher precision than random transects in highly spatially variable populations such as abalone (Cochran 1977; Byth and Ripley 1982). Systematic sampling is unbiased as long as the positions are specified without prior knowledge of abalone distributions.

3.4.3. A Future Improvement in the Leaded-Line Sampling Protocol: Spacing the two transects

One potential improvement in the leaded-line survey method has not yet been implemented. It seems probable that if these two 100-m transects at each leaded line were not directly side by side, but spaced apart by, say, 5 or 10 m, that the average density measure obtained at each leaded-line location would be more representative. Thus, it would ‘capture more of the within-sample variation’, i.e. yield a measure of density that more precisely estimates the population density in the neighbourhood of each leaded-line location.

In practice, this would require a way to deploy two leaded lines from the boat, spaced by 5 or 10 m. The two divers would then proceed as under the current sampling protocol, but follow transects on opposite sides of the two leaded lines on the bottom. An on-board method for deploying (and recovering) two leaded lines spaced by an approximate distance has not been developed, but remains a potential option for future implementation. Investigating the technical feasibility of deploying two leaded-lines simultaneously or in sequence remains a topic for future research.

3.4.4. Survey Information Trade-Off: 2-m Quadrats versus Lengths

In discussions with divers, it became clear that, under the leaded-line sampling protocol, it is not practical for a single diver to record 2-m counts and measure lengths simultaneously. Therefore information can be gathered on either (1) both absolute abalone density and their spatial distribution (from 2-m quadrat counts) or on (2) both absolute abalone density and length frequency. However using these tools (namely a slate with waterproof paper to record the 2-m counts, or a Shepherd length gauge), it is not feasible for divers to record both short-scale spatial information and length information at the same time. Potentially this could be achieved in the future if a computer measuring tool were developed which measured abalone length (from an attached electronic calliper) and also assigned these measured lengths to a separate record for each 2-m quadrat.

For current abalone management and stock assessment purposes, length frequencies often have a higher priority than measures of spatial clustering. Therefore, lengths will more often be measured in preference to 2-m quadrat counts. However when both are requested by managers, this can be achieved by the leaded-line survey protocol used here at Taylor Island where one diver records 20m quadrat counts and the other diver measures abalone lengths. One simple way to improve the spatial resolution of density by a factor of two when only lengths are measured would be to use two plastic length-recording tapes in the Shepherd length measuring gauge. The first tape would be used to record abalone lengths for the first 50 m of each 100-m transect, and divers would replace the first tape by a second tape for the second 50 m.

3.4.5. Proportion Legal

The variation in proportion legal is high. Fortunately, variation in proportion legal is uncorrelated with density. Therefore only imprecision, but not bias in the estimate of density is induced by the high spatial variation in proportion legal. Thus, this unexpectedly high variation from sample to sample in the proportion of abalone that are of legal size is understood as an additional independent random variable inducing error in the final estimate of mean legal density. Because they can be safely taken as independent, mean legal density is calculated as the simple product of these two random variables, density and proportion legal. Thus, by the approximate Taylor-expansion theory of error propagation (Taylor 1982), the overall standard error on legal density is calculated as the square root of the sum of standard error variances for density and proportion legal individually, where both are expressed as percentages of the mean. So, for example, if proportion legal has a 10% error, and overall abalone density has a 20% error, the error in legal density is $\sqrt{(0.1)^2+(0.2)^2}$.

This high variability in proportion legal is due to high levels of spatial variation in this quantity, much like the high spatial variation in abalone density. But, at least at the Taylor Island fish down site, the two are uncorrelated.

This high variability is not uncommon in South Australian (and plausibly many other) fishery data sets, namely higher than expected variances of binomial (2-possibility) population parameters such as proportion legal and proportion female. For example, South Australian King George whiting show similarly high variation in proportion female among juveniles sampled in beach seines at various coastal locations.

Almost all abalone fisheries require estimates of population size, as numbers or biomass, specifically for the legal-size size range. Because the proportion legal appears to express unexpectedly high levels of sample variation, abalone diver survey designs should take care to achieve the best (lowest variance) estimate of proportion legal that is practically feasible.

Thus, in future fish-down experiments of this project, and for greenlip abalone survey more generally, it is desirable to measure with more precision, the proportion legal. For Tiparra leaded-line surveys, 2-m quadrat counts were recorded in preference to length measurements for the specific purpose of investigating short-scale spatial variation in abalone density. However, in the long run, the best option for reducing the high variance in proportion legal was addressed directly in the sampling protocol used in the two Waterloo Bay leaded-line surveys (Chapter 6), where only lengths were measured on both sides of the leaded line and no 2-m quadrat counts were recorded (see Sections 6.2.2, 6.4.2. and 8.4.1.1).

Spatial variation in proportion legal can be due to two quite distinct causes. It quantifies genuine differences in the micro-populations at those locations. In addition, it is generally believed that the extent to which abalone remain cryptic, and thus not be counted by divers, can vary from day to day. Moreover, it is known that smaller abalone are generally more cryptic (and harder to detect) than larger abalone. This is shown by the general shape of all length-frequency curves where smaller abalone rise in measured abundance with increasing size. This increase in observed numbers with size for smaller abalone almost certainly reflects increasing levels of detectability, since smaller abalone are presumably more numerous. Therefore, differences in the measured proportion legal would also reflect differences in the ability of the survey to detect smaller abalone. If detectability of smaller abalone varies from location to location or day to day, either because of changing behaviour of smaller abalone, or because the tide and currents, visibility, or light conditions make it easier to miss smaller greenlip, this detectability variance could be an important component of the high variation in observed proportion legal.

There is one simple way to prevent variation in detectability of smaller individuals from affecting the estimate of legal-size density. If all abalone in each transect count are also measured for length, then the counts of legal-size abalone become independent of the counts of sublegals, because variation in sublegal counts do not affect the count for legals. This is because no additional calculation is needed to estimate legal abalone density, other than the raw diver counts. When not all counted abalone are measured, a survey estimate of proportion legal is also required to estimate legal density. In fact, if all abalone counted are also measured for length, the density from any chosen size range is unaffected by variations in the counts of abalone outside the chosen size range. This sampling protocol of measuring all abalone counted in each transect was used in the Waterloo Bay leaded-line surveys.

3.4.6. Stratification

Because of (relatively) high spatial variation in abalone distribution, one of the most promising strategies for improving precision in future surveys is to stratify the study regions. This is essential in study regions where more than about half is characterised by nearly zero abalone density. Broadly speaking, across the coastal zone, most of the bottom would be uninhabitable by abalone. Within any given study region, the subregions of non-abalone habitat such as dense seagrass or sand should be delineated and very few, if any leaded lines, should be placed there. This will improve survey estimate precision by placing most diver transects where most of the animals are located.

A large number of strata is unlikely to bring great advantage in reducing sample variance (Pennington 1996; Cochran 1977). We could suggest three general stratum categories, namely subregions of expected 'high abalone density', 'zero or near-zero density', and everything in between.

At Taylor Island, the purpose of stratification was not to reduce sample variance, but rather post-stratification was done to reduce potential bias in the actual leaded lines swum.

It would be feasible and advisable to examine stratification more closely, and in particular, to assess (by monte carlo simulation), what levels of improvement in survey precision could be expected. That remains a topic for future work.

3.4.7. Delta and Negative Binomial Distributions

The examination of the delta distribution was illuminating for an unexpected reason, namely it suggests that, compared with other marine survey sampling, the overall levels of sample variation in greenlip abalone survey counts are much lower than those examined by Pennington (1996), which notably included populations with a partially three-dimensional distribution sampled in the pelagic, or by bottom trawl. The delta distribution estimator (Pennington 1996) was developed for data sets with very high levels of lognormal variation, showing factors of difference from small to large samples of 4 to 6 orders of magnitude. The example data sets of Pennington (1996) show that this very high level of sample variation is not uncommon. Trawl samples are capable of searching much bigger areas of bottom, (or filtering much larger volumes of water) than abalone diver surveys. This is part of the reason for such huge variation in trawl samples, namely the potential for large areas of bottom to be covered in a single tow. For greenlip abalone, very high densities of more than say a hundred in a sample (for transects of 100 m^2) are rare, and we have encountered only 3 counts greater than 100 (specifically, of 156, 114 and 105 at Tiparra Coal Ground) out of 156 leaded-line transects swum in this project. Part of the reason for this relatively moderate variation in greenlip counts is that there is some tendency for greenlip to spread out, (though they do aggregate for spawning and also align along habitat features like ledges and the edges of seagrass). Greenlip abalone are known to space themselves on the bottom more evenly than blacklip and paua abalone species.

Thus variation in greenlip abalone counts encountered in this project was much lower than in the examples cited by Pennington (1996). Probably for this reason, the delta estimator was less precise than a standard sample (i.e. arithmetic) mean.

Thus the inadvertent lesson from the analysis using the delta distribution is that the overall level of variation in greenlip abalone transect counts is not extreme. While still fairly skewed, it is reasonably well-enough behaved that a regular arithmetic (i.e. sample) mean is still the logical and potentially even the best estimator. Thus by comparison to other marine survey data, the observed levels of variation should present no major obstacles to statistically sound estimates of absolute density. In the past, high sample variation in space was the main reason why relative rather than absolute density was accepted for abalone survey designs, as a less ambitious survey objective. We argue that the levels of variation are not nearly extreme enough to forbid the more ambitious and far more informative survey objective of estimating absolute greenlip abalone abundance.

3.5. References

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Appendix 3.1. Leaded-Line Diver Survey Sampling Protocol

Specifications of the leaded-line greenlip abalone survey sampling protocol were as follows:

Specifications of the leaded-line survey sampling protocol for greenlip abalone were as follows:

1. The depths, substrate types, and vegetation of the study area were mapped using boat-based sounder and video (McGarvey 2005, Chapter 1).
   1.1. When possible, the habitat mapping would cover one or more catch and effort statistical reporting blocks (map codes).
   1.2. In the absence of a habitat map, prior knowledge of fishing grounds, and, where available, depth contours, in combination with the layer of map code boundaries, can be used as the initial GIS map on which the survey study region boundaries are drawn.
2. The boundaries of the specific area (the ‘study region’), whose density and thus absolute abundance are sought, were drawn on an ArcView GIS map.
3. Leaded-line transect were located systematically, i.e. distributed uniformly, inside the survey study region, or inside each stratum.
4. In general, these are drawn parallel to the prevailing currents to assist diver movement.
5. A colour waterproof laminated map of the study area with transect lines drawn (Figure 4.1) was provided to research divers a few days ahead of time. On the back were start and finish GPS positions of all leaded-lines. These GPS marks were entered by divers into their on-board plotter prior to departure.
6. Feedback from the divers viewing these mapped leaded-line transect positions was possible at this stage. Proposed locations for leaded-lines can be redrawn if depths are excessive which would require shortening the transect length, if any other diver safety considerations inhere, or if it is desirable to re-orient the bearing of transect lines. When transects are moved in such a way as to induce non-proportional sampling, the study region must be stratified, and leaded-line locations allocated uniformly within each stratum.
7. Leaded lines (LLs), 100 m long, of nylon rope woven with lead, were deployed onto the bottom from the boat between the pairs of GPS positions specified. The line is laid into the water while being held taught by a crew member on board to keep it free of kinks.
   7.1. The line the divers used stayed rigid along its length, providing a generally accurate 100 m length.
   7.2. Distances along the length of the leaded rope were marked every 2 m.
   7.3. A winch was added to the abalone research boat for retrieving the leaded line. Because divers were also crew members, this relieved the strain on divers after being at depth of manually retrieving the leaded rope line.
8. Two divers swam either side of the leaded line.
   8.1. They swim with the prevailing current.
   8.2. Survey divers operating in pairs fulfils this safety requirement of two divers operating within eyesight of each other on each dive.
9. All abalone lying within 1 m on either side of the leaded line are counted.
   9.1. Divers consistently reported that 1 m was a comfortable width of bottom to search. Any wider would require sidewise swimming movement which is highly inefficient.
   9.2. All weed is pushed aside, but no rocks are overturned.

9.3. To precisely define whether an individual abalone lies within 1 m of the leaded line, we have taken, as a point-location identifier, the spiral crown on top of each abalone shell. If this lies within the 1-m transect strip, the abalone is counted.

10. Along both sides of the line, the counts in the 50 2-m quadrats were recorded by divers onto waterproof paper, a space in the data form provided for the abalone count in each 2x1 m^2 quadrat.
    10.1. These were recorded by the 'count diver' searching and counting abalone along one side of the leaded line.
11. The other diver (called the 'length diver') measured the lengths of all abalone inside the 1x100 m^2 transect along the opposite side of the leaded line from the count diver.
    11.1. This was done using the Shepherd (1985) abalone length-measuring gauge.
12. TIPARRA OPTION:
    12.1. In Tiparra leaded-line surveys, along both sides of the leaded line, the counts in the 50 2-m quadrats were recorded by divers onto waterproof paper.
    12.2. No abalone lengths were measured.
    12.3. Additional transects that lay perpendicular to the direction of the leaded line were swum by each diver, at 30 and 70 m along the leaded line. These 30-m perpendicular lines were wound off a reel by divers themselves. The divers counted abalone within 1-m of the line as they laid the line, recording a single count of abalone (rather than multiple 2-m quadrat counts) along the farther 25 m from the leaded line, on one side only. Divers then swam back to the leaded line, re-spooling the line onto the reel. Divers then recommenced 2-m counts along the leaded line.
13. WATERLOO BAY OPTION: In the leaded-line surveys at Waterloo Bay, no 2-m quadrat counts were recorded. Instead abalone lengths were measured on both sides of the leaded lines. In other words, all abalone counted by both divers within 1 m of each leaded line were also measured for length.

Appendix 3.2. Leaded-Line Diver Survey Data Analysis Methods

A3.2.1. Calculating the Estimate of Legal-Size Abalone Density: Arithmetic Mean

Because only legal-size animals were removed by commercial divers, for the fish-down experiment, survey estimates of density were sought specifically for legal-size abalone (in this Western Zone, ≥ 145 mm SL). The need to obtain density estimates for legal-size abalone will extend to surveys for stock assessment and fishery management, notably quota setting.

With the Taylor Island sampling protocol, one diver measures lengths, and the other, recording 20m quadrat counts, does not. From the 'length-diver' side of the leaded line, legal density was obtained directly because all abalone counted were also measured for length. The count used in subsequent calculations of mean legal density simply included only those abalone that were above legal size. This gave a direct (and thus independent) measure of legal density at each leaded line.

However, the '2-m count diver' recorded no information about length. Therefore estimating legal density from the count-side diver transect required an estimate of the proportion legal obtained from the length measurements of the length diver as a simple proportion (i.e. a ratio estimate). An average was taken over all 15 leaded-line transects swum by the length diver.

Multiplying this overall estimate of proportion legal by the all-sizes density gave a legal density measure from the count diver at each leaded line.

Overall legal density at each of the 15 Taylor Island leaded-line locations was obtained as a simple average of the two density measures from length and count diver transects. The overall legal density estimates were calculated, for both pre-fish-down and post-fish-down leaded-line surveys, as the mean (unweighted by transect length) over the independent legal density measures from each leaded line in each stratum.

A3.2.2. Stratified Survey Design

Because the placement of leaded lines inside the Taylor Island study region was not strictly systematic or random, post-stratification was done to avoid bias. By diver request, more transects were placed in the central region (LL's 6-9, Figure 3.1) where higher densities of abalone were observed. Also, it was necessary to differentiate the subregion of seagrass where no abalone were observed in the two transects (LL 4) (pre- and post-fish-down surveys) swum in the seagrass habitat. To fully partition the Taylor fish down study region, a total of four strata were required. These stratum boundaries are shown and numbered in red in Figure 3.1.

The areas of each of the four strata were calculated using ArcView GIS. Weightings of each stratum were given by the proportion of area covered by each. The stratified mean density estimates for the Taylor study region overall (both pre- and post-fish-down) were obtained as the stratum-weighted (i.e. as standard stratified) means (Cochran 1977).

The standard errors of these stratified means were obtained by natural extension of the 2-level bootstrap to a stratified survey design, taking resamples from the set of leaded lines within each stratum, and employing the area weightings in calculating the mean density from each bootstrap replicate.

A3.2.3. Confidence Intervals About the Estimate of Abalone Density: 2-Level Bootstrap

Estimating the confidence range about the estimated mean density was done using a 2-level bootstrap. A bootstrap is a computational random re-sampling (i.e. monte carlo) method, using the data itself as the set from which resamples are drawn (Efron and Tibshirani 1993). The two important advantages of a bootstrap are (1) it makes no requirement that the data be normally distributed—in fact, no pre-defined distribution need describe the data unlike with likelihood methods, and (2) it can be applied to essentially any estimator of mean density, no matter how complicated. Thus a bootstrap is applicable to virtually any survey data set, and is straightforward to program and use.

The two levels of bootstrap resampling correspond to the two levels of survey sampling namely resampling (1) from among the primary sampling units of 15 leaded line locations and (2) from among the secondary sample units of individual count measurements from the two transects at each leaded-line location. These two levels quantify 'between-primary-unit' and 'within-primary-unit' sample variance (Cochran 1977).

The nature of these two levels of sample variation (between- and within-leaded-line) are distinct. At the between-primary-unit level, each leaded line is at a separate location, and thus each provides a separate measurement of density that reflects the spatial variation of abalone density across the study region. The within-sample variation in counts from the two sides at each leaded line is understood as repeated measurements at each location because the two transects are literally side-by-side, with no distance between them. By taking bootstrap re-samples at both levels, the full extent of sample variation is quantified, namely of within- and between-primary-unit, in the survey estimate of mean abalone density.

The 2-level bootstrap method is as follows. The sample data are the diver-measured legal densities on both sides of all 15 leaded lines. For the count sides, the proportion legal has earlier been incorporated into this vector of legal densities from which monte carlo samples are drawn. At the primary level of each bootstrap 'replicate', a resample with replacement was drawn from the 15 leaded lines (i.e. a random selection of 15 leaded-line samples from among the actual 15 leaded line density observations). For example, the leaded-line numbers from one bootstrap resample (using SPlus) was { `10 15 5 2 6 1 4 10 14 4 1 4 3 14 10}.` This simulates an experiment in which another survey was run and happened to encounter this set of leaded-line locations. Then at the secondary level, that is within each leaded line selected, a second random resample is drawn from the 2 sides. With only two possibilities to choose from, the complete set of possible side (i.e. secondary unit) resamples is {(length side, length side), (length side, count side), (count side, length side), (count side, count side)}.

Thus for each 2-level bootstrap replicate, 30 densities are randomly selected from the original diver-sampled data set. The mean density from each replicate was calculated in exactly the same manner as for the original raw-data estimate of the mean: first the arithmetic means were taken of the two resampled sides on each leaded line giving mean density at each leaded line, and then these are averaged over all 15 resampled leaded lines. Thus for each bootstrap replicate, we draw a 'possible' outcome for the survey mean which might have occurred under the bootstrap paradigm. These are treated as if the survey had been repeated and each set of 30 newly selected densities were the observed outcome. 3000 bootstrap replicate estimates of mean legal density were obtained. The standard error of the mean was calculated as the standard deviation of the 3000 bootstrap mean density estimates. Quantiles from among these 3000 bootstrap replicate mean densities, (i.e. 1%, 5%, 25%, 50%, 75%, 95%, and 99%) can also be formed, giving 1%, 5% etc. confidence intervals as needed.

A 2-level bootstrap algorithm was used to quantify uncertainty in the estimate of mean density for all leaded-line surveys at the four fish-down experiments in this project.

Appendix 3.3. Timed-Swim Diver Survey Data Analysis Methods

A3.3.1. Shepherd Density Estimation Formula

A formula was developed by Shepherd (1985) to calculate the area searched. An average of 4 seconds are assumed to be needed to measure each abalone. This "measuring time" is subtracted from total time spent searching. When searching, a swimming speed of 20 metres per minute swum is assumed. With these assumptions, the total area searched can be estimated. The timed-swim formula for distance searched in each 10-minute abalone swim (Shepherd 1985) is

$(\text{Area searched, m}^2) =$

$$\left\{10 \text{ minutes } - \left(\text{Number of abalone measured}\right) \bullet 4/60 \text{ minutes})\right\} \bullet 20 \text{ m per minute} \bullet 1 \text{ m wide}$$

For timed swims, because the area searched can vary, the estimate of legal density is obtained using a ratio estimator, which is the simple ratio of the means. The ratio estimate of legal (absolute) density for timed swims is:

$$\text{Ratio estimate of (Legal density, m}^{-2}) = \frac{\text{mean(Count of legal-size abalone)}}{\text{mean(Area searched, m}^2)} \quad .$$

A3.3.2. Ratio-Estimate Confidence Intervals

No statistically rigorous method for estimating confidence intervals on the timed swim estimate of absolute density is currently in use. However, to compare the performance of timed swims with leaded lines, and specifically to assess whether the change in absolute number that timed swims estimate from before to after the fish-down harvest agrees, given sample variance, with the number actually removed, formal confidence intervals about the timed-swim estimates of density obtained using the area-searched formula above were needed. For a ratio estimator, the approximate Taylor-expansion estimated ratio-estimate for standard error of the timed swim estimate of legal density is written (Rice 1995, p. 208):

Var(RatioEst(Legal dens)) =
(1/n) * [1/mean(Area covered)]^2 *
{ [Est(Legal density)]^2 * [SD(Area searched)]^2 + [SD(Count legals)] ^2 –
2 * [Est(Legal density)] * cov(Count legals, Area searched) },

where n = number of 10-minute timed swims.

SE(Est(Legal dens)) = sqrt{Var(Est(Legal dens)) }.

The main problem with this ratio-estimator approach (or any attempted quantification of error based on this formula for timed-swim area searched) is that it implicitly assumes that this formula is an actual measured amount of area covered. In fact, this formula must be subject to wide variations in its closeness to true area searched by divers in a timed swim. In current practice, because the area searched under a timed swim is, in fact, not measured, and can vary due to current speeds, diver swim speed, uncertainty in the width of area searched, and deviations from the strict 4 seconds per abalone measured assumed in the Shepherd formula, the timed-swim density estimate is generally interpreted as a relative measure of abundance.

Thus, because we will assume the formula for $(\text{Area searched, m}^2)$ above is correct without error, the timed-swim estimates of standard error for density (being based on this assumption) are almost certainly underestimates. In particular this formula quantifies none of the random variation in area covered. Neither do we account for bias when divers swam towards ‘good bottom’ to maximise their counts, which was standard practice under that protocol. By contrast, the variance in the ‘top’ (i.e. numerator) of the density ratio is rigorously quantified by measurement, namely as variation in the observed counts of abalone in each 10-minute swim. Thus, we will consider these ratio estimates of standard error to quantify only a lower bound of uncertainty in the estimate of timed-swim density and bear in mind that there are several additional sources of error that remain unquantified.

CHAPTER 4. Leaded-line Surveys at Tiparra: Assessing Sample Variances of Absolute Density Estimates

R. McGarvey, S. Mayfield, B. Foureur

4.1. Introduction

In this chapter, we describe the diver sampling protocol and results for leaded-line transect surveys in the two Tiparra Reef fish-down study regions. The focus of this chapter (which can be skipped on a first reading of this project report) will be to examine the levels of sample variation observed in abalone counts over several spatial scales. As noted, high spatial variation is a principal reason why abalone surveys in Australia, New Zealand, and South Africa have sought only relative measures of abundance. A transect method for achieving the more ambitious survey objective of measuring absolute density can be recommended only if the observed levels of sample variation are small enough to be informative for fishery management. We have, in the past, set a precision of ±20% as an approximate objective. More recently, this leaded-line survey method has been applied to give an estimate of absolute density and thus total abalone population number with a standard error of ±40% in a very large, previously unsurveyed and unfished region of 42 km^2 in NW Spencer Gulf (Dixon et al. 2004).

Two of the four fish-down experiments in this project were undertaken at Tiparra Reef (Figure 1.5). Tiparra is the principal fishing ground of the South Australian Central Zone greenlip abalone fishery, producing about 85% of the Central Zone's greenlip harvest (Mayfield and Ward 2003). We located these experiments in two areas at Tiparra of high greenlip abalone density. The fish-down experimental results are presented in Chapter 8.

The leaded-line survey sampling protocol chosen for Tiparra focused on assessing the ability of leaded-lines to gather spatial information on abalone density. At Taylor Island (Chapter 3), one diver at each leaded line measured abalone lengths and the other diver counted abalone numbers by 2-m quadrat. At Tiparra, to quantify spatial information, both divers recorded 2-m quadrat counts (on side of all leaded lines). Spatial analysis of the Tiparra leaded-line quadrat counts, assessing the ability of leaded-line counts to statistically quantify spatial clustering and to provide contour maps of density, are presented in Chapter 5.

This Chapter 4 will focus on quantifying the sample variation in survey measures of absolute density. Specifically we present (1) modifications to the leaded-line diver-sampling protocol, (2) how the 2-level bootstrap was modified to estimate confidence intervals for the survey estimate of legal abalone density under the more elaborate leaded-line sampling protocol adopted at Tiparra, (3) results for the five Tiparra leaded-line surveys, including the distributions and corresponding standard deviation of observed diver counts for (3.1) 2-m quadrats, (3.2) 25-m perpendicular transects, and (3.3) combined (quadrat and perpendicular transect) counts in each leaded-line, (4) length frequencies of absolute abalone population numbers before and after the two fish-down experiments, and (5) a power analysis of the absolute density estimate as a function of leaded-line sample size. The reduced skewness of count distributions with increasing area of the transect sampled, provides an indication of what size sample unit (2-m quadrat, 25-m perpendicular transect, or 100-m transect), if any, can adequately sample the population to surmount the high spatial variation in abalone density.

4.2. Methods

The habitat mapping (Chapter 1) identified two areas at Tiparra of high abalone density, Detail Areas #1 and #2. There we ran the detailed 50-m and 100-m grid video transects (Figures 1.9 and 1.10). Two 200 m x 500 m study regions, at Coal Ground (Figure 4.1, Detail Area #1) and West Bottom (Figure 4.2, Detail Area # 2), where video sightings of abalone were numerous, were chosen as locations for the two Tiparra fish down experiments. Leaded-line and timed-swim surveys were run before and after the fish-down harvest in both study regions. In addition, at West Bottom, a second post-fish-down leaded-line survey was run.

Rigorously systematic sample locations were used for all five Tiparra leaded line surveys. To avoid the need for stratification that arose at Taylor Island, the 8 leaded lines were spaced evenly inside the rectangular study regions. From east to west, leaded lines were 60 m apart, with a 40-m distance from east and west ends of the 500-m-wide study regions (Figures 4.1 and 4.2). The north-south dimension of the study regions were 200 m, with the transect lines beginning 10 m from both the northern and southern boundaries. The position in either the northern or southern half was alternated for the 8 lines from east to west. The exact same spatial disposition of transects was used for the first four leaded-line surveys, at Coal Ground and West Bottom. A second post-fish-down survey was run at West Bottom (a fifth leaded-line survey overall) with the leaded line locations rearranged in a largely non-overlapping mirror-image of the spatial pattern used in the other four.

In close collaboration with (1) the SARDI abalone research team, notably the sub-program leader, Steve Mayfield, and all research divers, Brian Foureur, Peter Preece, Thor Saunders, Kate Rodda, (2) the external statistician, Karen Byth, and in (3) occasional discussion with Scoresby Shepherd, Cameron Dixon, Rob Day, and last year, Harry Gorfine, a diver survey protocol was developed in this project that meets the seven stock-management information objectives, including a measure of absolute abalone density.

The leaded-line method was first described in Chapter 3. The primary sampling unit of this survey design is a transect 100 m long by 1 m wide. This is the primary area over which bottom is searched by each diver for abalone. The transects are located at designated GPS positions by deploying a visible straight leaded rope line on the bottom from the boat. Divers in pairs swam either side of the leaded line, counting all abalone within 1 m of the line, and recording the count in every 2-m quadrat adjacent to the line. At Tiparra, 4 additional 25-m secondary transects were swum perpendicular away from the leaded-rope line.

Length frequencies at Tiparra were obtained only from timed swims. A timed-swim survey was undertaken both before and after the fish downs at Coal Ground and at West Bottom. Four 10-minute timed swims were run along 4 of the 8 leaded-line locations for each survey. These provided length-frequency samples using the Shepherd abalone length measuring gauge. As with all timed-swim surveys in this project, these followed the current protocol of the South Australian survey method.

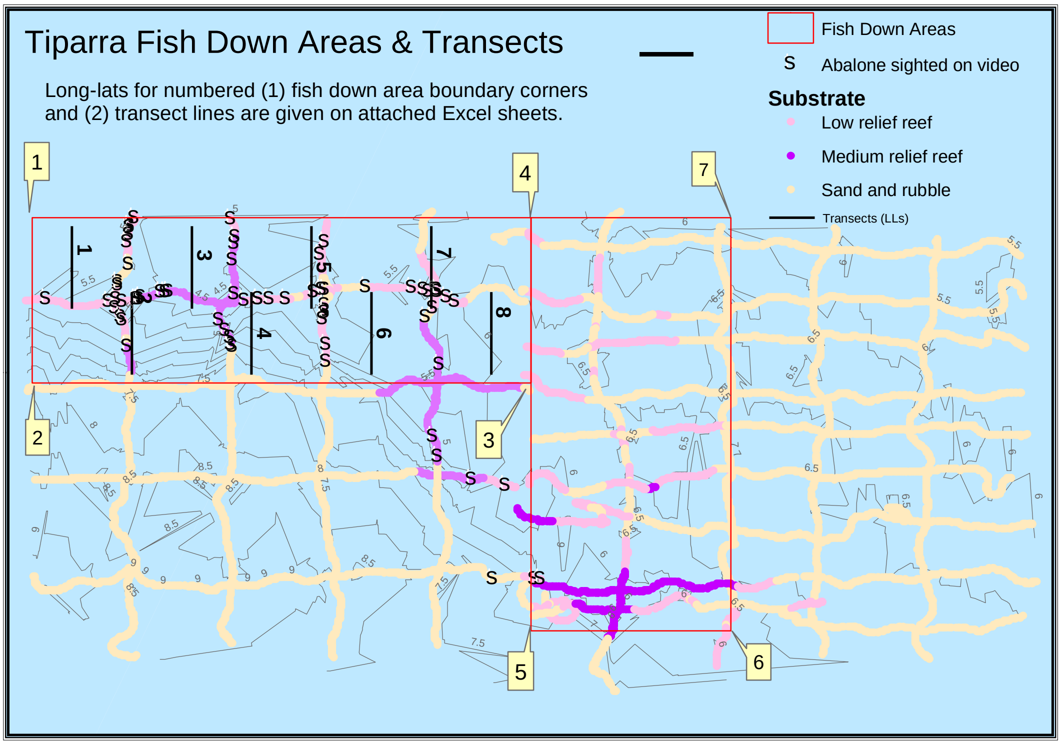


Figure 4.1. Map of the Coal Ground fish-down experimental study region distributed to research divers prior to the survey. GPS positions of all 8 transects were also provided. Only the first of two proposed study areas (demarcated by boundary corners numbered 1 to 4) at Coal Ground was used in the fish down and surveys.

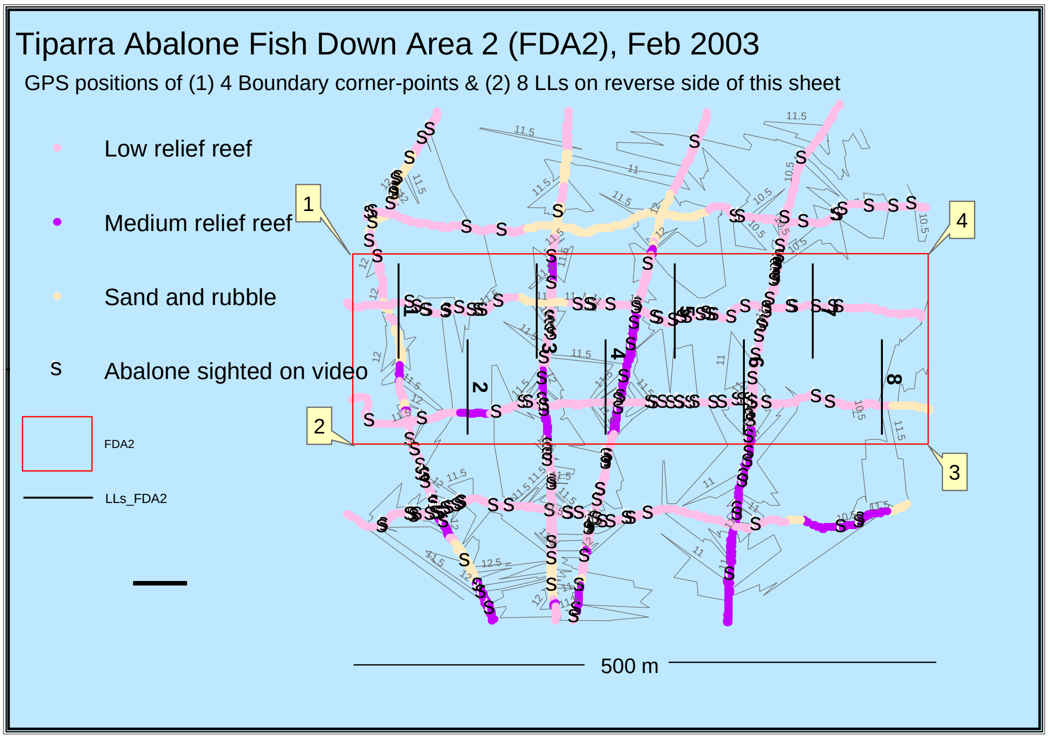


Figure 4.2. Map distributed to research divers prior to the survey on West Bottom (i.e. ‘FDA2’) (demarcated in red). GPS positions of all 8 transects were also provided.

4.2.1. Statistical Modifications to Survey Estimates: Mean Legal Density and 2-Level Bootstrap

At Tiparra, count samples were taken at each 2-m quadrat along the leaded line, and inside 25-m-long perpendicular transects, a total of 50 2-m quadrats and 2 perpendicular transects per side. With two divers, each swimming one side of the line, this provides a sample of 100 2-m quadrat counts and 4 25-m perpendicular transect counts at each leaded-line location.

With these modifications to the sampling protocol at the secondary sampling level (within each leaded-line sample location), the 2-level bootstrap method of estimating sample variance was altered accordingly. No change was needed at the primary level for resampling leaded-line locations in each bootstrap replicate. However, at the secondary level, bootstrap resamples were drawn from the full set of 100 2-m quadrats, treating each 2-m quadrat as an identical independent sample of density at that leaded-line location, and in a second stage of resampling at that level, over the 4 25-m transects. Density at each leaded-line replicate was calculated as the resample abalone count divided by the total area searched (300 m^2).

To obtain leaded-line estimates of legal-size density, the estimates of overall density obtained from each (leaded-line) survey were multiplied by the proportion legal obtained from the timed swims.

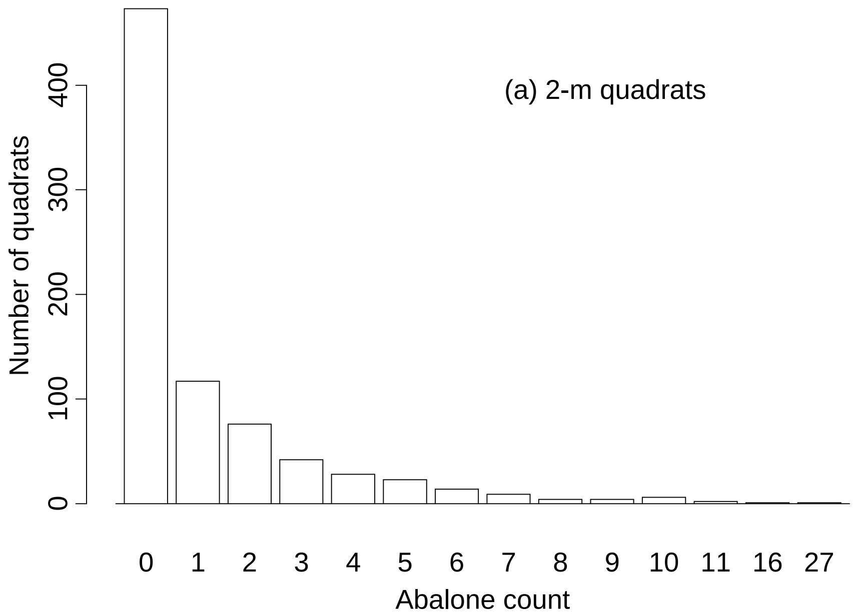
Confidence intervals on legal density were obtained by combining the estimates of confidence interval from proportion legal and all-sizes density. This is done using the theory of error propagation for the product of two random variables, overall density and proportion legal, as described in Section 3.4.5. These confidence intervals are presented along with the comparisons of pre- to post- absolute legal population numbers in Table 8.1.

4.3. Results

4.3.1. Sample Variation

The extent and distribution shape of variation in observed counts is an important factor in how precisely the survey estimates of abalone density can be measured. In this chapter, shape and extent of variation were quantified for the three levels of survey counts. Distributions of counts from (1) 2-m quadrats were highly skewed and many zero counts were recorded. Thus, variation was high at this short-distance spatial resolution of a metre or two. Distributions of counts for larger-size samples, that is, of (2) 25-m perpendicular transects, or larger still, of (3) summed counts of both 2-m quadrats and 25-m transects at each leaded line, yielded less skewed distributions with a more uniform shape. For the leaded-line results in this chapter, the densities estimated are for all sizes of abalone combined.

Typical variation for counts from quadrats and transects is shown in histograms from the pre-fish-down leaded-line survey at Coal Ground (Figure 4.3). For the leaded-line results in this chapter, the densities estimated are for all sizes of abalone combined. The smaller search area of the 2-m quadrats results in a highly skewed distribution (Figure 4.3, top). The 25-m perpendicular transects are less skewed and zero counts occur with much lower frequency (Figure 4.3, bottom). The more smooth distribution for 2-m quadrats is due to a much larger sample size of 800 versus 32 25-m transects in each 8-leaded-line survey.



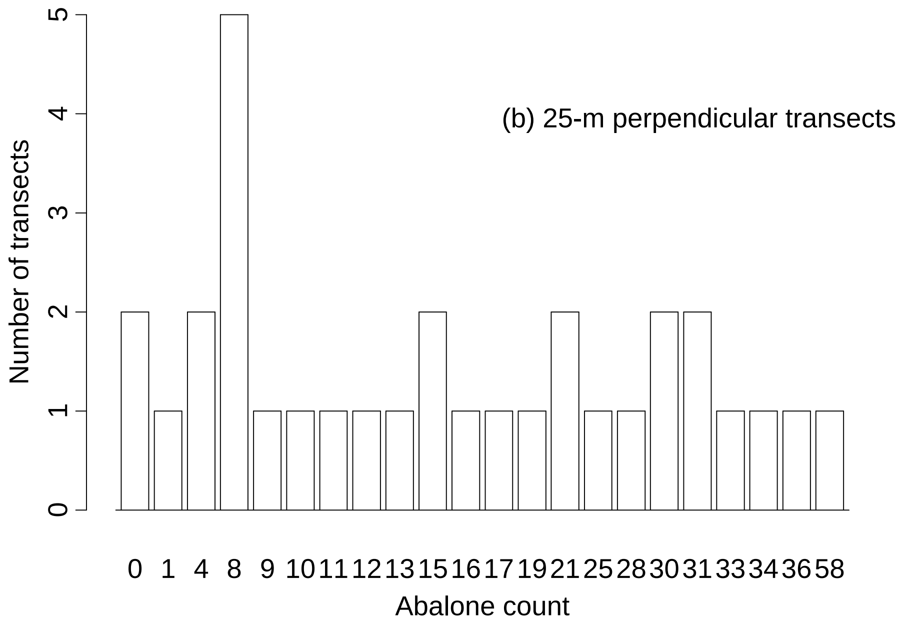


Figure 4.3. Distributions of diver abalone counts (all sizes) from the two sample search areas, (a) 2-m quadrats along the leaded line, and (b) 25-m transects perpendicular to the leaded line, from the Coal Ground pre-fish-down leaded-line survey.

The distributions of count frequency versus density measured from Coal Ground for 2-m quadrats and 25-m transects are shown in Figures 4.4 and 4.5. Boxplots (Figure 4.4) show the full range of observed densities, notably including the much wider spread for 2-m quadrats (left two boxplots in Figure 4.4), with the medians (the solid circles) sitting on zero density, implying that at least 50% of the counts were zero. High-density outliers, above 3 abalone per m^2, are from quadrat counts in clusters of abalone. The highest value shown (at 13.5 m^{-2} in Figure 4.4, see also Figure 4.3a) was a single quadrat in which 27 abalone were observed. Histogram bar plots of these same distributions (Figure 4.5) focus on densities up to 3 abalone per m^2 where most quadrat counts occurred. Clearly the 2-m quadrats (Figure 4.5, a and b) are more skewed with many more zero counts than 25-m transects (Figure 4.5, c and d). Some skewness is still evident for 25-m transects.

Similar levels and shape of variation were observed at the three West Bottom leaded-line surveys (Figures 4.6 and 4.7).

When these leaded-line data are summed into a total count per m^2 at each of the 8 leaded lines (Figure 4.8), no skewness is evident and no zero counts were recorded. Thus, at this more highly aggregated level of sampling, namely of all 100 2-m quadrats and all 4 perpendicular transects at each leaded line (total area searched of 300 m^2), the extreme features of zero counts and skewness that make sample means more highly uncertain average away.

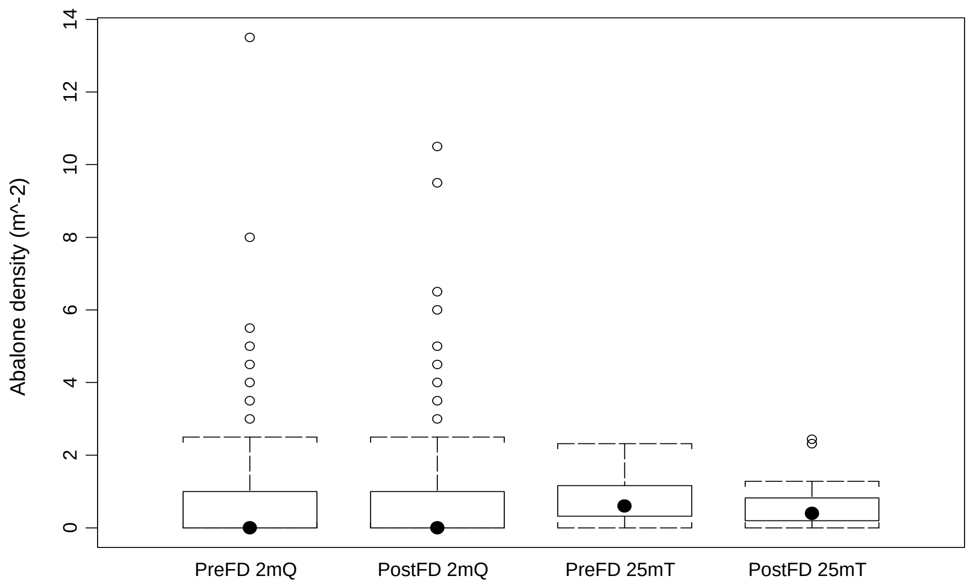


Figure 4.4. Boxplots of counts (as densities) for the Coal Ground study site leaded-line surveys, prior to (pre FD), and following (post FD) the fish down. Research divers swim along either side of the 8 leaded lines (LLs) in each survey. The densities shown are from 2-m quadrat counts (2mQ, 100 per LL) and 25-m perpendicular-to-LL transects (25mT, 4 per LL). Circle markers for outliers can signify one or many outliers at the designated density.

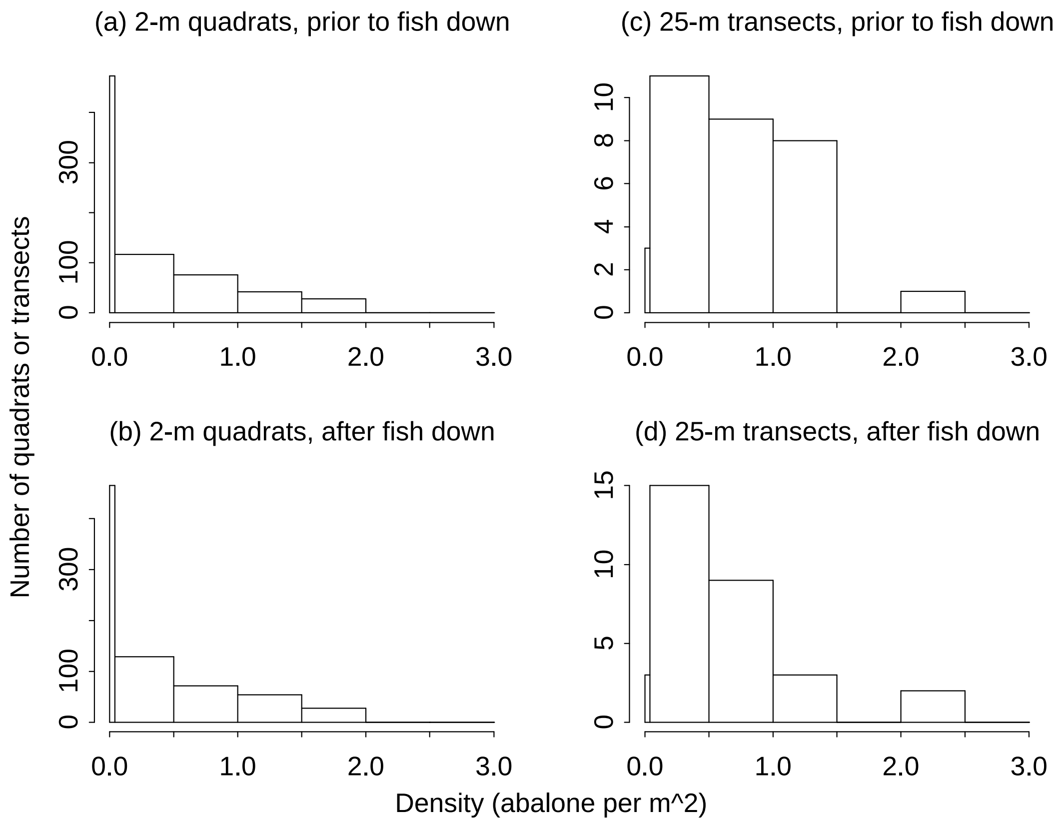


Figure 4.5. Histograms of leaded-line density measurements, at the Coal Ground study site. The same data were box-plotted in Figure 4.4, re-presented here as histograms to show the low end of densities, including the numbers of zero-counts (thin bars above 0). There were totals of 800 2-m quadrats and 32 25-m transects.

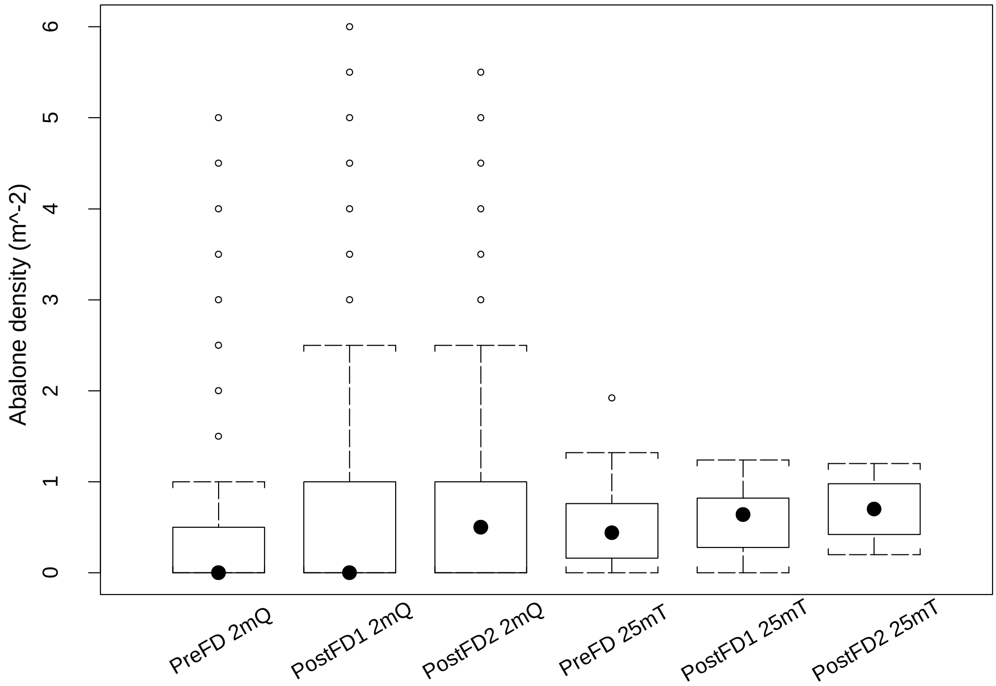


Figure 4.6. Boxplots of densities for the three West Bottom leaded-line surveys. Notation as in Figure 4.4, with the additional distinction of PostFD1 and PostFD2 denoting the first and second (of two) post-fish-down surveys.

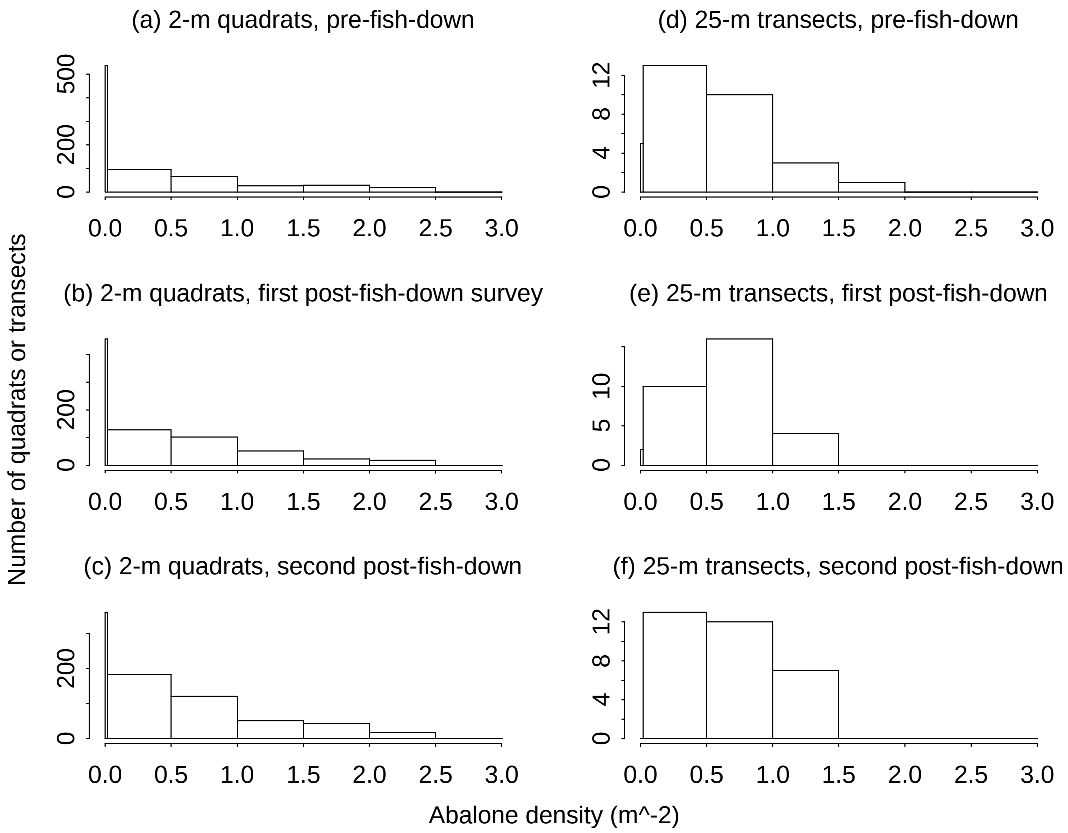


Figure 4.7. Histograms of diver-survey densities at the West Bottom study site (FDA2). These are the same survey count densities plotted in Figure 4.6.

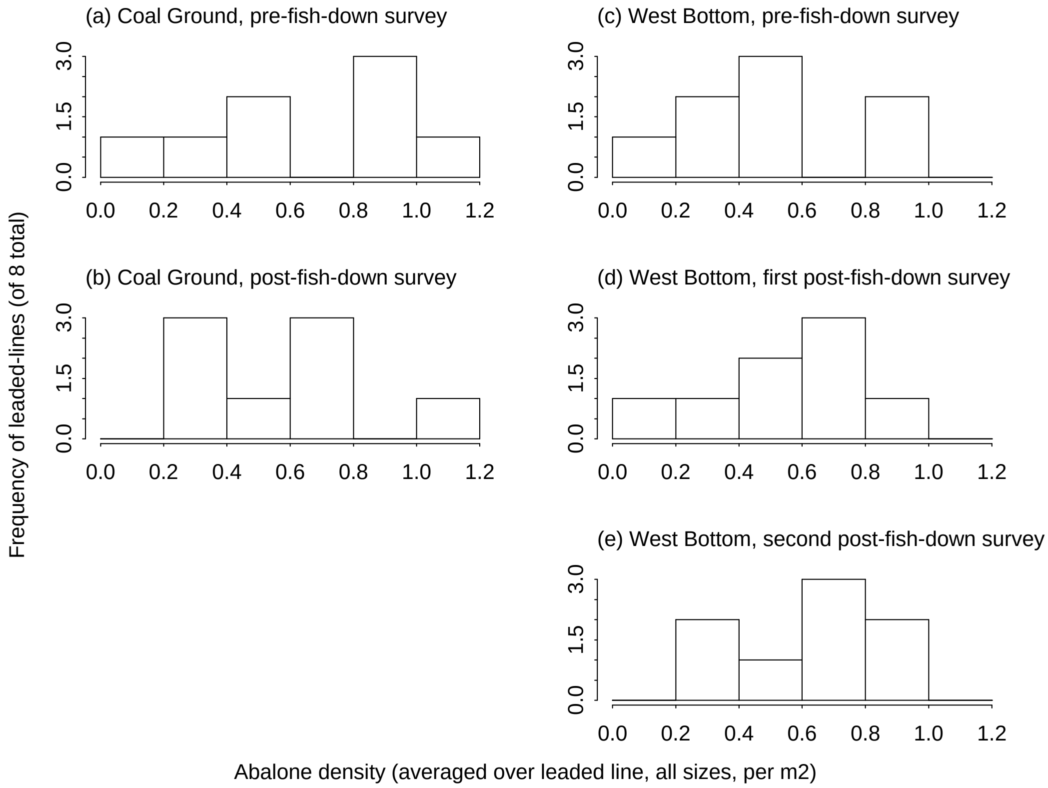


Figure 4.8. Histograms of density from the 8 leaded lines in each of the 5 leaded-line surveys at Tiparra.

4.3.2. Estimates of Density

The absolute density of abalone at both Tiparra study sites was high. Mean legal densities of about 0.2-0.3 m^{-2} (Table 8.2) are about 3 to 4 times higher than observed from leaded-line surveys at Taylor Island (~0.07-0.08 m^{-2} > 145 mm SL, Table 3.3) or pre-fish-down Waterloo Bay (~0.07 m^{-2} > 130 mm SL, Section 6.3.1).

For comparison, the mean density estimates from 2-m quadrats and 25-m transects were summarised separately (Table 4.1 and 4.2). Standard errors on these estimates were calculated two ways, (1) using the standard approach of estimating standard error (SE) as the standard deviation divided by the square root of sample size, and (2) using a standard (1-level) bootstrap. These two methods gave identical estimates of SE (Table 4.1, comparing columns 2 versus 4 and 6 versus 8). Both estimates of SE treat each quadrat or transect as an identical independent sample. Close agreement confirms that the bootstrap works.

The mean densities were higher for perpendicular transects, suggesting bias, as discussed in the next sub-section.

Both kinds of leaded-line counts (quadrats and transects) were incorporated in the overall Tiparra survey estimates of mean density (Table 4.3). The leaded-line measured density decline was 7.5% in the Coal Ground fish-down experiment (Table 4.3). The estimated mean density rose by 14.6% in the West Bottom study region from before to after the fish down. This was associated with (2-level bootstrap) standard errors of 19% and 16% for Coal Ground and 20% and 17% at West Bottom. This rise in estimated density at West Bottom was observed independently for 2-m quadrats, 25-m transects, and timed swims, with timed swims estimating a much larger increase. This rise in the West Bottom experiment is investigated further in Section 8.4.1.

To investigate how much difference is seen in two surveys of the same study region, with largely non-overlapping leaded-line locations, a second leaded-line survey was run at West Bottom after the fish down. The leaded-lines in this second survey overlapped by about 6% with the first post-fish-down survey. The results gave a 21% higher estimated density from the second post-fish-down survey (Table 4.1 and 4.3). This is not much higher than the SE-CV for the first survey (16.7%) and therefore is not beyond the 95% confidence range of the first survey. To that extent, the two surveys are not statistically inconsistent. Nevertheless, it does exemplify the well-know fact that abalone distributions are spatially variable, and to get the best estimate of mean density, the most uniform (and thereby representative) coverage of the study region is required.

The 2-level bootstrap mean, averaging over 3000 bootstrap iterations was close (Table 4.3, bootstrap measure of 'bias') to the raw data estimate mean for absolute density. For all 5 surveys the difference was < 0.33%. This close agreement of estimate mean and bootstrap mean is often cited as a bootstrap indicator of low bias, though this comparison does not account for most potential sources of bias which are due to various violations of perfect representativeness or measurement error. However, the close agreement of bootstrap and estimate means does effectively rule out the possibility of error in the way the 2-level bootstrap was written and coded.

The spread of observed estimates of mean density from 3000 bootstrap iterations quantifies uncertainty in that estimate. The confidence range distributions on mean density (all sizes) obtained from the 2-level bootstrap were graphed as histograms (Figures 4.9 and 4.10) and tabulated as formal confidence intervals of 1% and 99%, 5% and 95%, and 25% and 75% (Table 4.4). A rising mean is visually evident in Figure 4.10 from before to after the fish-down. A formal statistical test of whether the survey-observed changes in legal abalone numbers differ from the numbers removed in the commercial fish down (using the double-difference bootstrap method) is presented in Chapter 8.

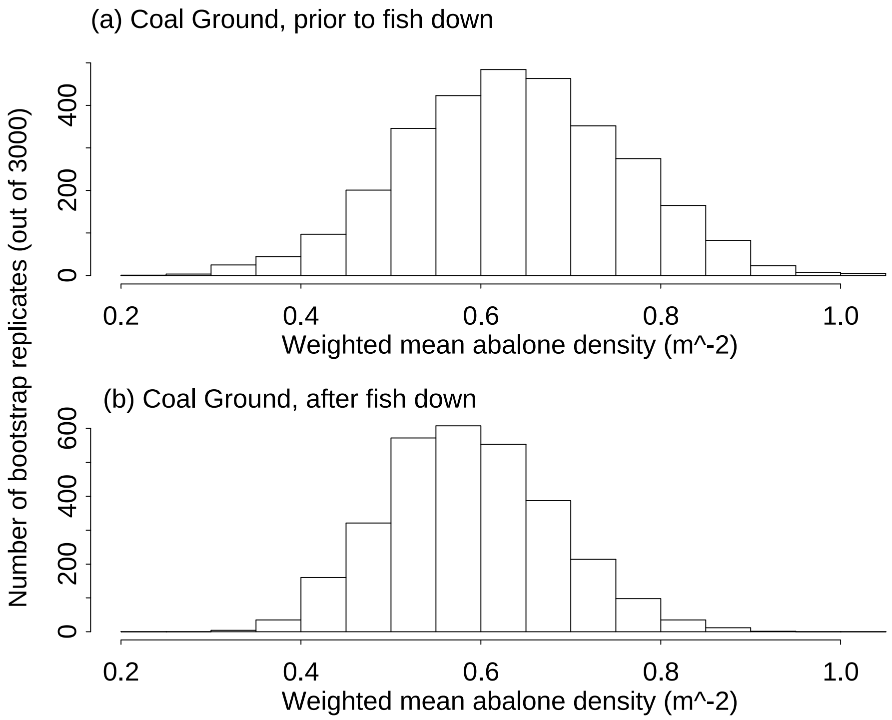


Figure 4.9. Confidence range for estimates of mean abalone density (all sizes included) from the pre- and post-fish-down surveys at Coal Ground. A 2-level bootstrap was used to generate the above histograms, illustrating the distribution of uncertainty in the estimates of mean density.

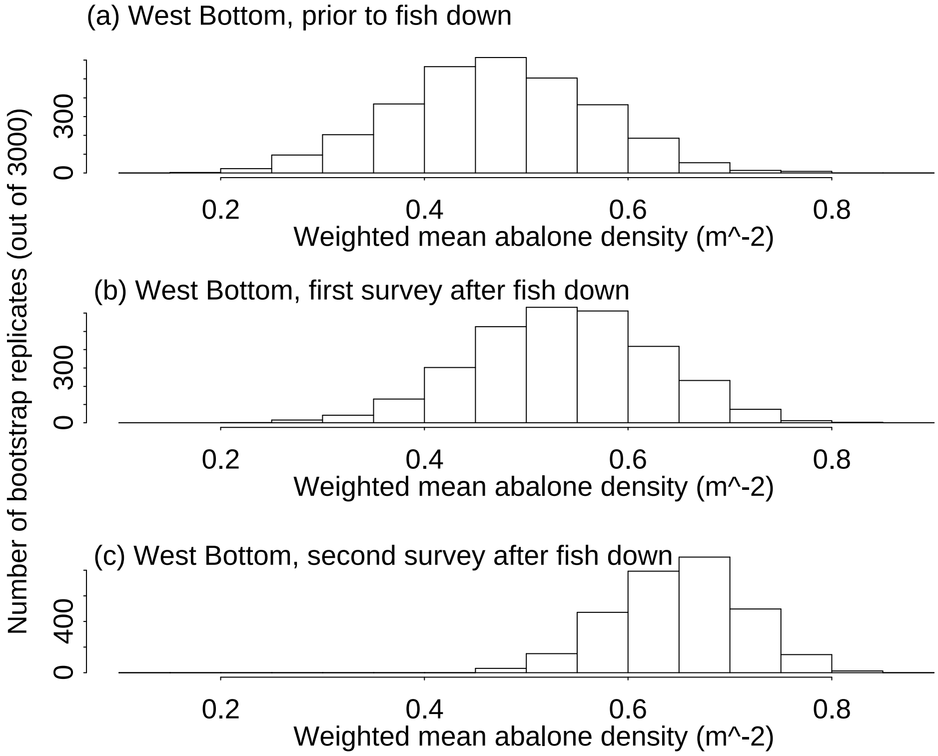


Figure 4.10. Bootstrap confidence range for estimates of mean abalone density (all sizes included) from the 3 surveys at West Bottom.

Table 4.1. Summary statistics of abalone density (all sizes) from counts in both quadrat types individually: (1) 800 2x1 m^2 quadrats alongside each leaded line, and (2) 32 1x25 m^2 transects running perpendicular away from each leaded line. The 1-level bootstrap (bs) standard errors (SE) were run as standard bootstraps with replacement from the samples of count densities. 1000 bootstrap replicates were re-sampled for this Table and Table 4.2. Analytic SE's were computed using SD/$\sqrt{n}$. SE-CV = SE/mean. 'FD' denotes the commercial fish down.

	2-m quadrats				25-m perpendicular transects			
Survey	Mean density (m^{-2})	SE density (1-level bs)	SE-CV (from 1-level bs)	SE density (analytic)	Mean density (m^{-2})	SE density (1-level bs)	SE-CV (from 1-level bs)	SE density (analytic)
Coal Ground pre-FD	0.60	0.04	6.6%	0.04	0.71	0.09	13.3%	0.09
Coal Ground post-FD	0.58	0.04	6.4%	0.04	0.60	0.10	16.6%	0.10
West Bottom pre-FD	0.45	0.03	6.7%	0.03	0.50	0.08	15.4%	0.08
West Bottom post-FD1	0.52	0.03	5.7%	0.03	0.58	0.06	10.4%	0.06
West Bottom post-FD2	0.63	0.03	4.6%	0.03	0.69	0.06	8.3%	0.06

Table 4.2. Bootstrap and analytic 95% confidence bounds of abalone density (all sizes) from counts in quadrats and transects separately.

	2-m quadrats				25-m perpendicular transects			
Survey	1-level bs lower 95% conf bound	1-level bs upper 95% conf bound	mean – (analytic SE * 1.96)	mean + (analytic SE *1.96)	1-level bs lower 95% conf bound	1-level bs upper 95% conf bound	mean – (analytic SE * 1.96)	mean + (analytic SE *1.96)
Coal Ground pre-FD	0.53	0.67	0.52	0.68	0.55	0.87	0.52	0.89
Coal Ground post-FD	0.52	0.64	0.51	0.66	0.44	0.78	0.41	0.80
West Bottom pre-FD	0.40	0.50	0.39	0.51	0.38	0.63	0.35	0.66
West Bottom post-FD1	0.47	0.57	0.46	0.57	0.48	0.68	0.46	0.70
West Bottom post-FD2	0.58	0.68	0.57	0.69	0.60	0.79	0.58	0.80

Table 4.3. Statistics of survey estimated density (all sizes, 2-m quadrats and 25-m perpendicular transects combined): mean, 2-level bootstrap (bs) SE's, 2-level bootstrap means, and % change from pre-FD to post-FD. The 2-level bootstrap samples with replacement first from the 8 LL's in each survey and then again, at the second level, among the 100 2-m quadrats and 4 25-m perpendicular transects at each LL selected.

Survey	Mean density (m^{-2})	2-level bs SE of density	SE-CV	Bs-mean	Percentage change from pre- to post-FD	number of 2-level bootstrap replicates run	bs-measure of 'bias'
Coal Ground pre-FD	0.64	0.12	19.1%	0.64		3000	-0.0032
Coal Ground post-FD	0.59	0.09	16.0%	0.59	-7.5%	3000	0.0005
West Bottom pre-FD	0.47	0.10	20.3%	0.47		3000	-0.0024
West Bottom post-FD1	0.54	0.09	16.7%	0.54	14.6%	3000	0.0002
West Bottom post-FD2	0.65	0.06	9.6%	0.65		3000	0.0007

Table 4.4. Confidence intervals for density (all sizes): 2-level bootstrap quantiles from the same 3000 resample replicates summarised in Table 4.3.

Survey	1%	5%	25%	50%	75%	95%	99%
Coal Ground pre-FD	0.35	0.44	0.55	0.64	0.72	0.84	0.90
Coal Ground post-FD	0.39	0.44	0.52	0.58	0.65	0.75	0.82
West Bottom pre-FD	0.26	0.31	0.41	0.47	0.54	0.62	0.69
West Bottom post-FD1	0.32	0.38	0.48	0.54	0.60	0.69	0.73
West Bottom post-FD2	0.50	0.55	0.61	0.65	0.69	0.75	0.79

4.3.3. Bias in Density from Perpendicular Transects

The 25-m perpendicular transects yielded higher estimated mean density than the 2-m quadrats for all 5 surveys at Tiparra (Table 4.1), averaging about 11% higher. Recall that, for perpendicular transects, the lines marking the area to search were drawn out by divers as they swam away from the leaded lines giving the divers some choice in where the perpendicular line was laid. No diver choice was possible for the placement of 2-m quadrats which ran along the leaded line deployed from the boat. Here we will assume the 2-m quadrats provide an unbiased measure thus providing true levels of density and test for the probability that the higher densities observed for perpendicular transects could have occurred by chance alone.

The appropriate statistical test for bias is a simple t-test. The 5 leaded-line surveys at Tiparra give a sample size of 5. Specifically, we tested the 5 differences in mean density measured by perpendicular transects and 2-m quadrats (columns 5 and 1 in Table 4.1), one from each leaded line survey. The null hypothesis was that this set of 5 differences is not different from zero. A one-sided test was used because we are specifically testing whether perpendicular transects overestimate. The mean difference of 0.059 m^{-2} as higher density for perpendicular transects would have occurred randomly under the null hypothesis with p = 0.006, i.e., about 6 times in 1000. This p-probability is nearly an order of magnitude less probable than a standard 95% confidence would have required (of $\alpha = 0.05$). So we reject the null hypothesis and assume that this level of overestimation did not happen by chance alone.

4.3.4. Power Analysis

To assess the relationship of legal density standard error versus sample size, a power analysis was undertaken. Specifically, the aim was to calculate the average expected level of precision under different choices for the number of leaded lines swum. The trade-off is clear: more leaded-lines means higher cost in diver time and resources, but brings more precise estimates of density in any survey study region.

The analysis was done for the one case where 16 leaded lines were swum, namely combining the two post-fish-down surveys at West Bottom. The expected precision was quantified for nine scenarios of survey sample size (1, 2, 4, 6, 8, 10, 12, 14, and 16 leaded-lines). To quantify precision for each sample size scenario, a 2-level bootstrap, as described above and in Chapter 3, was used. The only modification needed was to modify the number of leaded-lines chosen in each bootstrap replicate, namely resampling for 1, 2, 4, etc. leaded lines under each of the 1000 replicates for each scenario tested.

The results (Figure 4.11) show a rapid improvement in precision that tapers off with increasing sample size. This is nearly always observed in power analysis because (standard error) $\propto 1/\sqrt{n}$. So, generally, to double precision requires 4 times as many leaded lines.

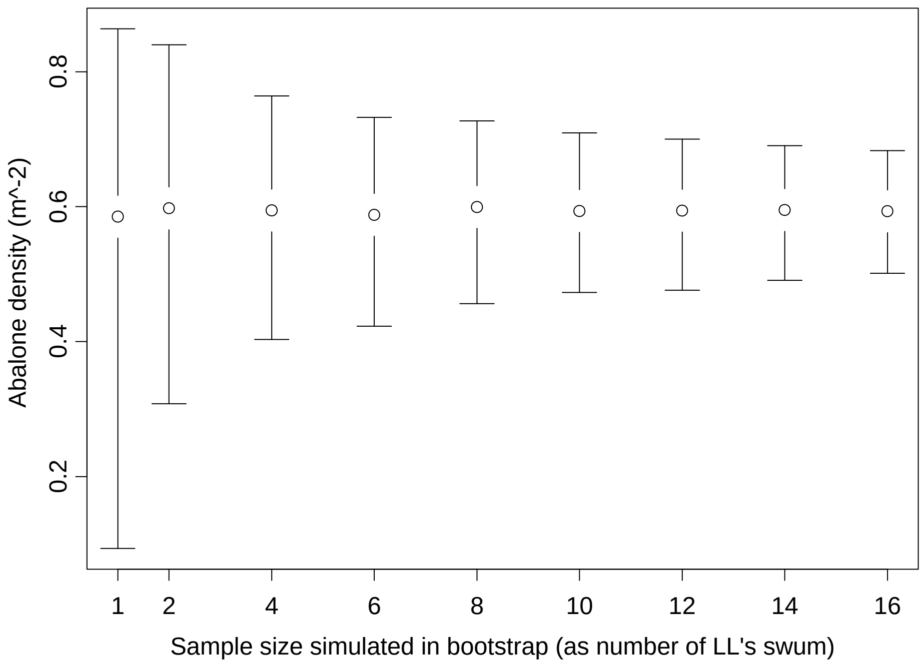


Figure 4.11. Monte carlo bootstrap simulations of precision under varying tested levels of survey sample size. Error bars indicate 95% confidence intervals for each survey sample-size scenarios shown. Data used were the combined survey diver counts from the first and second post-fish-down survey at West Bottom, a total of 16 leaded lines swum. For each simulated sample-size scenario of leaded lines (LL's) swum (1, 2, 4, …, 16), the 2-level bootstrap method was used to calculate the 95% confidence intervals shown, but with differing numbers sampled only at the primary sample unit level (namely of leaded lines). The number of bootstrap replicates was 1000 for all 9 scenarios tested.

4.3.5. *Abalone Length Frequencies*

Length-frequency samples from timed swims were combined with estimates of total population number to obtain curves showing the numbers in each length interval of 1 mm SL. Absolute abalone numbers by length would be a highly informative data input for future stock assessment modelling in regions where leaded-line surveys have been carried out. This is usually the principal output that abalone stock assessment models seek to infer, rather than be available as a measured input.

The Coal Ground length frequencies (Figure 4.12) show the expected fish-down experimental outcome of (1) essentially no change in the numbers of sublegal-size abalone, and (2) a decline in the number of legals.

The West Bottom length frequencies (Figure 4.13) showed a different pattern, of again (1) no change in sublegal numbers, but (2) an increase in legals. That legals rather than sublegals increased from before to after commercial harvest reduces the probability that the observed increase in density at West Bottom was due to randomness in detectability of sublegals. Nevertheless, to obviate this potential source of error due to random variation in the proportion legal (discussed in Chapter 3), all abalone counted were also measured for length in the last remaining fish-down experiment at Waterloo Bay.

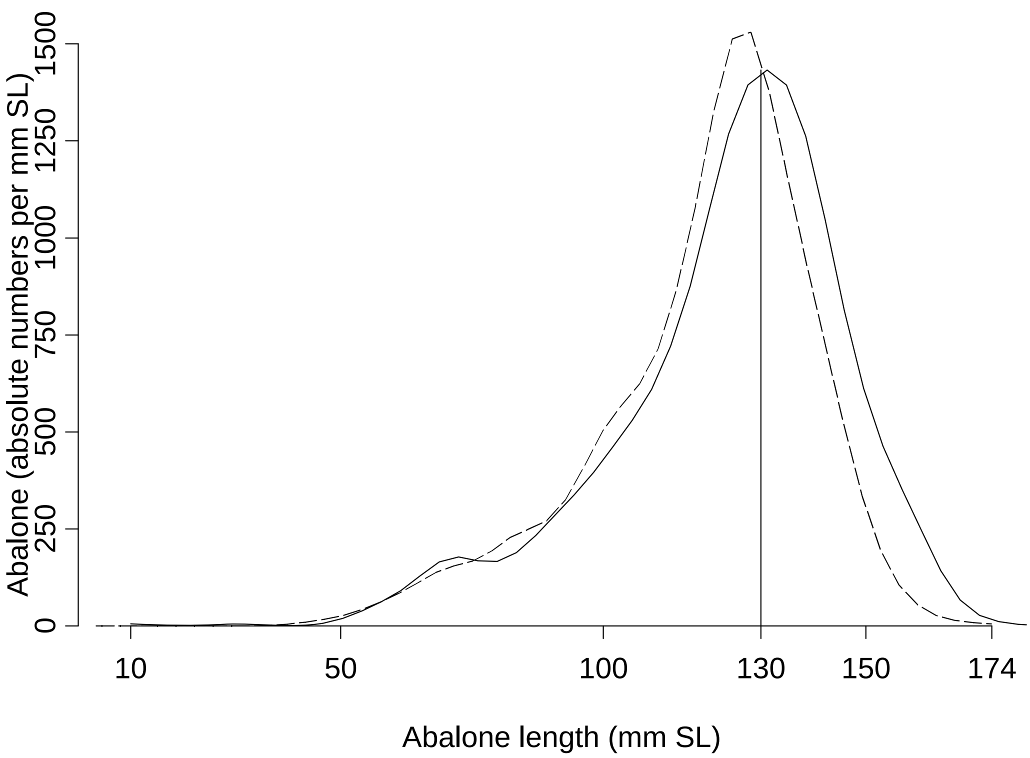


Figure 4.12. Coal Ground length frequencies, pre-fish-down (solid line plot) and post-fish-down (dashed line) from timed-swim surveys. The legal minimum size of 130 mm is shown. The length samples were (1) smoothed using kernel density, and (2) scaled by leaded-line estimated absolute density so that the y-axis quantifies total numbers of abalone in the study region per 1 mm SL. The values of 10 and 174 were the minimum and maximum greenlip abalone lengths observed in the sample.

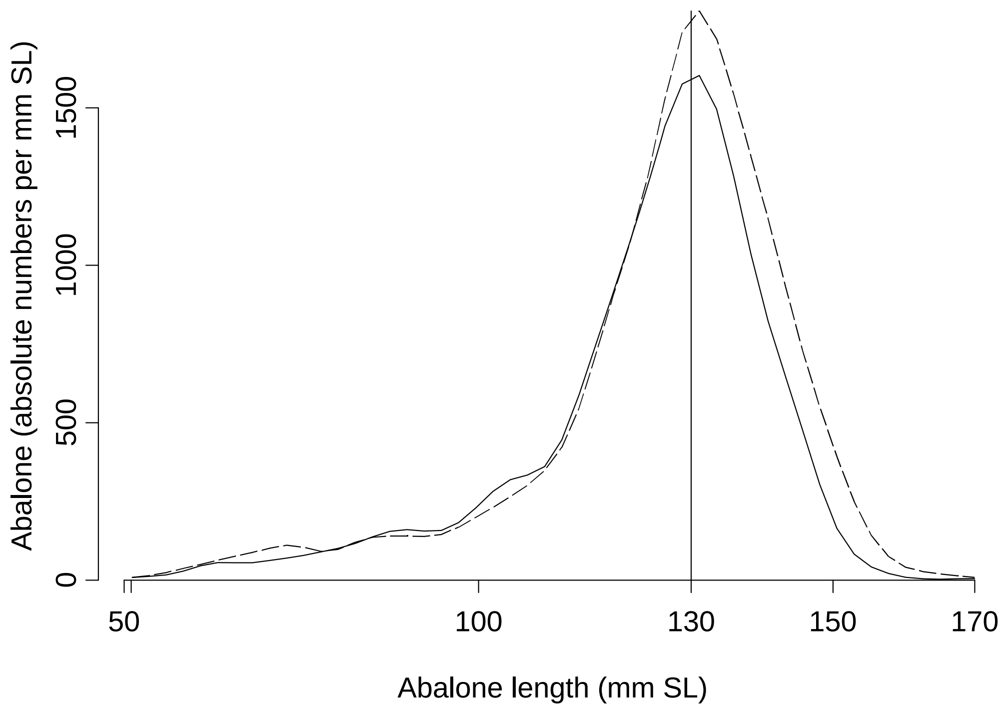


Figure 4.13. West Bottom length frequencies, pre-fish-down (solid line) and post-fish-down (dashed). Length data were from the timed-swim surveys and absolute scaling of the y-axis from the leaded-line absolute abundance estimates, as in Figure 4.12. The values of 51 and 170 were the minimum and maximum lengths observed in the sample.

4.4. Discussion

4.4.1. Sample Variation

The extent and general shape of variation in observed counts is an important factor in how precisely the survey estimates of abalone density can be measured. In this chapter, shape and extent of variation were quantified for the three levels of survey counts. Distributions of counts from (1) 2-m quadrats were highly skewed and many zero counts were recorded. Thus, variation was high at this short-distance spatial resolution of a metre or two. Distributions of counts for larger-size samples, that is, of (2) 25-m perpendicular transects, or larger still, of (3) summed counts of both 2-m quadrats and 25-m transects at each leaded line, yielded less skewed distributions with a more uniform shape.

The leaded-line samples showed a relatively low level of variation. There were, thus, no zero leaded-line counts. For this level and shape of variation, estimated means of absolute density can be expected to yield acceptable (i.e. useably precise) standard errors.

However, this conclusion would not be reached from smaller sample units tested. 2-m quadrats, and to a lesser extent, 25-m perpendicular transects, were still subject to relatively wide variation, due to high spatial variation in abalone abundance over these shorter spatial scales.

A further improvement in spreading the search area more widely over the vicinity of each leaded line, namely separating the two 100-m transects at each leaded line, in place of two immediately adjacent transects, was discussed in Section 3.4.3.

4.4.2. Quantifying Abalone Density in Different Regions of the Fishery

The fish-down experimental results presented in this chapter and the previous one tested the ability of the two remaining survey methods, timed swims and leaded lines, to detect change in population size over short times with fishing. Thus, these fish-down field trials and statistical tests quantified how well the two survey methods could detect change in legal numbers over time at a fixed location.

The second management use for a measure of absolute abundance is to compare greenlip abalone densities at different locations in the South Australian fishery. For this kind of spatial comparison, an absolute measure of density is generally needed. Absolute density can potentially provide a valuable indicator to fishery managers about the relative prospects of long-term sustainability on different fishing grounds. This would be critical in abalone management as it becomes increasingly spatially specific.

Legal densities observed at Tiparra were 3 to 4 times higher than at Taylor Island or Waterloo Bay. Such large observed differences in the mean imply that with typical leaded-line confidence intervals, spatial differences in absolute density can be reliably quantified. Confidence intervals on mean density, as standard errors, were estimated to be around ±20% in this report using the leaded-line survey method. But with differences in mean legal density between study regions of 300-400% (notably Tiparra compared with the others), the survey precision is about an order of magnitude greater than required to differentiate the greenlip density in different locations of the fishery.

The high densities measured in the Tiparra study regions have two causes. They first reflect the high abundances of greenlip that have historically and recently been recorded on Tiparra Reef overall as high catches, high catch rates, and a large legal mean size (Mayfield and Ward 2003). In addition, we intentionally selected specific areas of higher greenlip density for the Tiparra fish downs to balance the two Western Zone fish-downs that were not located in the highest-catch areas of that fishery.

Video habitat mapping identified high concentrations of abalone in these two Tiparra study areas. These were observed inside the two Detail Areas where boat-based video was run over a tight (50-m) habitat mapping grid (Chapter 1, esp. Figures 1.8-1.10). Initially, the two study regions were to have been the two rectangular areas at Coal Ground shown on Figure 4.1. However, the video mapping yielded very few sightings of abalone in that second area (inside corner points 4-7, Figure 4.1). For that reason, the second Tiparra fish-down experiment was shifted to the new location at West Bottom (Figures 4.2 and Detail Area #2 in Figure 1.8). That high densities of greenlip in these two study regions were subsequently found by both commercial divers and the leaded-line surveys confirm the power of boat-based video to identify areas of high abundance and suggests that boat-based video may yet provide opportunities for mapping and course-resolution but large-scale (greenlip) survey.

4.4.2. *Diver Choice Bias*

Overestimation bias was observed in the perpendicular transects. Measured densities were significantly higher in the perpendicular transects for all 5 leaded lines.

Thus, it appears that the perpendicular transects overestimated density. Divers, when laying out the line, must have sometimes swam towards patches of abalone. A bias of 11% is too large to be acceptable for survey measurements of absolute density.

Moreover, perpendicular transects require 2 to 4 times as much swimming per m^2 of bottom searched. The reason is that divers must first lay out the perpendicular line (using an additional cable and reel which they must carry with them) while counting abalone, and then swim back to the leaded line retrieving it. There was also a 5-m gap from the leaded line to the start of the perpendicular line, a total of 30 m each way. Most divers swam this 30-m distance only out and back (though one diver, to alleviate this bias, swam it four times). This means an extra 60 (or 120) m of swimming for each perpendicular transect. Assuming the minimum of 60 m, with two perpendicular transects on each side of leaded line, the total distance swum is 220 m, compared with only 100 m per transect when no perpendicular transects are added. But the area searched only increases from 100 to 150 m^2 per diver.

Moreover, since the leaded lines are laid parallel to the current, the perpendicular transects require swimming perpendicular to the prevailing currents, which at Tiparra are strong when the tide is running. Thus, because (1) they are overestimation biased, and (2) they require more diver effort per m^2 searched than the 1-m-wide transect lying to either side of the leaded line, perpendicular transects were not used at Waterloo Bay. For these reasons, and to achieve statistically higher precision estimates, it will, in general, be optimal to forego future use of the perpendicular transects and require, in the survey protocol, searching only directly adjacent to (1 m on either side of) the leaded lines which are deployed from the boat where no divers can see where they will fall along the bottom. This will eliminate this source of bias, greatly ease the effort required of divers, and if more leaded lines can be laid, will reduce the overall sample variance by allowing more primary units, that is, more leaded lines locations to be swum in each survey study region.

This source of overestimation bias in diver surveys results when divers have choice about where to search. Since abalone abundance can vary greatly over short distances, this bias can be substantial. And it seems likely that the more choice divers have, the more bias there will be. The only evident way to eliminate this bias, is to remove essentially all choice from where to search.

For the timed swim survey method, giving divers the choice to swim towards habitat of high abundance is an intentional specification of the survey protocol. Divers are instructed to seek out abalone habitat and to avoid non-habitat in their choice of where to search (Shepherd 1985). Moreover, the start of the 10-minute count does not begin until the first abalone is located. Both of these timed-swim sampling protocol specifications imply that abalone abundance will be overestimated. The estimate of absolute abundance is obtained from the Shepherd formula (1985; see also Section 3.2.2.1 of this report) which estimates the area covered in each 10-minute swim. However, there is no correction factor for this decision to direct divers to higher density patches. In this report, timed swims using this formula and sampling protocol have overestimated density from leaded lines by a mean of 52% for the 8 fish down surveys. Shepherd (1985, Table 3) in comparing field-trial timed-swim estimates to transects over the same ground also found that timed swims overestimated by from 18 to 135%, with a mean overestimation by timed swims of 57%.

This diver-choice bias is eliminated by leaded lines. Because the leaded line is deployed from the boat at pre-chosen locations, divers never have to face the decision about whether to leave the patch of abalone just off to one side out of the count. They never search outside a 1-m distance from a pre-specified line. In this way, an unbiased measure of (visible) abalone density is achieved.

4.5. References

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CHAPTER 5. Spatial Analysis of Leaded-line Survey Counts at Tiparra: Density Maps and Clustering via Spatial Autocorrelation

R. McGarvey, J.E. Feenstra

5.1. Introduction

In this chapter, we examine the spatial disposition of leaded-line density measurements from the pre- and post-fish-down surveys in the two Tiparra study regions (Figures 4.1 and 4.2). The basic question addressed in this chapter is, Can the leaded-line survey design provide spatial information on abalone distributions?

Current abalone survey methods, including timed swims and fixed transects, do not provide information on spatial distributions in either the short scale of a metre or two, or on broad-scale trends across a chosen study region. For these relative survey measures of abundance, designated boundaries for each study region are not usually defined. Rather, a set of fixed locations are searched in areas of known ‘good bottom’, where abalone are harvested yearly.

Under the proposed leaded-line survey design, boundaries for each study region will always be drawn in GIS software. Similarly, all transect lines are drawn on this map. Thus, the GPS positions of all study region boundaries, and all transects in each study region, are known. The counts from these transects provide location-specific information about abalone density.

In Chapter 4 we emphasized that the spatial spread of leaded-line samples should be representative across the study region. We chose to employ systematic rather than random point locations for the leaded lines because regularly-spaced samples provide better spatial information about abalone density than random locations do. Both random and systematic sample locations are representative and thus unbiased. But systematic (i.e. uniformly spaced) locations, are likely to yield a more precise estimate, even for the overall non-spatial estimate of density (Cochran 1977; Byth 1983). Thus, a systematic disposition of leaded-line sample locations provides benefits both in spatial mapping, and for estimating overall absolute density in survey study regions.

In this paper we assess the ability of the leaded-line survey method to estimate two spatial features of abalone population dynamics which relate to management of this resource.

The first abalone spatial pattern to be described in this chapter extends over the broader scale of the study region. Maps are generated showing how absolute density varies across the study region. The principal advantage of a spatial map of abalone density, even an approximate one, would be to monitor for changes in the spatial extent of the abalone population in management areas of interest. In South Australia, one question asked by management is whether the spatial extent of the harvestable meta-population has contracted under four decades of exploitation. By mapping abalone densities yearly or once every few years, the change in these maps over time provides information about whether the populations may be contracting. Thus, when the spatial distribution of abalone as absolute density across the study region is measured by leaded lines, evidence for spatial contraction and expansion, or movement, of areas of high abalone density can be monitored and reported to managers.

The second abalone spatial pattern to be quantified using leaded-lines in this chapter is clustering. A survey measure of short-scale spatial clustering is of use in monitoring abalone fertilisation success. Currently, most of the world's abalone fisheries outside of Australasia have collapsed, including those in North America and South Africa. One hypothesis about why abalone, more than most other exploited marine organisms, are so highly subject to collapse under exploitation is that abalone must aggregate to successfully spawn, and that fishing primarily targets these aggregations (Prince 1992; Prince 1989; McShane 1998; Shepherd and Rodda 2001) and thins them out or removes them. Dowling (2002; Dowling et al. 2004a; Dowling et al. 2004b) examined the greenlip abalone cluster size data of Shepherd and Partington (1995) from Waterloo Bay and concluded, by monte carlo analysis, that fishing did preferentially reduce larger aggregations. Fertilisation of gametes at time of spawning occurs in the water column. If abalone fertilisation success depends on the females and males being close together at time of spawning so that sperm and eggs have a chance to encounter one another in the water column, then the thinning out of abalone clusters would act to increase the mean distance between males and females during spawning and thus reduce the fertilisation success rate. By this hypothesis, fishing can potentially neutralise the reproductive core of the population, specifically by targeting aggregations. Babcock and Keesing (1996) have investigated the dependence of fertilisation success on mean distance between greenlip abalone and observed a rapid decline in fertilisation success when mean distance between individuals grew much above 1 m.

Thus, a means to quantify the degree of clustering could provide an additional fishery indicator for abalone. It could indicate when, whether through fishing or otherwise, the reproductive viability of a local population has been compromised from a spatial distribution that spaces males and females too far apart during spawning. Often fishing is the cause, based on the recent histories of abalone fisheries in North America and South Africa, where populations lasted about a human lifetime once exploitation had begun. A leaded-line indicator of abalone clustering could thus assist in quantifying the risk of stock collapse.

5.2. Methods

We investigated long-distance spatial distributions of abalone density and short-distance clustering, for 5 diver-survey data sets of greenlip abalone counts from leaded-line transects at Tiparra Reef.

5.1.2. Mapping Density

Maps of abalone density in each study region interpolate the data on density obtained from counts in quadrats and transects. Interpolation involves averaging the surrounding data points to estimate density at any point location. Quadrat and transect counts can be approximated as point measures of density by using the centre of each quadrat or transect as the corresponding point location. GIS lat-long positions for all quadrat or transect density measures taken from leaded-line diver surveys are thus the data input for this analysis by which density maps are generated.

To generate density maps that span the study region, the 2-m quadrats were considered too fine scale, and were too highly variable. Therefore, the two sides of each leaded line were aggregated giving a 2-m wide region, and the 100-m length was subdivided into 5 equal lengths of 20 m each. Thus, the 100 1-m x 2-m quadrat counts, 50 on either side of the leaded-line were summed to yield 5 20 x 2 m search areas. In addition, we employed the perpendicular transect counts, each of 1 m x 25 m. Dividing the count by the area gave a density measure for each. The centre point of each transect was taken as the point location of each density sample. Thus, in each leaded-line survey, we fitted to density measures from 40 2 x 20 transects running along the 8 leaded lines, and 32 perpendicular transects.

To map contours of similar density across each survey study region, both triangulated (TIN) contours and kriging were applied in ArcView GIS. TIN contours require no statistical estimator, and employ only information from the three data points in the immediate neighbourhood of each interpolation area. These use Delaunay triangulation, in combination with linear interpolation. As such, they require no user decision-making in the interpolation algorithm, providing a less-than-smooth empirical map of density.

Kriging, now widely applied in mining and environmental spatial interpolation (Burrough and McDonnell 1998), provides smoothed maps, and is based on an estimator that can, when all assumptions are met, give an estimator that is minimum variance and unbiased. Ordinary krigs, in particular as implemented in ArcView, require the user to choose (1) the number of surrounding data points to use for each interpolated value and (2) what curve to fit to the variogram, (3) lag-bin size, and (4) the number of lags. These decisions are informed by examination of the semi-variogram for evidence of declining spatial autocorrelation with distance between sample points. In addition to variograms, the predictive success of interpolated maps from different krig parameter choices can be directly assessed using cross-validation methods, also supported in ArcView (Geostatistical Analyst). Cross-validation removes data points one at time, refitting to the data set with each data point removed, and compares the resulting model-interpolated value to the actual measured density that had been removed. The level of agreement, e.g. least squares difference, summing over all data points quantifies the ability of each model to predict the data points observed. Plainly those krig maps that best predict the data are preferred. Summary statistics of these variograms, and the krig parameter choices are listed in Tables 5.1 and 5.2.

5.2.2. Quantifying Clustering from Spatial Autocorrelations

When populations are clustered, densities are higher than average, and thus correlated, over short distances of approximately the width of a cluster. Likewise, a positive autocorrelation over short distances will also result if lower-than-average density in one quadrat means lower-than-average density in neighbouring ones, as in areas of non-abalone habitat. A measure of clustering can thus be obtained from leaded-line survey counts by quantifying how the autocorrelation of abalone density varies with increasing distance between pairs of quadrats.

For clustering, the information in the highest spatial resolution is used, namely 2-m quadrat counts, in order to investigate the short-scale variation in abalone density.

In spatial autocorrelation analysis, the correlation in density among pairs of 2-m quadrats is calculated for all possible separation distances between quadrat centres. One correlation is calculated using all the pairs of quadrats that fall into a given distance class. Example distance classes include (1) all side-by-side pairs of quadrats, on the two sides of the leaded line, whose centres are 1 m apart, (2) all successive pairs of 2-m quadrats along each side of the leaded line whose centres are 2 m apart, and all subsequent more distant pairings of 2-m quadrats along both sides of each leaded line. Perpendicular transects were not used in quantifying clustering, 25-m being too large to investigate the short-scale variation over which abalone cluster.

Because, in clustered populations, neighbouring quadrats tend, on average, to have more similar densities than more distant ones, spatial autocorrelation will usually decrease with increasing distance between pairs of density locations. How far apart this similarity in density persists, quantified by where this decrease in autocorrelation versus distance levels off, is a rough measure of cluster width. Cliff and Ord (1981, p. 22) citing Sokol (1979) give general rules of thumb about how to interpret correlograms for identifying spatial patterns. They note that when cluster diameter is greater than quadrat diameter, we can expect low-order correlations.

The statistic used to measure correlation in density among quadrat pairs in each distance class was Moran's *I* (Moran 1948, Cliff and Ord 1981), commonly used in spatial autocorrelation analyses. It has the important property that the covariance is defined relative to the overall mean abalone density in the study region. The test for statistical significance of the Moran's *I* autocorrelation is given by Cliff and Ord (1981, pp. 14, 21 & 46; see also Upton and Fingleton 1985), summarising Moran (1948; 1950). This derivation shows that the Moran's *I* autocorrelation, for any given distance class, is expected to vary normally with a fixed mean near zero, and a standard deviation that varies with the number of pairs counted in each distance class, and the number of joins among pairs.

We restricted the autocorrelation analysis to quadrat pairs both of which lie along the same leaded line. The reasons for this are threefold: (1) We are interested primarily in shorter-scale distances of 0 to about 20-50 m for purposes of investigating clustering, and the shortest distance separating quadrats in neighbouring leaded lines at Tiparra (see Figures Figure 4.1 and 4.2) is 60 m. (2) For distances above 60 m, these inter-leaded-line autocorrelations would not be consistently comparable to those that we present from quadrats along each leaded line, because the set of distance bins would be entirely different, and the sample sizes by distance bin highly variable. (3) The total number of pairs of quadrats in each survey is 800 x 799 = 639,200, a computationally large and unwieldy number. The distances will all vary, and the Pythagorean distance would need to be calculated for each such 2-quadrat pair. This many pairings would then need to be partitioned into bins of similar distance, adding greatly to the complexity of the calculation and its interpretation. Thus for calculation feasibility and consistency of interpretation, the autocorrelations presented compare densities only for pairs of quadrats which lie along the same leaded-line.

5.3. Results

5.3.1 Mapping Density

The pre-fish-down survey maps of abalone density, in both fish-down experiments (Figures 5.1 and 5.3) showed distinct subregions of high abalone density. In the surveys run after fishing, these areas of higher density were both substantially reduced (Figure 5.2 and 5.4). This is consistent with the hypothesis that fishers targeted the high-density areas inside each fish-down study region. Thus it appears that leaded lines captured the spatial effect of fishing targeting the high-density patches of abalone.

At West Bottom, this effect of fishing was also evident, as the disappearance of two patches above 1.0 abalone m^{-2} (Figures 5.3 and 5.4), despite a survey-estimated rise of about 15% in overall density. This estimated pre- to post-fish-down increase in overall density (Chapter 4) is expressed spatially in these maps as density increases in what were lower density areas. This took two forms: (1) the appearance in the West Bottom post-fish-down map of a moderately high density area (0.8-1.0 abalone m^{-2}, i.e. light brown, Figure 5.4) to the southwest of the formerly high-density patches (Figure 5.3), and (2) a much larger spread in the area of medium density (0.6-0.8 abalone m^{-2} as darker orange, Figure 5.4).

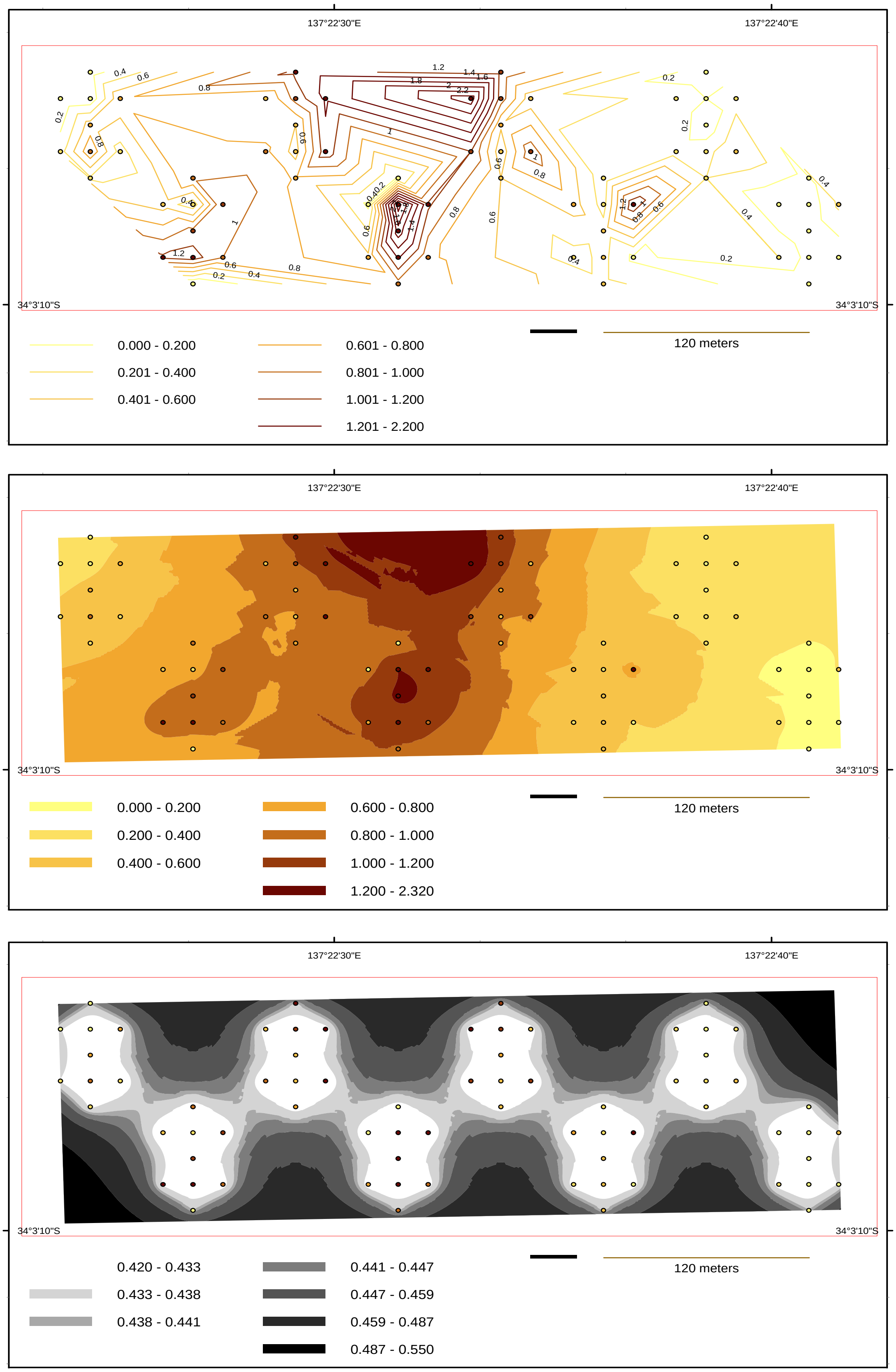

Figure 5.1. Maps of abalone density from aggregated leaded-line counts at Coal Ground, pre-fish-down: (top) TIN contours of density (abalone per m^2), (middle) krig-interpolated density, and (bottom) kriging standard error. Maps based on diver-count densities (all sizes) from transects of 20x2 m^2 along and 25x1 m^2 perpendicular to each leaded line.

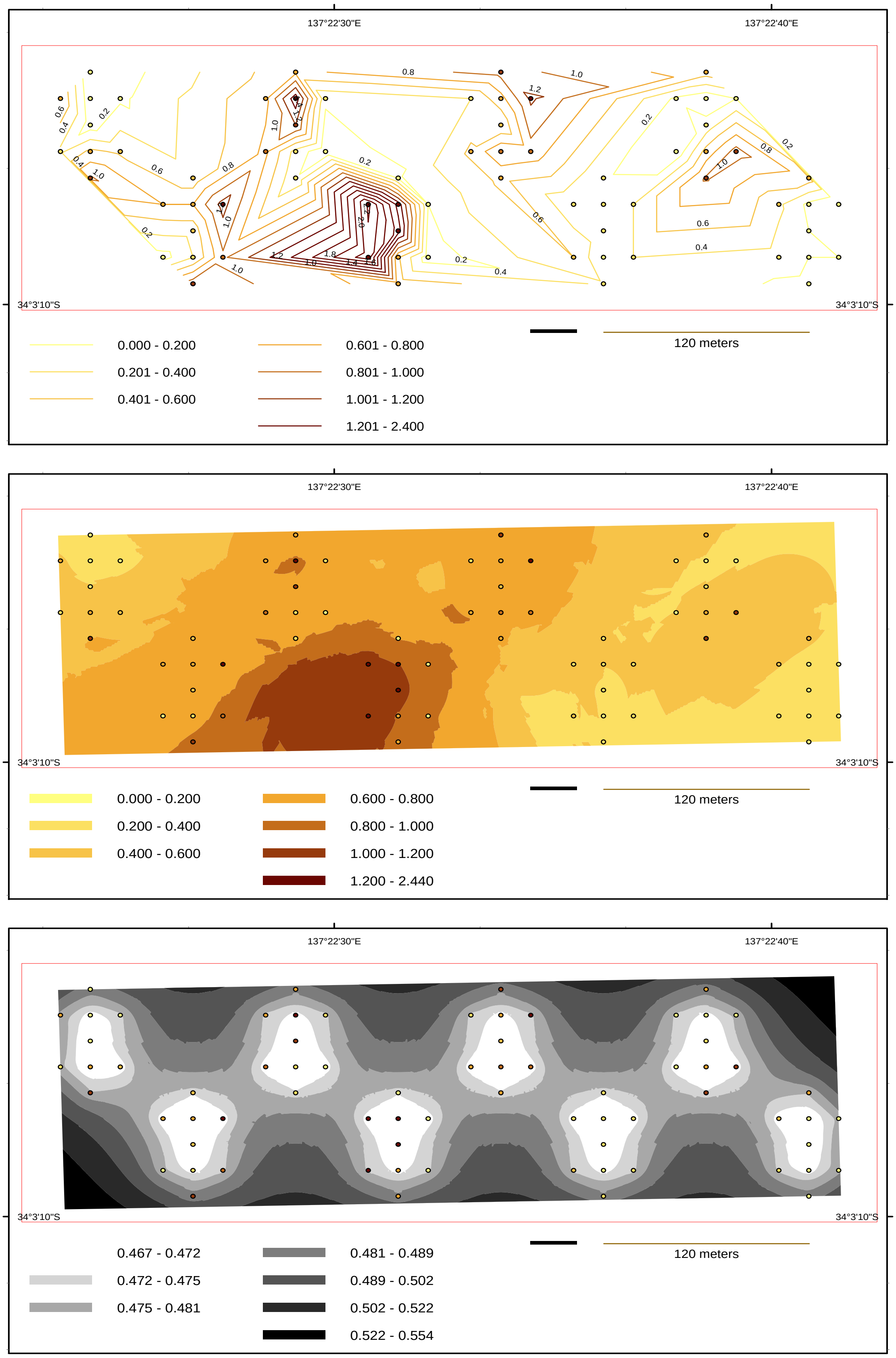

Figure 5.2. Maps of abalone density from aggregated leaded-line counts at Coal Ground, post-fish-down: (top) TIN contours of density (abalone per m^2), (middle) krig-interpolated density, and (bottom) kriging standard error.

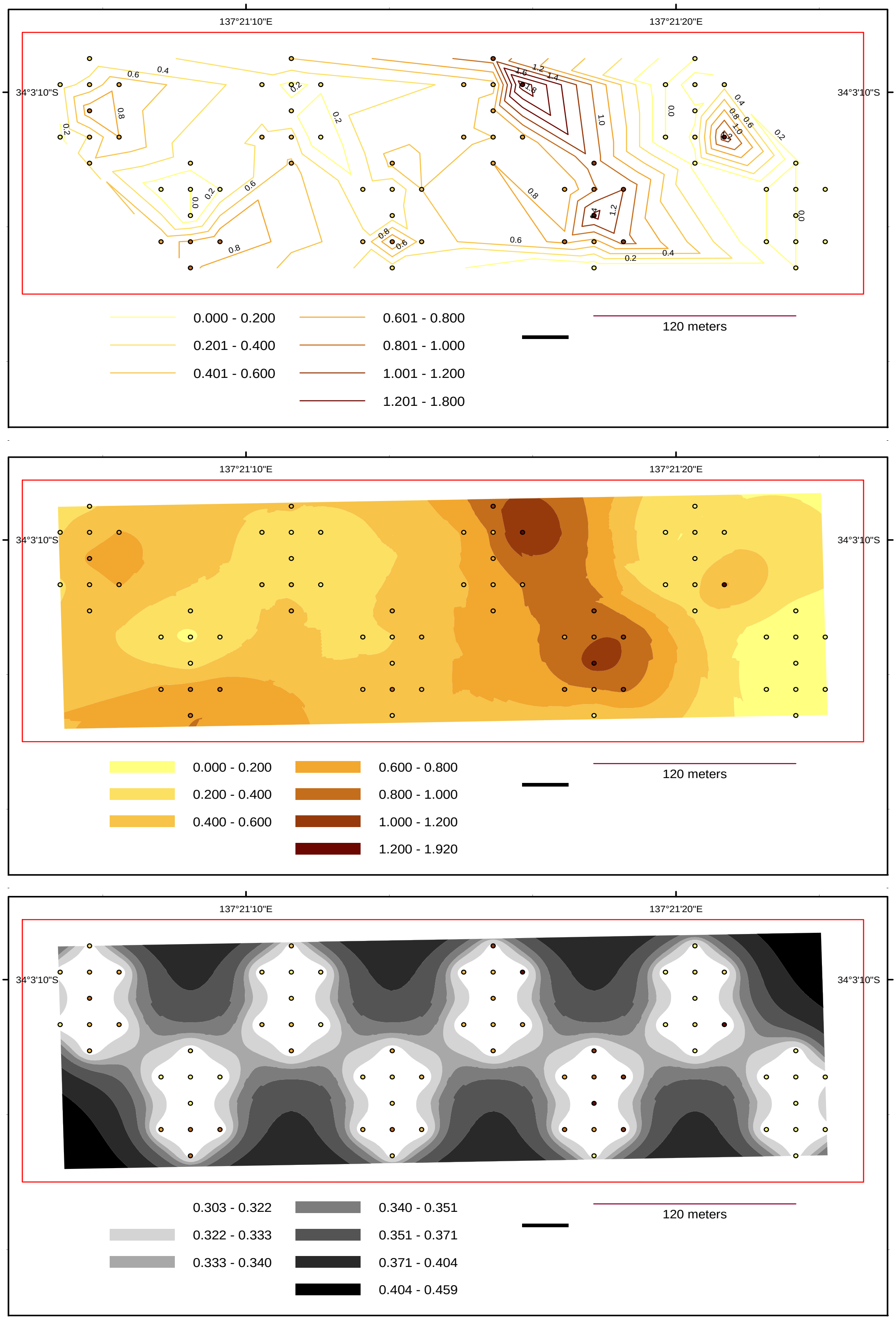

Figure 5.3. Maps of abalone density from aggregated leaded-line counts at West Bottom, pre-fish-down: (top) TIN contours of density (abalone per m^2), (middle) krig-interpolated density, and (bottom) kriging standard error. Maps based on diver-count densities (all sizes) from transects of 20x2 m^2 along and 25x1 m^2 perpendicular to each leaded line.

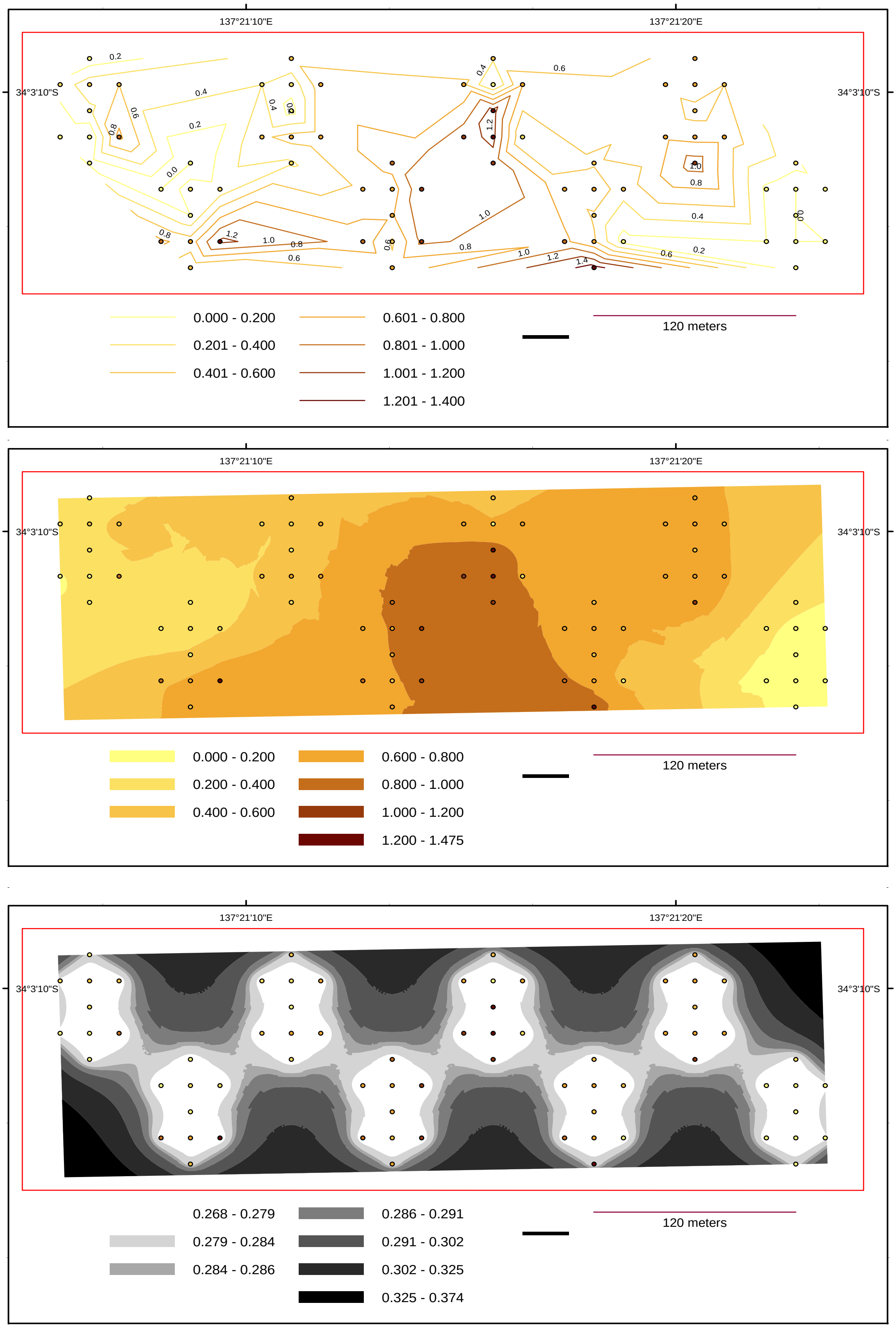

Figure 5.4. Maps of abalone density from aggregated leaded-line counts at West Bottom, first post-fish-down survey: (top) TIN contours of density (abalone per m^2), (middle) krig-interpolated density, and (bottom) kriging standard error.

5.3.1.1. Standard Error

The standard error maps (bottom maps in Figures 5.1-5.4) exhibit a rigid pattern that is symmetric around each leaded-line location. These maps of the estimated precision of the krig-interpolated densities (bottom maps in Figures 5.1-5.4), as spatially-specific standard errors, are generated by ArcView as an output of the krig model-fitting algorithm.

The density measurements at each leaded line (top maps in Figures 5.1-5.4) vary across space, but these standard error maps of density (bottom maps in Figures 5.1-5.4) do not. Thus, the estimated precision of the interpolated density at each point in the study region must express, principally or entirely, the closeness of the interpolation location to sample points where density was actually measured, which are shown as circle markers. We infer dependence only on distance from the sample points, with apparently no influence on these estimates of standard error from the measured density at each point, by this absence of variation in the standard-error map around each leaded line.

5.3.2. Quantification of Clustering

Abalone counts from all 800 2-m quadrats along both sides of each leaded-line are plotted in Figures 5.5-5.9, each figure covering one survey. Examination of these figures shows a variable tendency for quadrats of higher-than-average density (anything above 1 m^{-2}) and for low density quadrats (zero counts) to be encountered in variable groups of about 10 to 40 quadrats. Thus, clusters of non-zero density patches are evident, but variable in extent.

The autocorrelations among 2-m quadrat densities versus distance apart are given in Figure 5.10. There is one Moran's *I* autocorrelation value for each distance class inside which the self-agreement is measured. Each autocorrelation graph in Figure 5.10 represents one survey of 8 leaded lines.

Two trends in these five autocorrelation functions (Figure 5.10) are evident. The first is that in all 5 autocorrelation graphs, low-order correlations decline from ~0.2-0.4 to ~0.1 over the first 20 m of lag distance. Low-order correlations were said by Cliff and Ord (1981, p. 22) to signal clustering. The Moran's *I* correlation is well above the 95% significance limit (indicated by dash-dotted lines in Figure 5.10) at short separation distances of 1-10 m for all five autocorrelation functions, suggesting relatively consistent similarity in density over this spatial scale. Beyond 20 m, this similarity in abalone density dissipates. Thus, a cluster size is suggested of approximately 20 m in width, or about 10 2-m quadrats along the leaded-lines. Examining the plotted 2-m quadrat counts (Figures 5.5-5.9) suggests general though variable agreement with this interpretation of the first autocorrelation trend. Though 20 m is typical, the cluster lengths along each leaded line vary over a range of lengths, with 20 m somewhere in the middle of this range.

The second trend is that in some of the autocorrelation functions, the longer-distance correlations do not converge to zero, but remain above the zero-correlation line. This is explained by the observation (counts of Figures 5.5-5.9 and density maps of Figures 5.1-5.4) that some leaded lines showed higher density and some lower density across their full length. Since the autocorrelations only included pairs of quadrats within a leaded line, the higher correlation at longer distances expresses this general trend for within-leaded-line densities to be somewhat similar compared with the mean density of the study region overall.

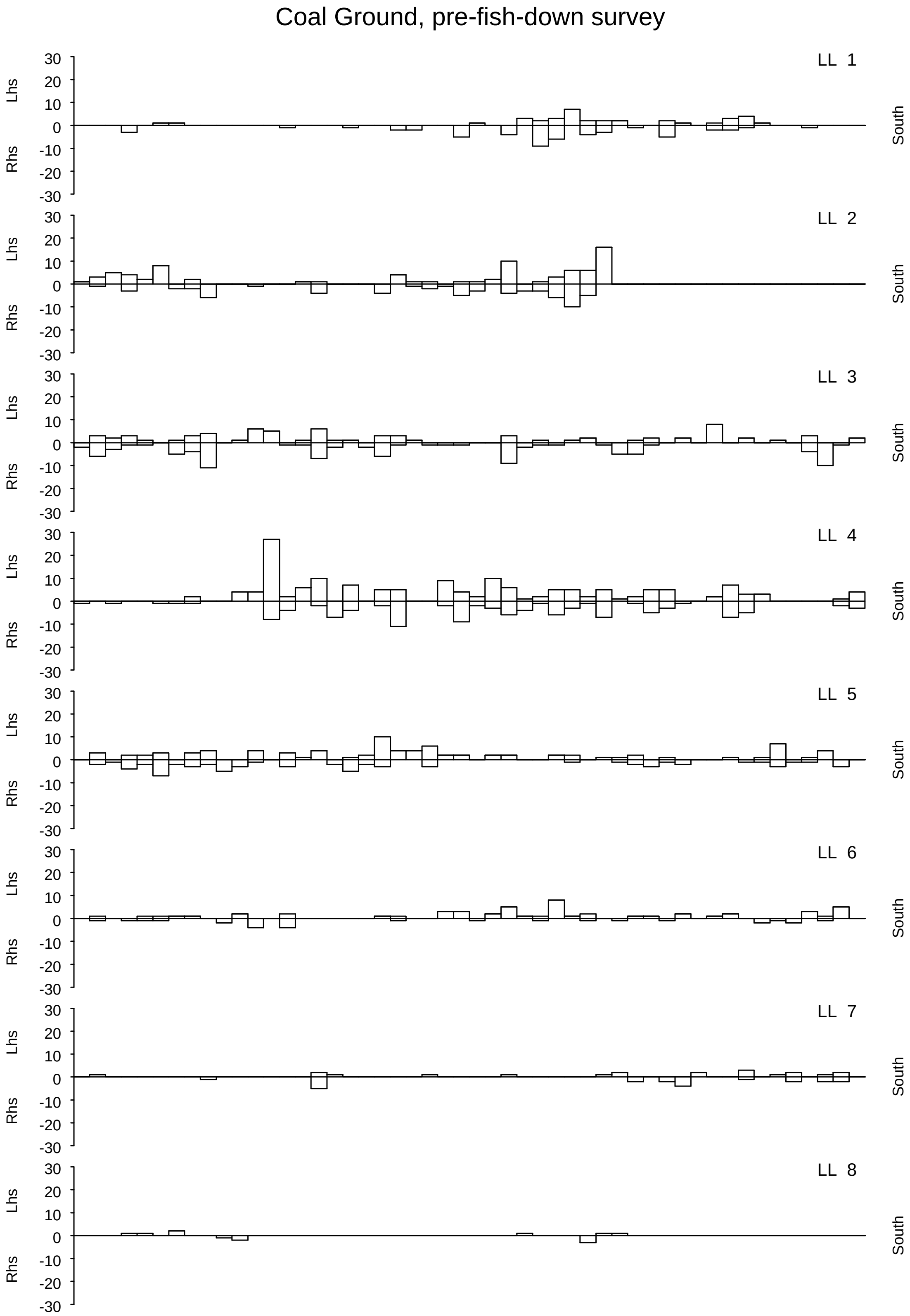

Figure 5.5. 2-m quadrat counts for the 8 leaded lines, with two transects on either side of each leaded line, recorded by divers at the Coal Ground pre-fish-down survey.

Coal Ground, post-fish-down survey

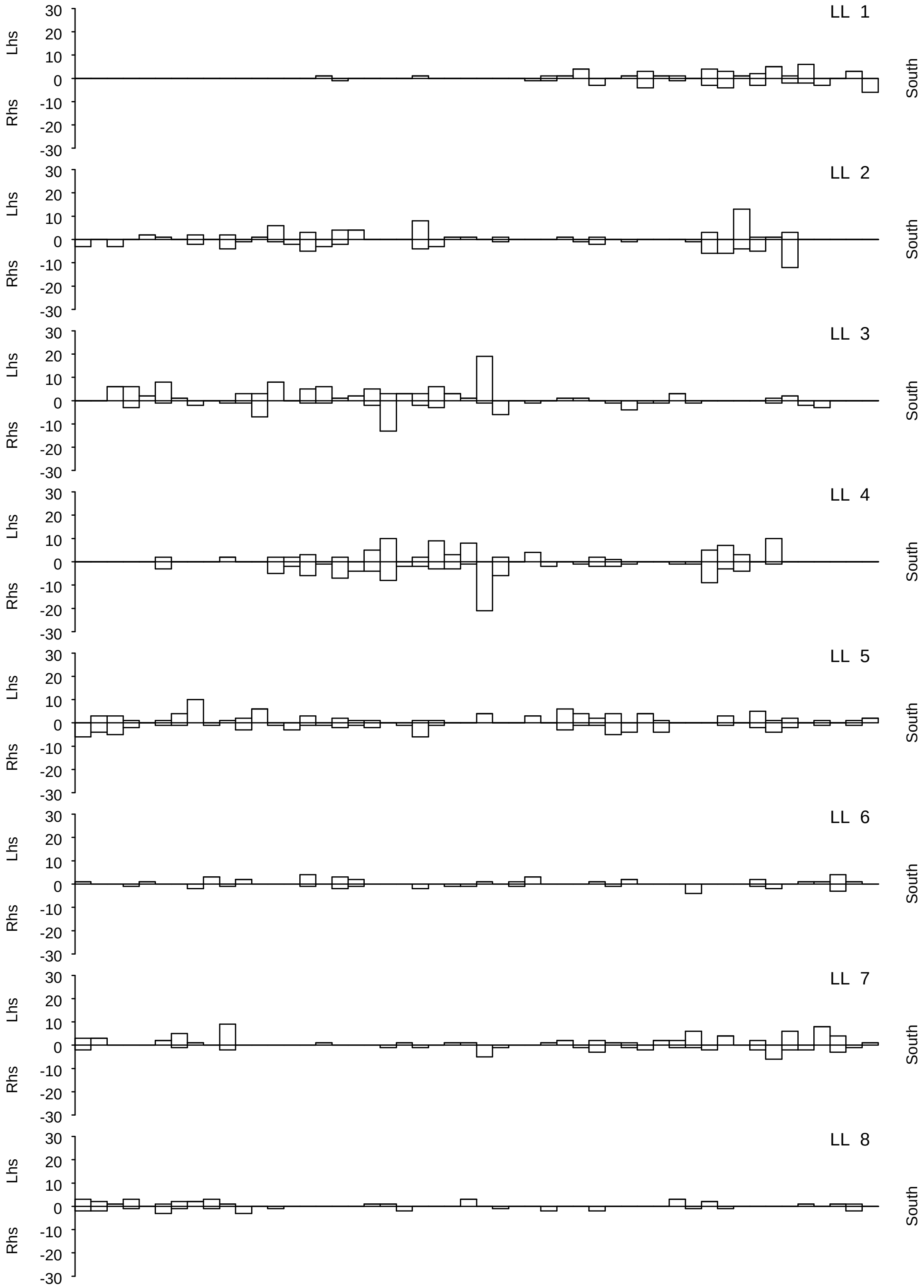

Figure 5.6. 2-m quadrat counts for the 8 leaded lines, at the Coal Ground post-fish-down survey.

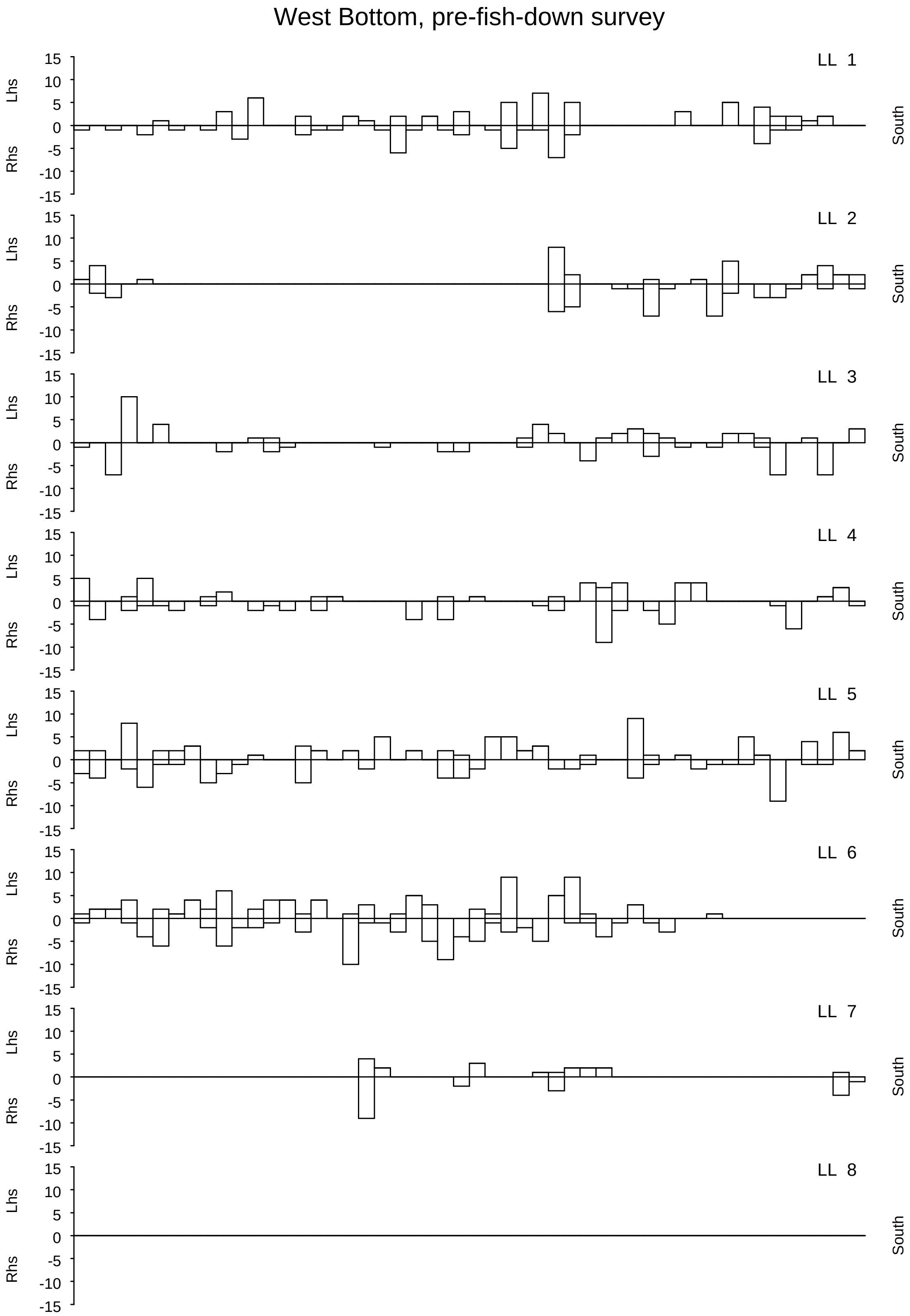

Figure 5.7. 2-m quadrat counts for the 8 leaded lines, with two transects on either side of each leaded line, recorded by divers at the West Bottom pre-fish-down survey.

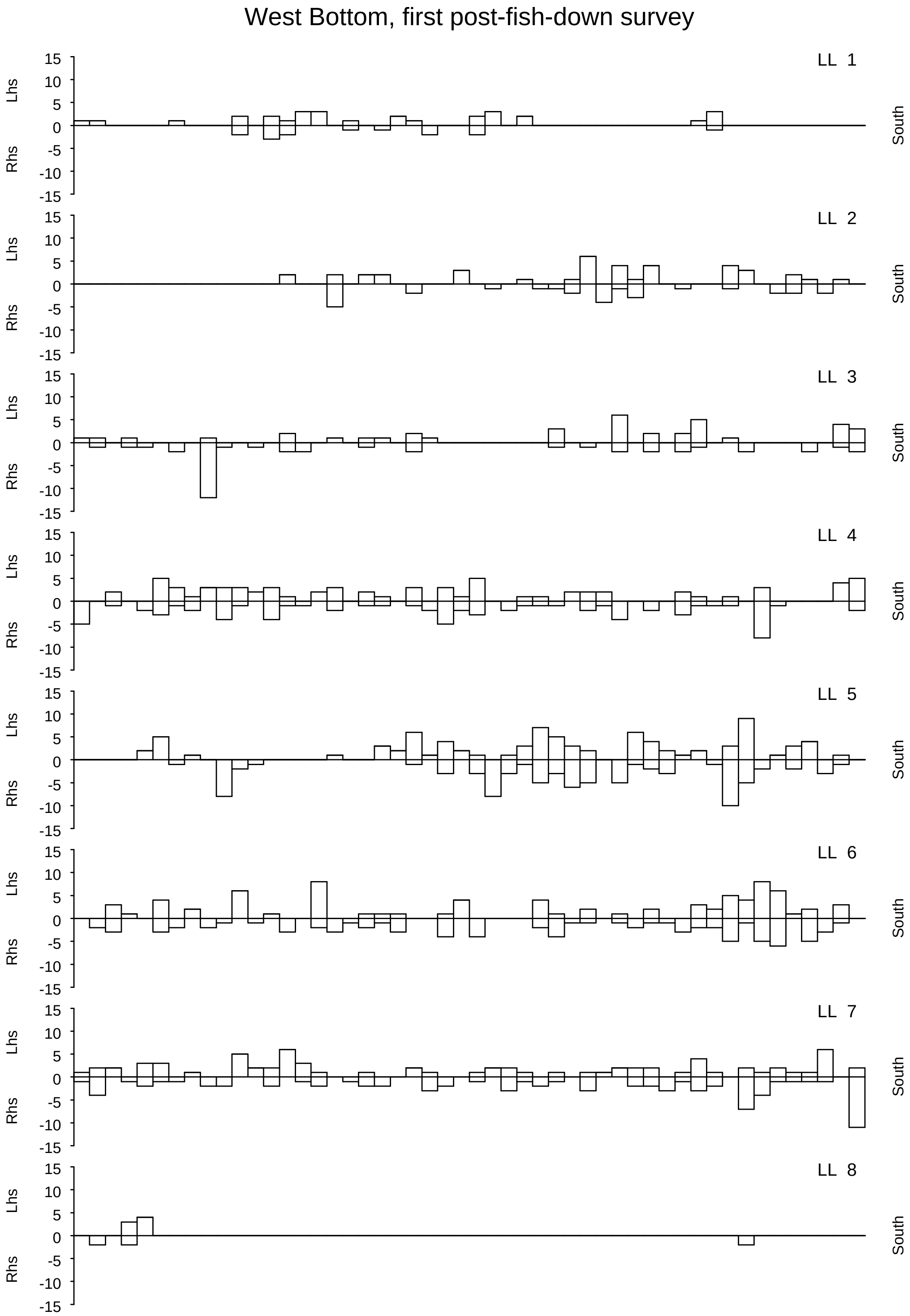

Figure 5.8. 2-m quadrat counts for the 8 leaded lines, with two transects on either side of each leaded line, recorded by divers at the first West Bottom post-fish-down survey.

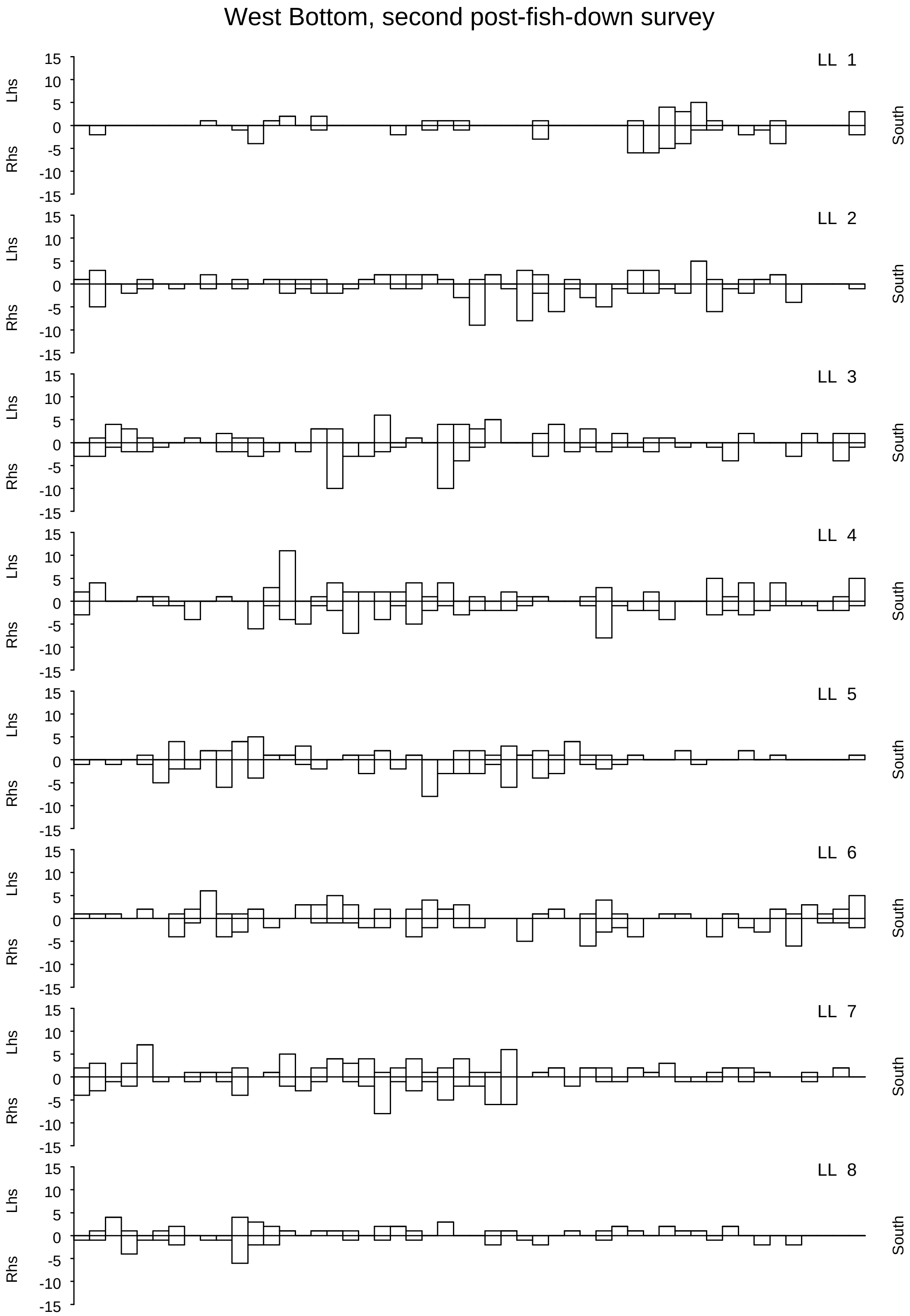

Figure 5.9. 2-m quadrat counts for the 8 leaded lines, with two transects on either side of each leaded line, recorded by divers at the second West Bottom post-fish-down survey.

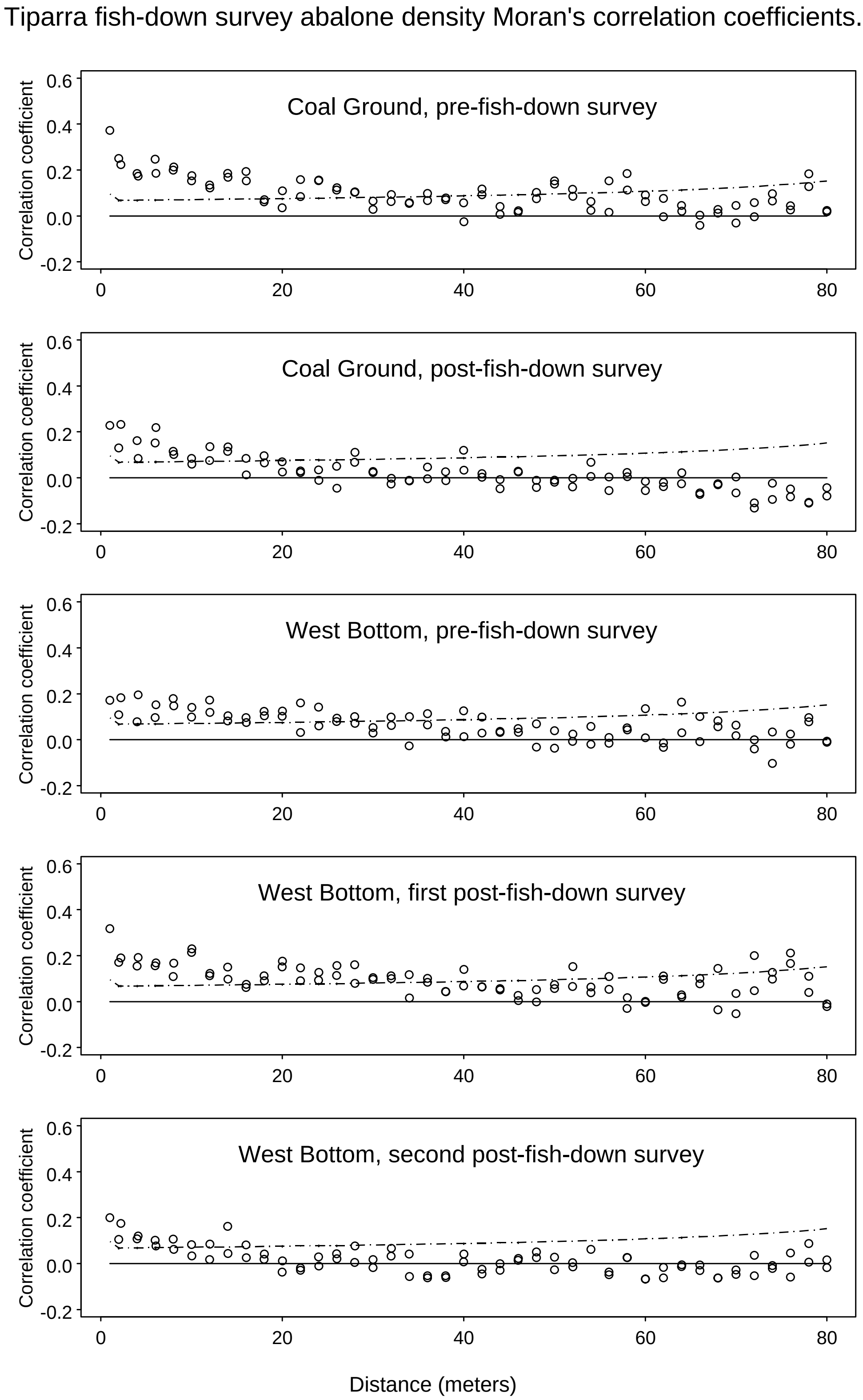

Figure 5.10. Spatial autocorrelations among 2-m quadrats from the five Tiparra leaded-line surveys. The Moran's *I* (circle markers) quantify the autocorrelation among pairs of quadrats spaced apart by the x-axis distances shown. The dotted line marks the 95% confidence interval under the null hypothesis of complete spatial randomness.

5.4. Discussion

5.4.1. Density Before and After Fish Down

In both Tiparra fish-down experiments, the principal declines in abundance from pre- to post-fish-down occurred in the subareas showing highest density in the pre-fish-down survey. Thus, the surveys appear to capture the spatial location of harvesting, or at least this is probable, since commercial harvesters in the fish down did not record where they fished in the Tiparra experiments. Nevertheless, it is probable that fishers targeted these patches of highest density. Similarly, at Taylor Island, the leaded-line locations with the biggest declines evident were in the areas indicated to be of high density in the pre-fish-down survey (Figure 3.3). In the last of the four fish-down experiments, at Waterloo Bay, fishers did record harvest locations (Chapter 9). Comparing where a large decline was evident in the post- versus pre-fish-down survey maps of density, with where fishers actually fished in Waterloo Bay, and where their highest catch rates were, showed good agreement. Thus, for the four experiments, all appear to have captured the spatial pattern of fishing, to the extent that high-density patches were identified in pre-fish-down leaded-line survey and these areas of high density were substantially reduced in all four fish-down harvests.

This ability to map the spatial pattern of fishing was a specified objective of the survey method to be developed in this project. The ability to provide broad-scale spatial information on density, and to identify areas of significant reduction under exploitation, are management-related capabilities of the survey design proposed.

Thus, the leaded-line method appears to provide the capability of quantifying spatial contraction or expansion of abalone populations. It is thought that this effect, of fishers moving to target successively contracting populations, may be the reason why CPUE provides relatively poor information on declining overall abundance. A spatially resolved survey method may supplement catch logs in this important way. Thus, in addition to estimating overall absolute density, the use of systematic samples of leaded lines appears to achieve the objective of mapping the locations of highest densities, and quantifying the impact of fishing on those high density patches.

5.4.2. Quantification of Clustering

The autocorrelation method, taking as data input, the 2-m quadrat counts along leaded lines, appears to offer some promise for quantifying clustering. The observed trend of autocorrelations declining from well above significant, to barely or not significant was the pattern predicted for clustered populations where the cluster diameter exceeded the quadrat diameter, as would be the case for most greenlip populations.

One feature that would be useful for management purposes was, however, not plainly evident in these autocorrelation graphs: there were not large declines in the levels of short-distance correlation from before to after the fish down. At Coal Ground (first two graphs of Figure 5.10), some evidence of declining overall correlation over short distances was perceptible, though it is doubtful this would be significant. At West Bottom, there was clearly no autocorrelation decline over the first 20 m. Thus, this autocorrelation measure of clustering did not detect a short-term reduction in cluster density which might result from fishers targeting these aggregations and which could signal reduced mean distance among abalone during spawning. However, it is certainly plausible that the observed rise in density at West Bottom from pre- to post-fish-down survey could have obscured this autocorrelation effect.

For other abalone species, such as blacklip and especially New Zealand paua, clustering can be considerably tighter than for greenlip. In these more tightly aggregated populations, the autocorrelations would be higher over shorter distances. In those cases, these transect-count autocorrelation tools have the potential to provide information about changes in the extent of clustering under exploitation.

Other methods to quantify the extent of abalone clustering include PNN (Chapter 2) whereby the distance of abalone from random points or other nearest-neighbour abalone are measured by divers. These methods have been shown to provide biased estimates of absolute density (Byth 1982; Chapter 2) but, using the Hopkins test, can provide relatively powerful measures of abalone clustering (Hopkins 1954; Byth and Ripley 1980; Diggle 1983; Chapter 2). However, the searches needed for nearest-neighbour distance measurements are very time consuming for divers underwater, and it is often difficult or impossible to get a representative (i.e. random or systematic) sample of the abalone population in a designated study region (Hines and Hines 1979; Byth and Ripley 1980; Diggle 1983).

The methods presented here, based on abalone counts in quadrats along the leaded line, are more feasible for divers in an abalone diver survey for reasons summarised in Chapters 3 and 4. The measure of absolute abundance that leaded-line transects provide is unbiased and this method is practical underwater so it is preferred to point-nearest-neighbour. With clustering provided as an added measure of the leaded-line survey design, its implementation in real abalone surveys becomes feasible. It should require little additional survey cost other than diverting diver survey effort to recording 2-m counts, along with the primary objectives of most surveys, namely measuring absolute density and a length sample.

As noted elsewhere in this report, in survey field practice, the choice for each diver swimming a 1 m x 100 m transect is between either measuring lengths or recording 2-m quadrat counts. In either case, a measure of absolute density is always obtained.

5.5. References

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Appendix 5.1. Krig Mapping Technical Specifications: Variograms and Cross-Validation

In this Appendix we summarise technical information about the krigs that were run. These parameters and other choices constitute decisions that the user needs to make to implement a krig map of density. Often these choices are somewhat arbitrary, a major drawback of kriging as the method used to construct interpolated density contours from raw point-location data. As noted, ArcView does provide the powerful model selection tool of cross-validation for assisting in this choice of the best set of krig control parameters, notably including the standardised root-mean-square cross-validation error, reported below in Table 5.1.

Table 5.1. Selected krig control parameters for the two Coal Ground krig-interpolated density maps (of Figures 5.1 and 5.2).

Survey	Number of leaded lines	Number of sample points in survey	Number of sample points included per kriging interpolation point	Semi-variogram model	Semi-variogram lag bin size (m)	Semi-variogram number of lags	RMSS prediction error statistic
Pre-fish-down	8	72	14	spherical	17	12	1.017
Post-fish-down	8	72	14	spherical	17	12	0.9866

Table 5.2. Selected krig control parameters for the two West Bottom krig-interpolated density maps (of Figures 5.3 and 5.4).

Survey	Number of leaded lines	Number of sample points in survey	Number of sample points included per kriging interpolation point	Semi-variogram model	Semi-variogram lag bin size (m)	Semi-variogram number of lags	RMSS prediction error statistic
Pre-fish-down	8	72	14	spherical	30	12	1.005
Post-fish-down	8	72	14	spherical	30	12	0.9885

CHAPTER 6. Leaded-line Surveys at Waterloo Bay: Optimising Survey Design for Higher Precision of Legal Density, Length Frequency and Density and Mean Length Maps

R. McGarvey, P. Preece, J.E. Feenstra

6.1. Introduction

The absolute density of legal-size abalone is the principal survey quantity sought. To estimate legal density, legal from sublegal abundance must be differentiated. Smaller (sublegal) abalone are often subject to larger sample variation than the legal sizes we principally seek to estimate. Smaller abalone are sometimes more cryptic, that is, better hidden than at other times. With survey designs where all counted individuals are not measured for length, the length-frequency sample must be measured partly (as at Taylor Island) or entirely separately (as at Tiparra) from the leaded-line counts. With these leaded-line survey designs, the estimated proportion legal obtained from the length sample is multiplied by the total mean density from the leaded-line counts to infer legal density. As discussed in Chapters 3 and 4, any error in the sample variation of smaller abalone will thus be incorporated into the estimate of proportion legal, and thus, in turn, into the estimate of legal density. An important objective in the Waterloo Bay leaded-line surveys will be to remove this need for a separate estimate of proportion legal. This can be achieved if all the abalone that are counted are also measured for length along each leaded-line transect.

A second objective is to increase primary-unit sample size. Previous study of fishery sampling survey designs (Pennington and Volstad 1994; McGarvey and Pennington 2001; Aanes and Pennington 2003) have consistently shown increases, sometimes large increases, in the precision of estimates of mean density of aggregated populations by altering the survey design to sample more primary units. Given equal cost, this can be achieved by taking smaller samples at each primary sampling location. These analyses have shown that when populations are aggregated this trade-off is nearly always highly favourable.

Specific objectives for improving the leaded-line survey design at Waterloo Bay were (1) to increase the number of leaded-line sample locations by reducing the time invested in each. Secondly, (2) we sought to eliminate the overestimation bias (of approximately 10%, see Section 4.4.2) that was observed from the perpendicular transects at Tiparra, caused (presumably subconsciously) by divers drawing out their lines on the reels they carried towards patches of higher abundance. Lastly, (3) we sought a design whereby all counted abalone were also measured for length.

Waterloo Bay has been the subject of numerous studies by Shepherd and colleagues, in studies of habitat and plant cover mapping (Shepherd and Womersley 1981), greenlip abalone movement (Shepherd 1986a; Shepherd 1986b), and recruitment dynamics (Shepherd and Partington 1995). Dowling (2002) directed a fish-down experiment here and tested a distance transect method of survey design, with the principal objective of quantifying the impact of fishing targeting aggregations (Dowling et al. 2004a).

6.2. Methods

6.2.1. Leaded-Line Survey Design: Modifications from Previous Fish-Down Surveys

To improve the estimates of mean density for the harvestable size range (set to be abalone of length > 130 mm SL for this Waterloo Bay fish-down experiment), a number of survey design modifications were implemented. The primary sampling unit remained the 100-m leaded line, but at each leaded-line sample location, the (secondary) quantities measured were reduced.

Positions for leaded lines were located to achieve a uniform distribution across the study region (Figure 6.1). The start and end positions of the 32 leaded lines, drawn visually by the GIS team, were provided to research divers. They swam the pre-fish-down transects on 29 September to 15 October 2003.

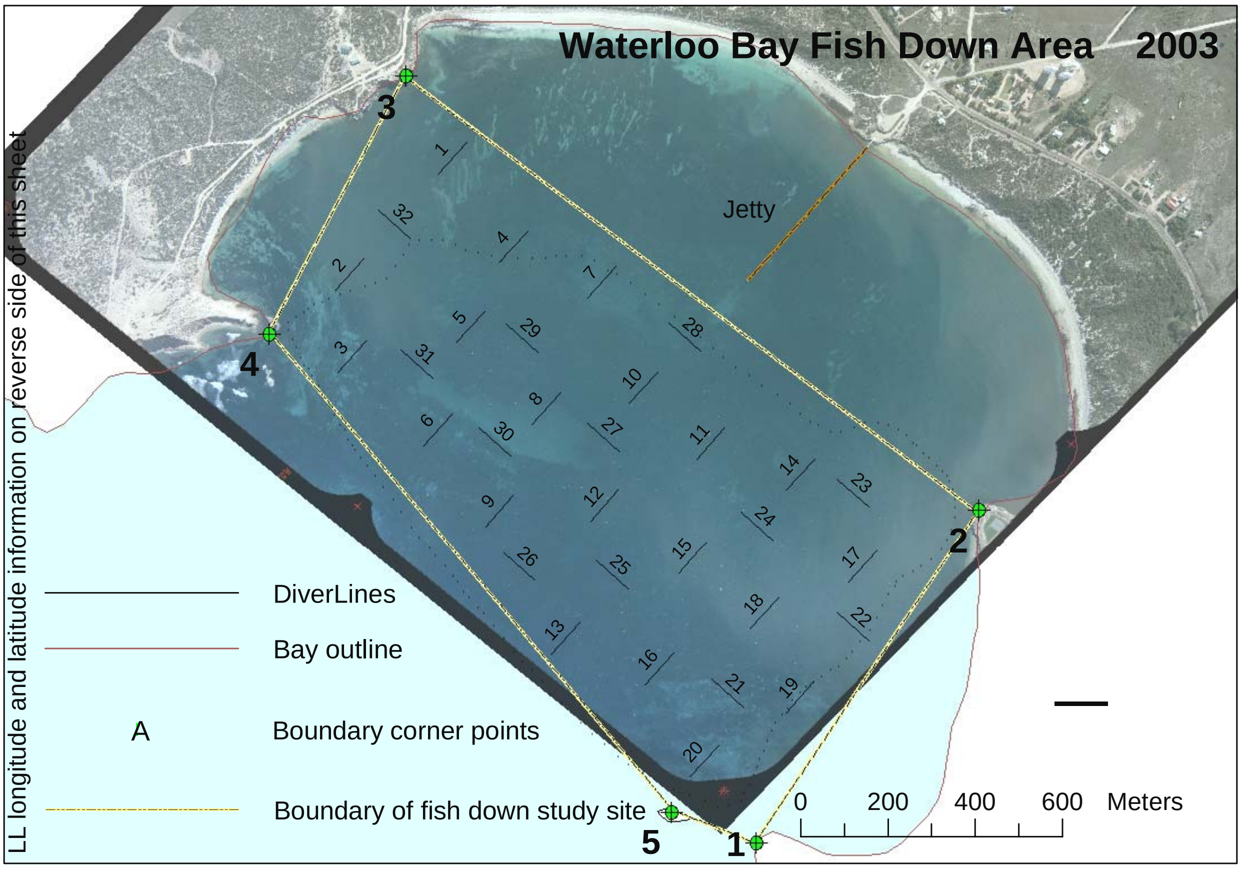


Figure 6.1. ArcView GIS map of Waterloo Bay distributed to research divers. The 32 100-m leaded-line survey transects are shown. An aerial photograph has been digitised, rectified and overlaid.

Survey design modifications were as follows. (i) The use of the 100-m leaded line was retained, but divers swam and counted abalone only along the 1-m wide transects adjacent to these leaded lines. No perpendicular transects were run. This permitted many more leaded lines over the approximately four-day survey period. Overestimation bias from perpendicular transect counts was thereby eliminated. Eliminating perpendicular transects also reduced the total distance swum at each leaded line (by each diver) from 220 m to 100 m. Survey leaded lines are often directed parallel to the prevailing current (though there is little current in Waterloo Bay) and by eliminating perpendicular transects, only downstream swimming is then required. Moreover, the two divers are thus never more than a few metres from each other, enhancing safety. In addition, for this survey, (ii) divers did not record the individual 2-m quadrat counts along each leaded-line transect. With research divers foregoing the clipboard used at Tiparra (and by one of the two divers at Taylor Island) for recording 2-m quadrat counts, both divers instead carried a Shepherd gauge for measuring abalone lengths. This permitted (iii) both divers to measure lengths and thereby, at the same time, count all abalone in their 1x100 m^2 transect. With this protocol, there was thus no need to add an additional day of diving to measure abalone lengths after the density counts were completed, and this day was used for adding more leaded-line primary sample units.

Overall, primary-unit sample size increased from 8 to 32 leaded lines per survey in Waterloo Bay. These were accomplished, including a day of timed swims, by a 3-diver team in 5 days for the pre-fish-down survey and in 4 days post-fish-down.

6.2.3. Statistics and Mapping

The statistical methods developed in Chapters 3 and 4 for calculating mean density, and for estimating the confidence intervals about the mean density estimate, were employed in the Waterloo Bay leaded-line surveys. These methods were applied to pre- and post-fish-down survey data sets to estimate absolute density for harvestable-size and all-sizes of greenlip abalone in the Waterloo Bay study region (Figure 6.1).

As with previous leaded-line surveys, confidence intervals for survey mean density were calculated using a two-level bootstrap. The first (primary-unit) level of re-sampling with replacement was from the full set of 32 leaded lines. At the secondary-sampling level, within each leaded-line, two counts were re-sampled from the two sides of each leaded line, rather than from a more extensive set of secondary unit counts, notably the 100 2-m quadrats and 4 25-m perpendicular transects, recorded at Tiparra.

Mapping of both density and mean length was undertaken using the 32 leaded-line locations inside the Waterloo Bay study region (Figure 6.1). These maps were generated in ArcView v. 8.2 for pre- and post-fish-down surveys. Two methods were employed to map each set of spatial-resolved samples in order to present a robust picture of the outcomes, since some variation in the maps will always result from the particular choice of mapping technique. The first method, linear contour mapping using a partition of the area into triangles (TIN), simply draws contour lines based on the three surrounding points. The second method was an exact method of interpolation known as ‘radial basis function’. This approach is based on a neural network, and as such, uses the computer’s ability to simulate human pattern recognition. However, like all neural network approaches, the algorithm for specifying the interpolation values is effectively hidden inside a black box. The more traditional statistically rigorous method of interpolation known as kriging was not appropriate for the Waterloo Bay spatial data where a gradual decline in correlation of sample values with increasing distance between them was not evident. Radial basis functions, unlike krigs, make no assumption of a quantifiable declining trend in spatial autocorrelation.

6.3. Results

6.3.1. *Mean Density*

6.3.1.1. Pre-Fish-Down Survey

The mean density of greenlip abalone in Waterloo Bay was estimated in the leaded-line survey at 0.134 abalone per m^2 for all sizes. Divided into two size ranges, the observed mean density of abalone in the fish-down harvestable size range ($\geq$130 mm SL) was 0.069 abalone per m^2 and, for abalone <130 mm SL, was 0.065 abalone per m^2. These estimates were from a total of 855 abalone counted by divers in the 32 leaded lines (each comprising two transects of 100 m^2).

These densities are about 4 times lower than observed at the two study sites on Tiparra Reef, though it must be noted that the two Tiparra study regions were specifically chosen to be areas of high density as identified by habitat mapping using sounder and boat-deployed video. At Waterloo Bay, the study site encompassed the outer two-thirds of the Bay, which probably included substantial areas of non-greenlip habitat, and in which many zero and near-zero transect counts were recorded.

Confidence on these estimates of mean absolute density, calculated as a percentage of the mean (~30%), were comparable but generally higher than previous surveys (~20%), notably due to high spatial variance, illustrated in maps (Figures 6.7-6.10) below. The two-level bootstrap standard errors were ±31% and 28% for harvestable sizes and all sizes respectively.

A high percentage, notably 21 (of 64) 100x1 m^2 transects, yielded a zero count of harvestable-size abalone (Figure 6.2), and at 17 transects divers found no abalone of any size.

6.3.1.2. Post-Fish-Down Survey

Post-fish-down all-sizes density declined to 0.088 abalone per m^2. For harvestable sizes, the post-fish down density was 0.044 abalone per m^2, a decline from before to after the fish down of 36% (Table 9.1).

The two-level bootstrap standard errors of mean density were ±24% for harvestable sizes and ±26% when all abalone are included. These standard errors expressed as a percentage of the estimated means, were lower than the pre-fish-down values of ±31% and 28%. And in absolute width of the confidence range, the standard errors of the post-fish-down survey were substantially smaller (Figure 6.3).

A smaller number of transect counts in the post-fish-down surveys were zero, at 16 zero transects for legal abalone and 11 for all sizes of abalone out of 64 transects total, compared with 21 and 17 transects in the pre-fish-down survey. This is not surprising, but probably reflects the minimal amount of fishing that harvesters would have spent in areas of near-zero abundance. Assuming that nearly no fishing took place in these areas, the count of zeros in the post-fish-down survey could have been higher or lower with nearly equal probability.

Histograms of transect numbers versus absolute count of abalone (Figure 6.2) show that most of the reduction in abundance from before to after the fish down occurred in the high-catch transects (greater than about 40 abalone per 100 m^2 transect), which are fewer in number in the two post-fish-down histograms of Figures 6.2b and 6.2d. More specifically, examination of Figure 6.4 shows that most of the reduction in harvestable population numbers occurred in the high-catch sample locations (notably at leaded lines LL11, LL24 and LL27). Thus, it appears that the leaded-line survey did capture the spatial distribution of harvesting principally on the patches of high density, and recorded declines there. The level of spatial agreement between these areas of survey high density and the location of the commercial harvest can be visually examined in the survey density maps of Section 6.3.4 (survey) and of commercial catch rate (Figure 9.1).

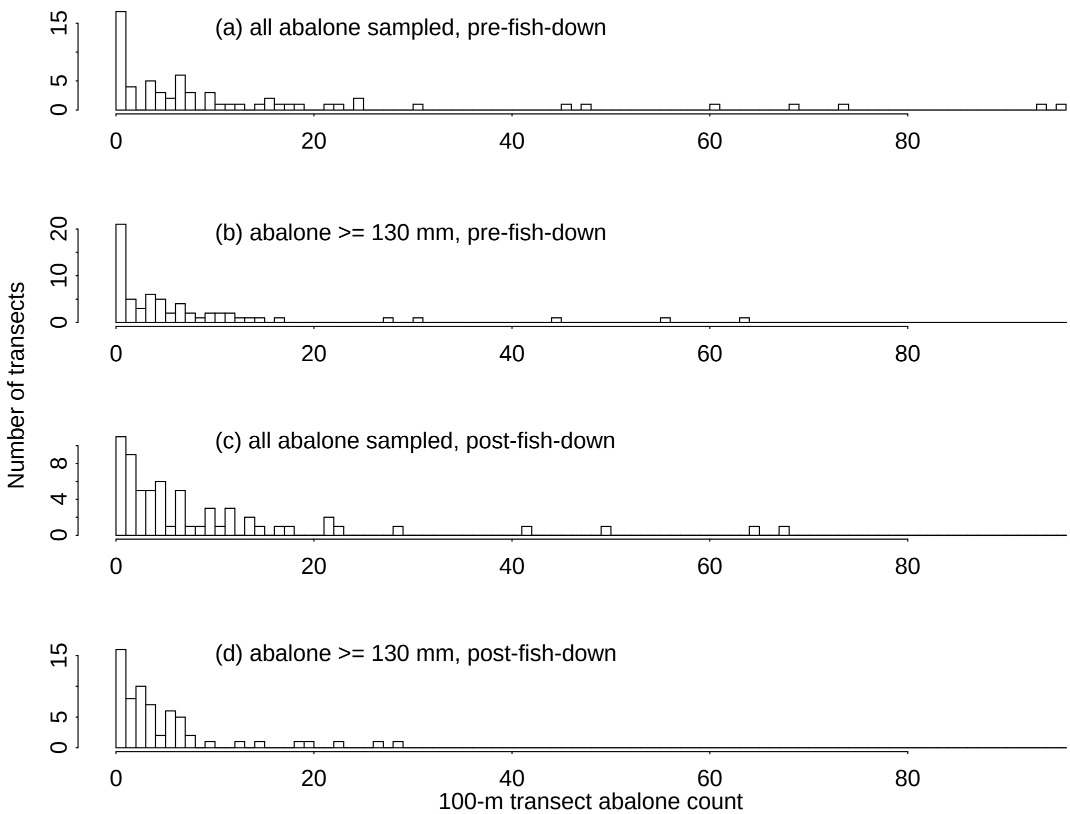


Figure 6.2. Histograms of diver counts, for (a & c) all sizes of abalone and (b & d) harvestable-size abalone, in the pre- and post-fish-down leaded-line surveys of Waterloo Bay. Diver counts are from the 64 100x1 m^2 transects (32 leaded lines, 2 transects per leaded line) searched at each leaded-line sample location shown on the map of Figure 6.1. The number of zero counts is shown as the left-most bar on each graph.

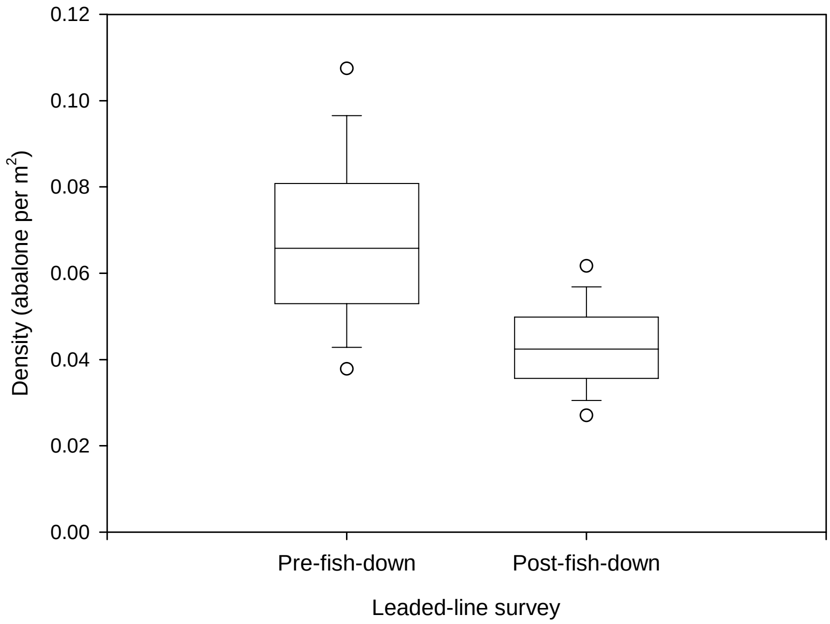


Figure 6.3. Confidence ranges for the two leaded-line survey estimates of absolute density: boxplots of bootstrap replicates for harvestable-size density, prior to and following the fish down harvest. Quantiles of the bootstrap replicates are marked by circles (5% and 95% confidence bounds), whiskers (10% and 90%), and boxes (25% and 75%).

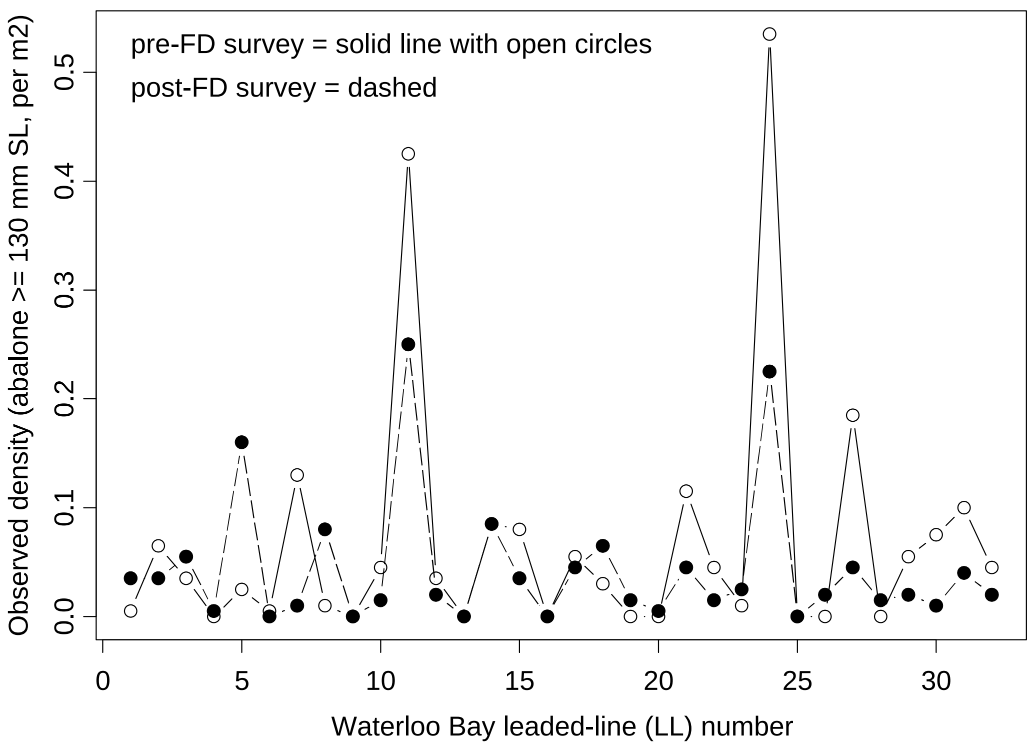


Figure 6.4. Densities by leaded-line from the pre- and post-fish-down surveys of Waterloo Bay. Each density point shown is an average of the two transects at each leaded-line location.

6.3.2. Length Frequencies

As in previous length-frequency figures of this report, the length frequency curves have been rescaled upward, so that the y-axis value at each point on the curve represents the estimated number of abalone present in the study region, in each 1-mm-wide length interval along the curve. The decline in numbers of harvestable-size abalone following fishing is evident.

Some evidence of lower numbers is also seen for those below harvestable size. This is presumably due to random sample variation, which as shown in the next section, is substantially higher for abalone in the smaller size range.

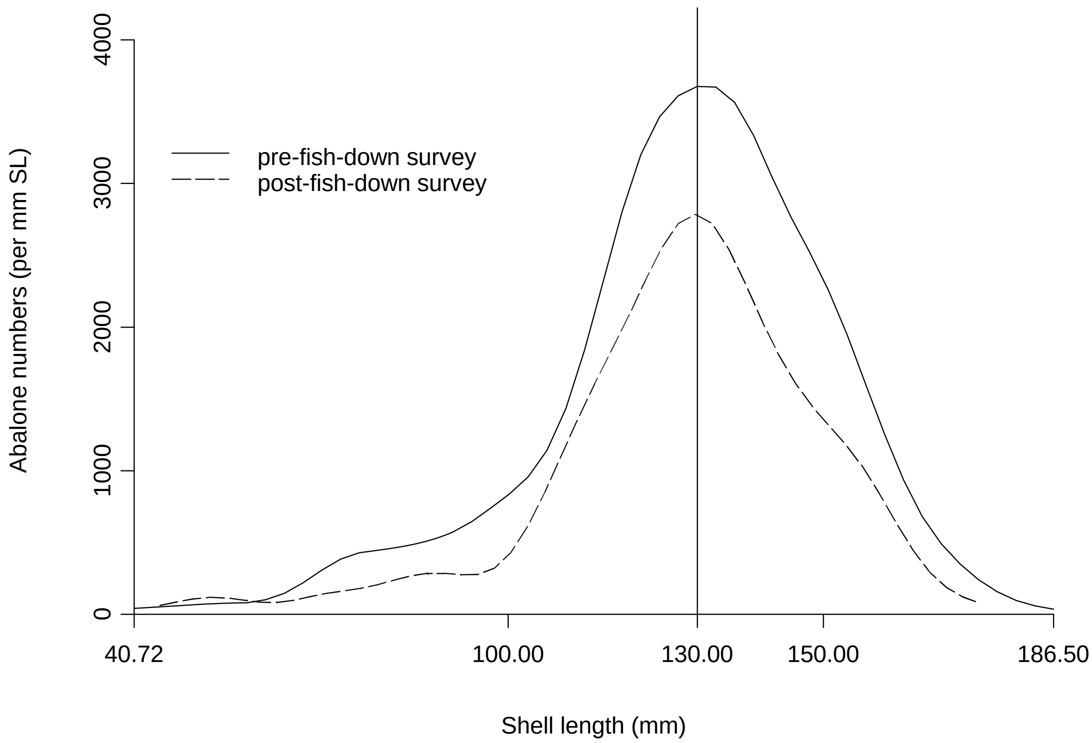


Figure 6.5. Leaded-line survey length frequencies. Kernel density length-frequency plots of greenlip abalone shell lengths in the pre- and post-fish-down surveys of Waterloo Bay ($n_{pre} = 855$, $n_{post} = 564$). Divers measured all abalone for length in 1-m transects along both sides of all 32 leaded-line locations. The y-axis has been rescaled so that the integrated numbers of abalone under the two curves equal the estimated total numbers present in the study region before and after the fish-down. The harvest minimum length of 130 mm SL is also shown. The upper and lower extents of the two curves show the minimum and maximum lengths recorded.

6.3.3. *Proportion Legal*

High sample variance in the proportion legal (the proportion of abalone ≥ 130 mm SL) observed in the Taylor Island and Tiparra surveys guided several aspects of leaded-line survey design at Waterloo Bay. One assumption underlying the decision to be able to separate the counts of smaller from harvestable size ranges of abalone (achieved by measuring them all) was that the sample variation in counts of smaller abalone was higher. To test this assumption, specifically to compare the relative extent of sample variation in the two size categories (above and below 130 mm SL), two-level bootstraps were also run on the survey counts of the sublegal size range (< 130 mm SL). For the pre- and post-fish-down leaded-line surveys, counts below 130 mm SL gave standard errors of ±31% and ±33% respectively. The comparable standard-error percentages were ±31 and 24% for harvestable sizes (≥ 130 mm SL), as reported above. Thus small abalone gave higher levels of sample variation only for the post-fish-down density counts.

The small size range (<130 mm SL) also yielded substantially more zero counts with 28 zero-count transects (of 64) in both pre- and post-fish-down surveys. The harvestable size range yielded 21 and 16 zero counts respectively. The lower number of zeros for harvestable sizes is not due to a lower sample size for smaller abalone. The sample counts in the sublegal size range of 416 and 285 for pre- and post-fish-down, were about equal to those in the harvestable size range (439 and 279). Thus, in post-fish-down standard errors, and in numbers of zero counts, smaller abalone show higher levels of randomness in sampling.

At Waterloo Bay, proportion legal was not correlated (or anti-correlated) with density. The correlation coefficient of proportion legal against all-sizes density among the 25 non-zero leaded-line samples was r = -0.17 (df = 23, p-value = 0.4157) which is not close to a significant difference from zero correlation. This correlation was calculated for the pre-fish-down survey data only, the post-fish-down survey being potentially biased in this context, with about 30% of the harvestable-size abalone already removed. Graphically, a scatterplot (Figure 6.6) also shows no evidence of relationship between proportion legal and overall density. This observation, among leaded-line locations, of no spatial correlation between proportion legal and abalone density, was also observed at Taylor Island.

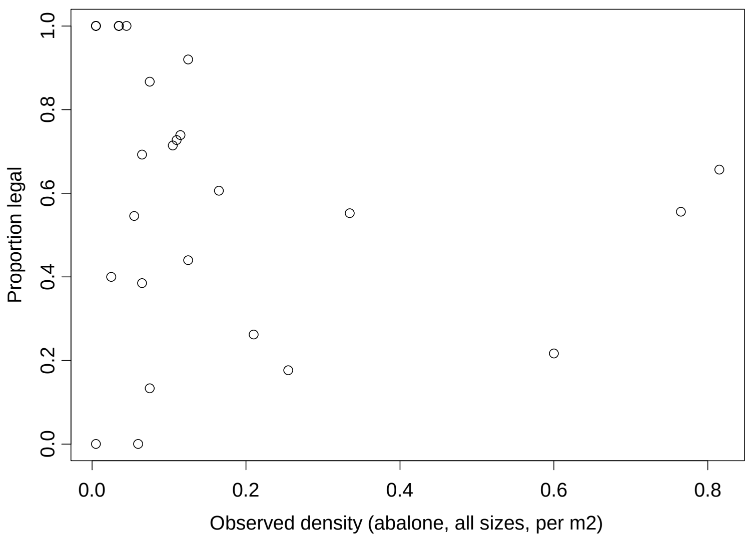


Figure 6.6. Scatterplot of the proportion legal versus density at (n = 25) non-zero-count pre-fish-down leaded-line survey locations.

6.3.4. *Maps of Density and Mean Length*

6.3.4.1. Density

The maps of abalone density identify one area in Waterloo Bay where high densities were found. This area, located south of the jetty and centred around leaded-line locations LL24 and LL11, is identified as the principal area of high density in both pre-fish-down (Figure 6.7) and post-fish-down (Figure 6.8) maps, and for both methods of mapping, namely triangulated contours and interpolation by radial basis function. It is also evident in comparing these two density maps (Figures 6.7 and 6.8) (also shown in the densities by leaded-line of Figure 6.4), that harvestable-size density declined substantially, and principally in this area.

In Chapter 9, we examine the spatial distribution of reported fish-down harvest locations. A test of the leaded-line survey method for use in spatial analysis of abalone fishing will be whether this general area identified by survey is, in fact, where fishing predominantly occurred. This comparison for Waterloo Bay will be undertaken in Chapter 9.

6.3.4.2. Mean Length

Mean abalone length also expressed a general spatial pattern observed in both pre- and post-fish-down surveys. This pattern is identified by three related features evident in the two survey maps of mean-length (Figures 6.9 and 6.10): (1) Greenlip abalone shell length was smallest along the northeastern study region boundary line (between corners numbered 3 and 2). This low-mean-size region, shown in light green, is evident from near the jetty's end northwest along that boundary approximately 400 m. (2) Second, there is a general tendency for mean length to increase as position moves away in all possible directions from this subregion of low mean length. Abalone are of generally larger mean length along the opposite (southwestern) boundary which is parallel and roughly coincident with the mouth of the Bay. Along this southwestern boundary (between boundary corners numbered 5 and 4), a barrier reef, called the 'Bar', rises to near-zero depth, broken by a narrow channel, permitting the discharge of water that washes as waves over the reef during periods of high swell from the southwest (Shepherd 1986a). Most abalone cannot presumably move beyond this boundary. The hypothesis of greenlip abalone movement in Waterloo Bay from the central basin of smallest mean length outward is discussed in Section 9.4.3.2.

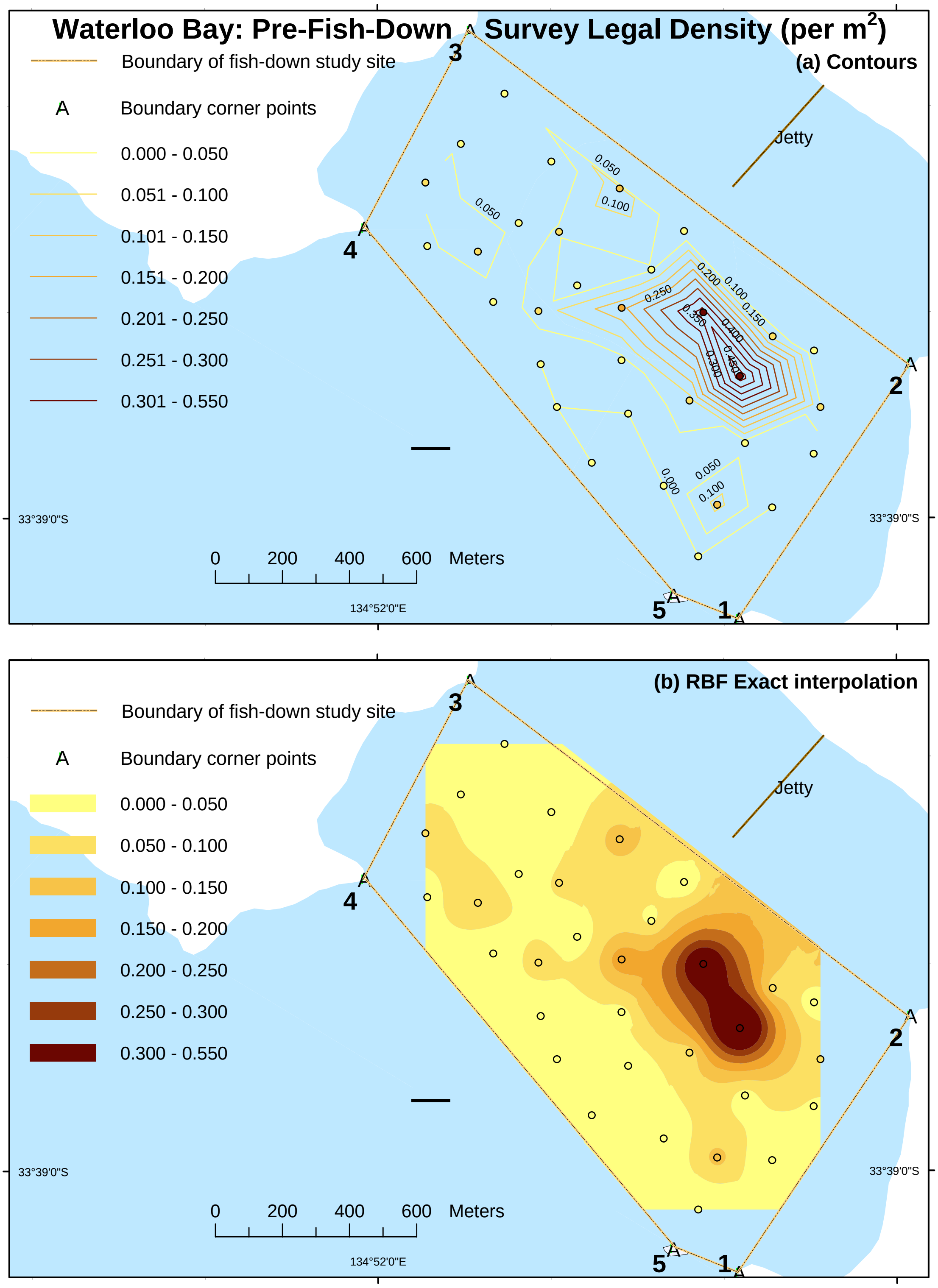


Figure 6.7. Density maps of greenlip abalone from the pre-fish-down survey of Waterloo Bay. Density of legal-size (≥ 130 mm SL) abalone is shown (a) by triangulated contours and (b) by spatial interpolation using the radial basis function (RBF).

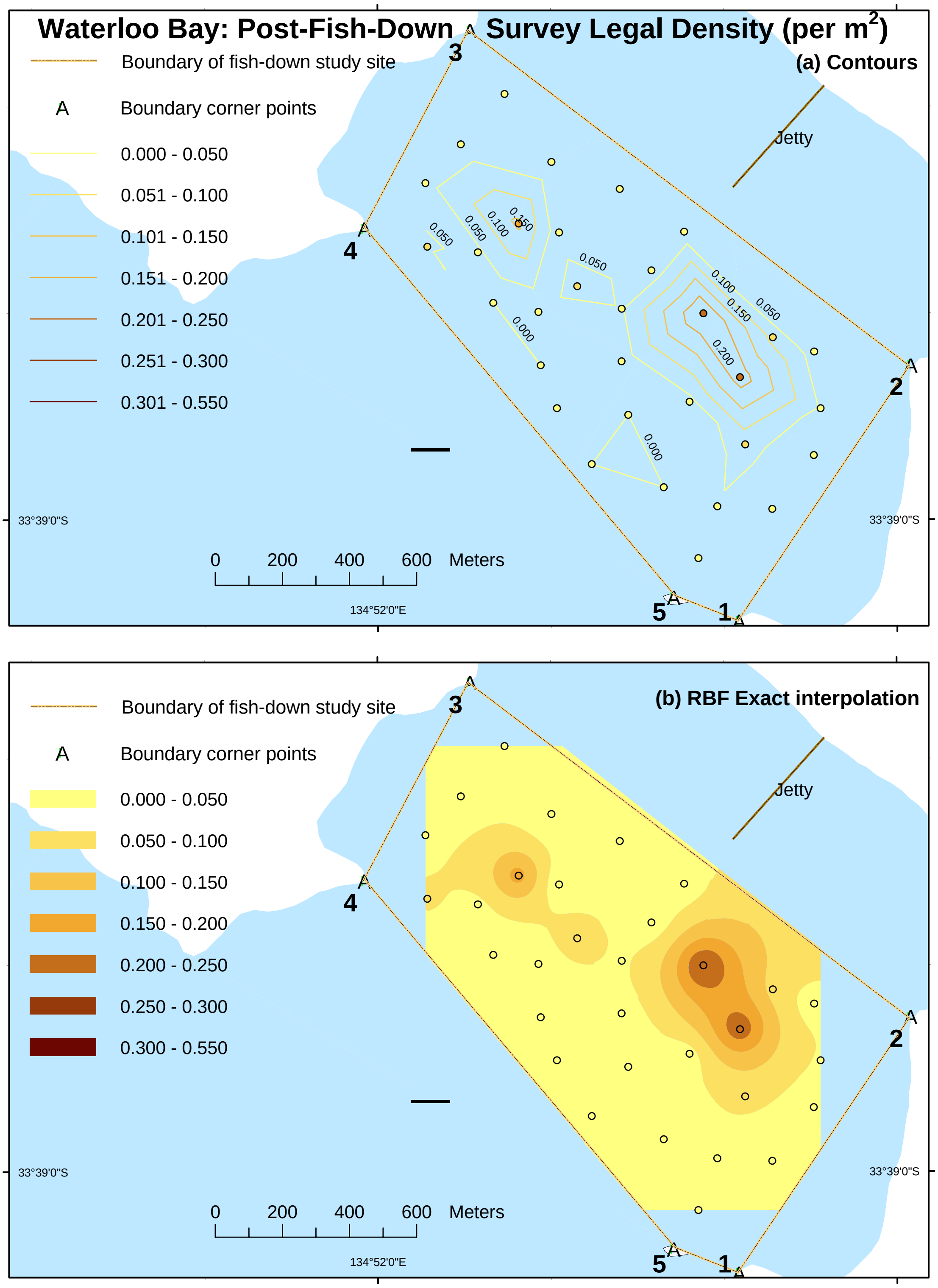


Figure 6.8. Density maps of greenlip abalone from the post -fish-down survey of Waterloo Bay. Density of legal-size (≥ 130 mm SL) abalone is shown (a) by triangulated contours and (b) by spatial interpolation using the radial basis function (RBF).

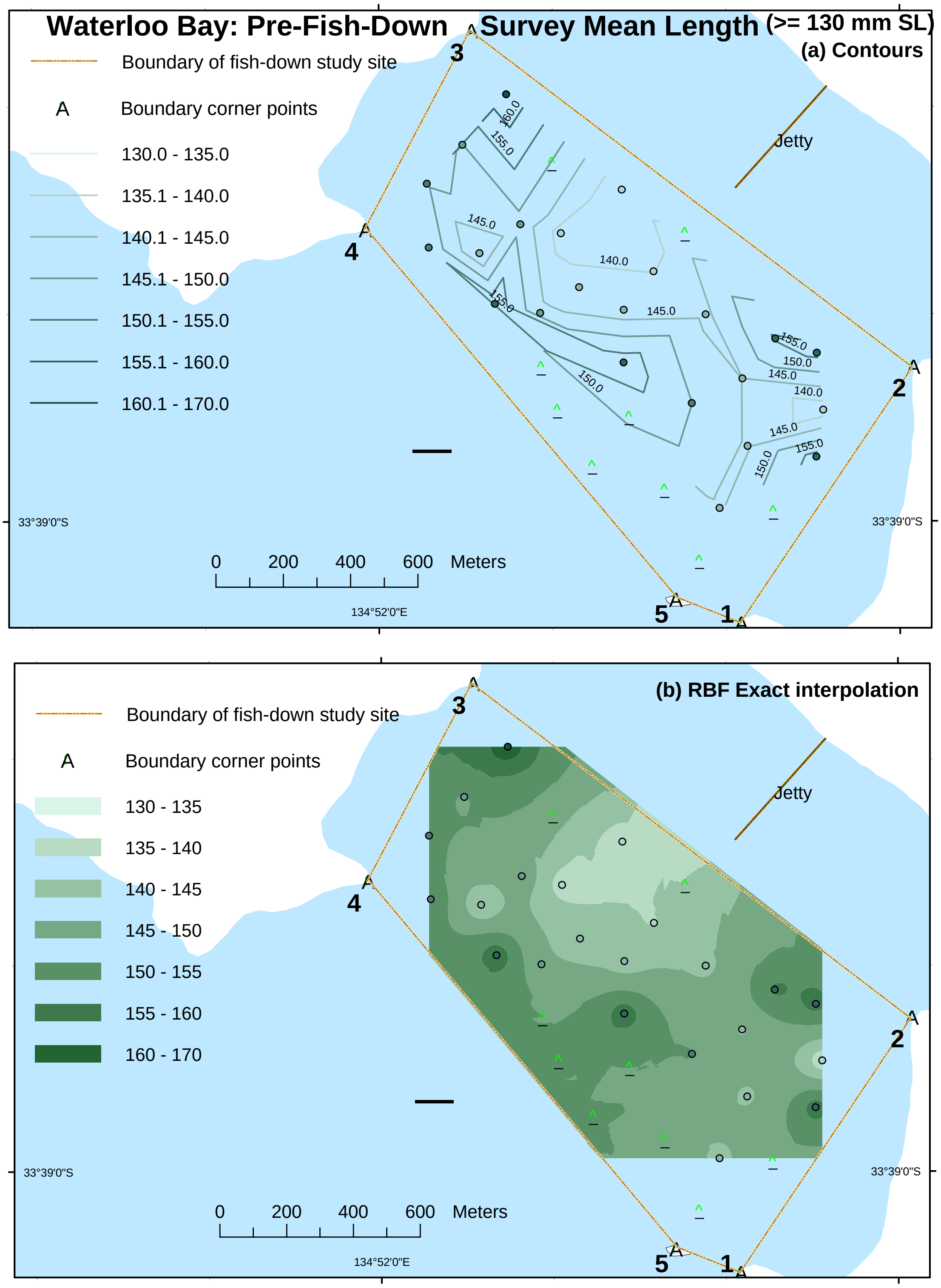
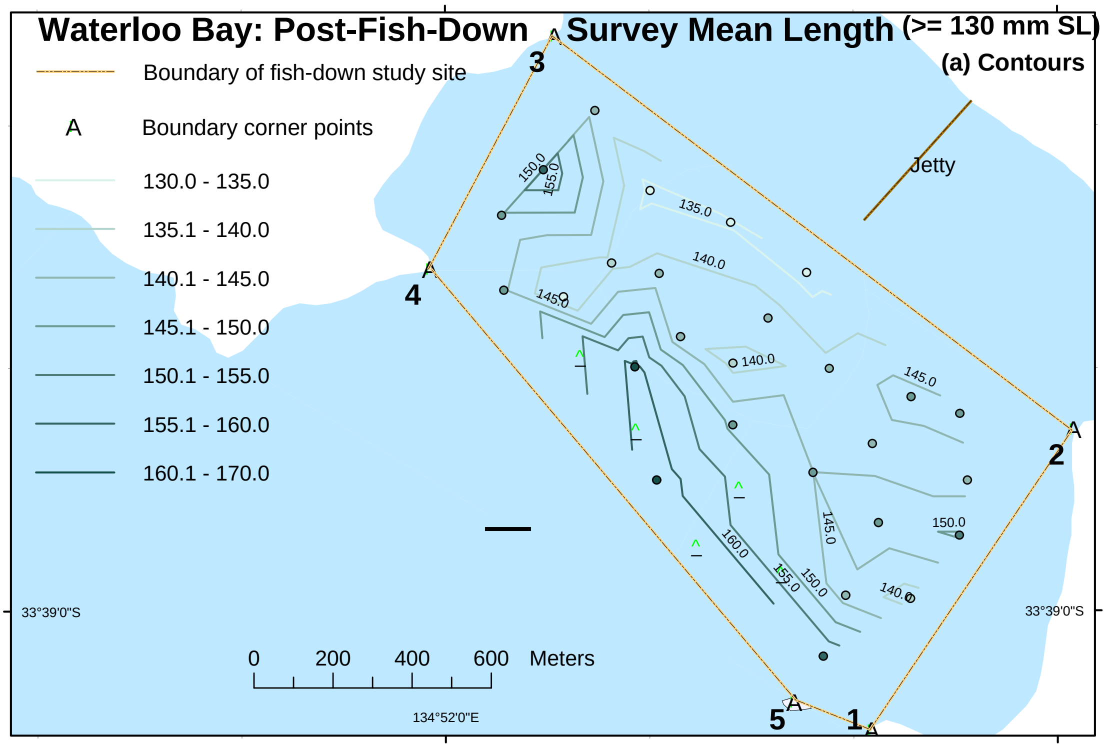


Figure 6.9. Maps of greenlip abalone mean length from the pre-fish-down leaded-line survey. Only abalone of legal-size (≥ 130 mm SL) were included in this survey measure of mean length for comparison with the mean length of abalone harvested in the commercial fish-down (Chapter 9). Triangulated contours are shown in the top map and the same spatial data is interpolated in the bottom map using the radial basis function (RBF). Leaded-line locations where no abalone were found are indicated by green stars.



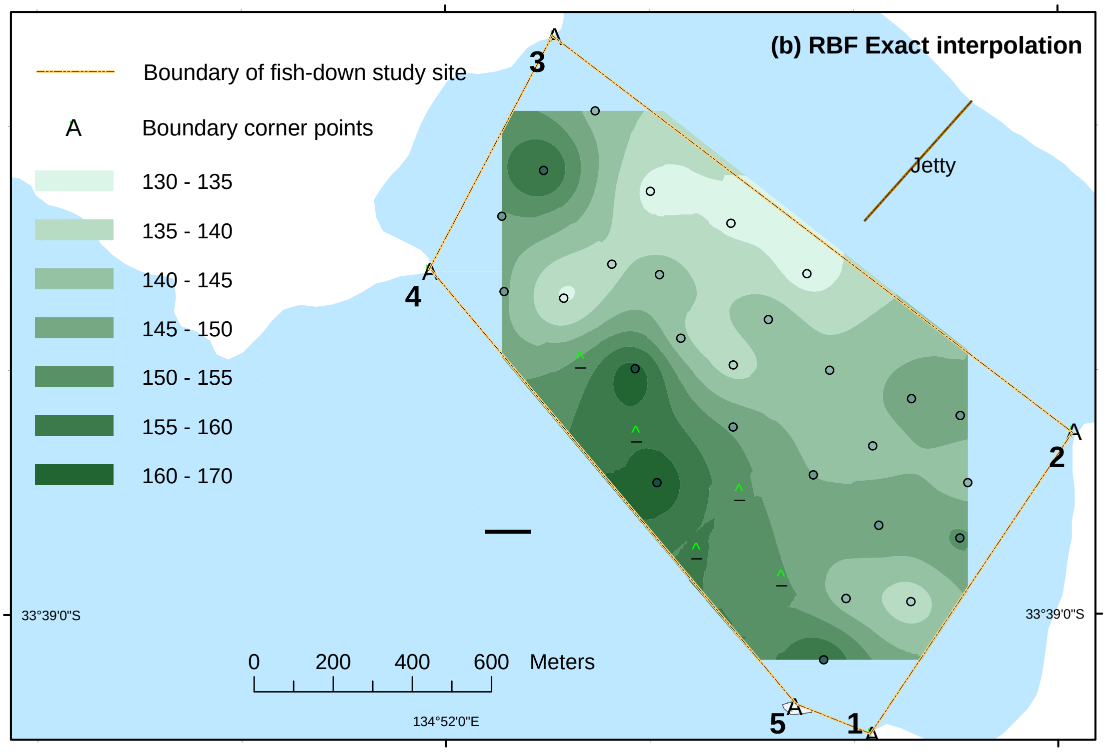


Figure 6.10. Maps of greenlip abalone mean length from the post-fish-down leaded-line survey. Only abalone of legal-size (≥ 130 mm SL) were included in this survey measure of mean length. Triangulated contours are shown in the top map and the same spatial data is interpolated in the bottom map using the radial basis function (RBF). Leaded-line locations where no abalone were found are indicated by green stars.

6.4. Discussion

6.4.1. Future Strategies for Stratification

Areas of zero count and an evident wide spread of counts overall scattered among a few very high counts, are the principal causes of high sample variance of the density estimates from these diver surveys. High variances reflect the typically highly clustered nature of abalone on the bottom, here specifically, of Waterloo Bay, where densities were high (i.e. > 0.4 abalone per m^2) in 3 of 32 and medium (0.2-0.4 abalone per m^2) also in 3 of 32 survey locations (Figure 6.6). Thus low density (< 0.2 abalone per m^2) comprises about 91% of the total surface area. The high and medium density areas constitute about 9%. That sample variances were higher in the pre-fish-down survey (Section 6.3.1) may reflect the spatially equalising effect on density of fishing targeting aggregations.

This broad-scale spatial distribution, of fishable densities being relatively localised inside an overall study region of interest, is typical of abalone, including greenlip. Because abalone are so patchy in distribution, stratifying the study regions will almost certainly bring increases, potentially substantial increases, in survey precision by comparison to the uniform (and systematic) coverage of leaded-line locations employed in the two Waterloo Bay surveys (Figure 6.1).

South Australian abalone commercial fishery catch and effort data are reported in spatial units, that is, statistical reporting blocks, of relatively small size called ‘Map Codes’. For purposes of abalone management and stock assessment, and for stock assessment modelling, survey study region boundaries should be drawn to overlap with existing Map Code boundaries.

In general, diver-survey study regions will be smaller than a Map Code, and so, when choosing survey strata boundaries, Map Codes would be partitioned into survey strata. The objective, in choosing strata boundaries, will be to obtain survey estimates of absolute mean density with the highest precision feasible inside each Map Code spatial unit of management interest.

The mapped distributions of abalone density in Waterloo Bay (Figures 6.7 and 6.8) illustrate one way that stratification could be undertaken in future surveys, here and elsewhere. Survey strata could be drawn following the general contours of the density maps such as those shown as boundaries between different colours in Figures 6.7 and 6.8. Probably the interpolated (here, RBF) boundaries would be used in preference to the straight lines of raw triangulated contours since the former incorporate more sophisticated methods of statistical inference, and they vary more smoothly. Then a strategy would be chosen for allocating leaded-line sample size of diver transects to each stratum.

A formal method for allocating the available leaded-line diver transects among strata is needed. Generally sample variance will be minimised by allocating relatively more leaded lines to high-density strata. This strategy may vary from one survey and study region to the next. But in general, we let the sample size (number of leaded-line transects) be proportional to the abalone population size times the expected sample variance in each stratum (Cochran 1977, Eq. 5.26), so-called Neyman allocation of sample units, which minimises overall sample variance of mean abalone density inside a stratified study region, such as a Map Code. This provides a method for allocating leaded-line samples using spatial information about abalone density from previous leaded-line surveys in the overall study region.

Both Neyman allocation and common sense predicate that no or very few transects be run in areas where the expectation of zero density is high. Diver time is costly.

In cases where we are interested principally in changes in abundance rather than simply a point estimate of mean density, because fishing concentrates mainly in high-density strata, a still greater proportion of leaded-line samples can be allocated to high-density strata.

In study regions where the variance in different strata can be approximated as roughly equal, leaded-lines are placed in strata proportional to estimated absolute population numbers (i.e. proportional to density) and variance can be ignored.

Preliminary discussions have raised the possibility that sometime in the future, fishers may provide more exact information about where they fish than a reported Map Code. Satellite–linked vessel monitoring systems are generally too expensive, but the adoption of the Victorian shell measuring machine on board fishing boats and used by the sheller would record the GPS position and length of every abalone processed on board. Or, fishers could volunteer to download marks from their GPS. Any of these methods would be of particular value for drawing survey strata. Specifically, we could locate surveys in specific areas of abalone habitat where fishing actually took place, and relate changes in estimated density from one year to the next to levels of harvesting, where that would be possible in high-fishing strata. Thus, with periods of fishing and known levels of removal in known areas interspersed between yearly surveys, we can monitor the changes in each survey study region to evaluate the impact of fishing on population size in those areas. This will be provided along with length frequencies and absolute mean density, in the survey regions (and/or Map Codes) overall.

The stratification strategy outlined above assumes that no boat-based habitat mapping has been undertaken. Rather it relies on a uniform coverage of leaded-lines diver transects swum in the first-year survey as we have done in Waterloo Bay. Alternatively, prior knowledge from fishers and researchers about areas of principal abalone habitat for drawing strata boundaries in the first year of a broad-scale coverage survey can be used.

When boat-based and/or diver-based habitat maps, or verbal input from fishers and research divers, are available, the strata can be drawn with the help of this information. Habitat maps generally comprise coarse-scale resolution of substrate and vegetation (Chapter 1). If the habitat categories constraining abalone density can be distinguished, and if these do not vary appreciably from year-to-year, then habitat maps can allow more precise delineation of survey strata, especially for identifying areas of zero-density (of sand or dense seagrass). Boat-based habitat mapping has particular potential for improving survey precision because (1) broad-scale features of the bottom where a given species of abalone simply cannot be supported is likely to vary little from year to year, (2) the zero-density habitat will often comprise the large majority in each Map Code, and (3) boat-based sounder and video, in combination with occasional diver ground-truthing, has the ability to identify non-abalone habitat (notably sand) with relatively high reliability. Thus, the first objective of boat-based habitat mapping is to delineate and thereby also quantify the surface area (in m^2) of non-abalone habitat. The main practical advantage of boat-based habitat mapping is that it can cover much greater areas than divers, (at effectively much lower cost per m^2 mapped). Moreover, the cost justification is greatly strengthened by the fact that, especially for identifying non-abalone habitat, it need be done only once.

In this project we have employed both of these strategies for habitat mapping. Boat-based sounder and video were used in the habitat maps of Taylor Island and Tiparra, discussed in Chapter 1. At Taylor Island, boat-based mapping was used in stratification (Figures 1.4 and 3.1). At Tiparra, boat-based mapping served to identify 500mx500m study regions (Figures 4.1 and 4.2) of high abalone density among a broader 5x8 km^2 area (Figures 1.6 and 1.7) on Tiparra Reef where the fish-down experimental study regions for surveys and fish-down harvests were subsequently located. In this section, based on the results for Waterloo Bay, a second strategy for abalone density stratum boundary delineation is proposed using only the results from previous diver-based abalone surveys.

For both methods, it is likely that stratum boundary lines will be altered in future years' surveys to reflect improving understanding about the spatial distributions of abalone in study regions of management interest. This re-design of the survey in future years is possible because the quantity measured, absolute density, is defined independent of any specific survey-sampling protocol, unlike with relative measures of abundance such as fixed transect locations or timed swim. Thus in future years, the precision of the surveys in each Map Code can presumably be improved

In addition, knowledge of abalone spatial distributions, including any long-term changes in those spatial distributions, can be monitored from the spatially resolved samples obtained in a time series of diver-survey density maps.

Stratification was explicit as one of seven survey design objectives. Some spatial information on abalone distribution was also sought. However, a small enough spatial resolution in density maps sufficient to monitor year-to-year changes in spatial distributions of abalone was not. The latter objective of a reliable yearly spatial map of abalone density will not always be possible, but will depend on the number of leaded lines swum in each study region. However, over longer times, it seems, from these results, that this objective is achievable using the leaded-line method.

For areas of principal management focus, the spatial mapping of areas of high density can address a critical issue for management and sustainability. Shepherd and Rodda (2001; Shepherd et al. 2001), in South Australia argued that the spatial range of greenlip abalone has been shrinking, notably in some areas of the Western Zone, a process called serial depletion. Thus, an added benefit for abalone management of the leaded-line transect survey design, when sample sizes are sufficient, is to provide the means to address this current, contentious and fundamental question in management of South Australian abalone.

6.4.2. Choice: Whether to Measure Length or Spatial Clustering?

As noted in the Introduction and Methods, a principal modification of the sampling protocol at Waterloo Bay was to measure all abalone that were also counted in each leaded-line transect. By getting a length measurement from every abalone counted, we prevented variation in the counts of sublegal animals from affecting the estimate of legal-size densities.

In fact, using this sampling protocol, the survey can measure absolute density for any size range chosen, by simply including only transect counts of abalone from that size range in computations of absolute density. Thus, the mean and standard error of abalone density can be estimated for each 5-mm length bin, for example.

Combining these length population curves with weight-length samples then permits the conversion to an estimate of absolute biomass. On this basis, quota decisions may be based. This extension from leaded-line measure of absolute density to absolute harvestable biomass is normally only possible when length samples are taken, in addition to measuring absolute density as numbers in each 100 x 1 m^2 transect.

The principal disadvantage to measuring all abalone as done at Waterloo Bay was that, under this protocol, counts in 2-m quadrats were not obtained. It is simply not feasible underwater to record individual 2-m quadrat counts and measure lengths at the same time. Thus, an information trade-off between measuring lengths and gathering spatially specific counts is imposed by practicalities of diver sampling.

In the Waterloo Bay leaded-line surveys, the goal of quantifying the degree of spatial clustering was set aside as a lower priority than obtaining higher precision in the estimates of legal density. In general, for abalone stock assessment, length samples are a necessary survey output. Spatial variations in density over short distances of a few metres are not generally monitored by current abalone surveys that we are aware of. Thus leaded-lines offer the new feature that being marked every 2 m along their length, they provide an easy way to quantify the extent of spatial clustering. It is quantified by the pattern of spatial variation over short distances of a metre or two. Clustering can, thus, be monitored as a second priority to length sampling, when managers request it.

When quantification of spatial clustering is sought, for example in evaluating the impact of divers targeting aggregations on abalone fertilisation success during spawning, it is possible to obtain both lengths and short-scale spatial information. This is achieved with the protocol employed at Taylor Island, where one diver measured lengths and the other recorded 2-m quadrat counts.

Thus, at Waterloo Bay, by measuring all abalone, spatial variation in abalone density over a short (~1-m) spatial scale was not obtained. However, when managers request it, unlike with timed swims and as currently practiced, fixed transects where no marked leaded line is laid, short-term spatial information can be obtained when needed. However, going up 1 or 2 orders of magnitude in spatial resolution, namely to the average distance between leaded lines of 50-100 m, the Waterloo Bay survey did provide spatial information. By using the density measure at each leaded-line location, spatial maps (Figures 6.7-6.10) were generated. Thus, in the Waterloo Bay leaded-line survey design, where all abalone are measured for length and no 2-m quadrat counts were recorded, we nevertheless retain the between-leaded-line spatial resolution, which allowed broad-scale spatial trends to be identified.

In future, if the technology becomes amenable, it should be possible for divers to record both lengths and 2-m quadrat counts using electronic callipers attached to a small underwater computer.

This would also eliminate the potentially significant reading error that results from counting holes in the plastic tape on which abalone length measurements are recorded by the Shepherd gauge. Holes from different abalone punched by the length gauge can coincide on the plastic tape, or the holes can be missed in the count once divers return to the surface. Reader sample test counts of punch holes by different researchers of the same tape do sometimes vary.

Thus, underwater computer technology, together with boat-based video, offer significant opportunities for enhancing the power of abalone surveys in the near- or medium-term future.

More elaborate boat and rope deployment technology could permit one additional major improvement in the Waterloo Bay design. That is, it would be a better measure of density at each leaded-line location if the two transects that the pair of divers swim at each leaded-line location were separated by 5 or 10 m, rather than being strictly adjacent on either side of the leaded line. We know, from autocorrelation analysis of 2-m quadrat counts in Chapter 5, that greenlip densities are relatively similar (spatially autocorrelated) with decreasing similarity to a distance apart of about 20 m. The biggest drop off in spatial autocorrelation occurs in the first few metres. Thus, in effect, the current design, with both transects spanning a total width in the sample space of 2 m, there is effectively not much more than 1 transect sample at each leaded-line, call it a transect of width 2 m. So an effective sample size of close to 1. As discussed in Section 3.4.3, if these two transects were spaced more widely apart, some of spatial correlation would be reduced, and the two samples would become more nearly independent at each leaded-line, so something closer to a fully effective sample size of 2. Spreading the two transects apart would increase the effective sample size by covering a wider range of the available habitat in the vicinity of each leaded line location.

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CHAPTER 7. Taylor Island Fish-Down Experiment: A New Test Statistic for Survey Change in Absolute Number

R. McGarvey, W. Ford

7.1. Introduction

In application to managing abalone fish stocks, one important use of diver surveys will be to quantify the effects of fishing on greenlip abalone populations. Therefore, a basic measure of the performance of survey estimates of absolute density from various survey designs to be evaluated is how well they can estimate the numbers removed by fishing from a given area. The 'fish-down experiment' was therefore proposed as the means by which the accuracy of abalone survey designs proposed in this project are evaluated. By 'survey design' we mean the diver sampling protocols and statistical analyses developed to estimate absolute abalone density.

The survey design evaluation fish-down experiment is done by running surveys that estimate absolute (legal-size) population numbers both before and after the removal of some known amount of greenlip abalone from a designated study region. The fish-down removal is done by commercial divers, who harvest greenlip abalone as they would in regular fishing, but with the requirement that they report numbers taken from the fish-down study region.

The difference in legal-size abalone numbers estimated by the pre-fish-down compared to the post-fish-down survey should equal the number removed. The experimental outcome, quantifying the closeness of the difference of pre-fish-down minus post-fish-down legal numbers to actual number harvested, thus serves as the test of each survey method's performance in detecting and quantifying change in population size.

Previous use of fish-down experiments include the study by Officer et al. of re-aggregation of greenlip abalone following exploitation (2001), and the fish-down experiments of Dowling et al. (2004a; Dowling 2002) to assess the impact of fishing targeting aggregations. Fish-down experiments were undertaken by Hart and Gorfine (1997) to assess the performance of a range of abalone stock assessment methods, and Hart et al. (1997) specifically focused on diver survey methods. Other studies sought to assess the impact of fishing in evaluation of survey methods using monte carlo simulated fishing (Gorfine et al. 1997; Officer et al. 2001b; Dowling et al. 2004b).

In this project, greenlip abalone fish-down experiments were carried out in four locations, two in the Western Zone (Taylor Island and Waterloo Bay) and two in the Central Zone (at two sites on Tiparra Reef). The Taylor Island fish-down experiment was the first to be run. Chapter 3 described the Taylor Island survey methods and outcomes. In this chapter, the results of this Taylor fish-down experimental test of the timed-swim and leaded-line survey designs are summarised.

7.2. Methods

The full fish-down experiment has 14 parts: (1) habitat mapping in the general area of the proposed fish-down, (2) choosing and mapping in GIS the boundaries, (3) choosing and mapping transect locations inside the fish-down study region, (4) swimming the pre-fish-down survey using leaded lines, (5) swimming the pre-fish-down survey by timed swims, (6) commercial fish-down harvest, (7) a post-fish-down survey using leaded lines, (8) a post-fish-down survey by timed swims, (9) developing, programming and running statistical methods to estimate mean absolute numbers of legal size abalone in the study region from the leaded-line survey method, (10) developing, programming and running statistical methods to estimate the standard error (i.e. confidence intervals) about the estimate of mean absolute numbers of legal size abalone from the leaded-lines, and (11) confidence intervals for timed-swim, (12) combining all this to statistically test the probability that the difference estimated by the pre- and post-fishing surveys for both (13) leaded-lines, and (14) timed swims were in agreement with the observed numbers removed.

In this chapter, details of the remaining parts (6) and (12)-(14) are presented. Part (1) was described in Chapter 2. Parts (2)-(5), and (7)-(11) were detailed in Chapter 3 where a stratified mean and 2-level bootstrap were used to analyse the current South Australian survey method of timed swim, and of leaded-line survey counts from one diver measuring lengths of all abalone and a second diver recording 2-m quadrat counts.

The pre-fish-down Taylor Island surveys were completed in December 2002 to allow fishers to target the Taylor fish-down site early in the quota year which starts 1 January. Maps of the fish-down areas were circulated to all commercial divers and licence holders (Figure 7.1). Buoys marked the fish-down boundaries. Minimum legal size for greenlip in the Western Zone is 145 mm SL.

Fishers were slow to respond to the request of a fish down in this study region and the fish-down harvest was completed in March 2003. Out of 23 licences, two participated in the fish down. A total of 985 legal-size greenlip abalone were harvested in four visits to the site over three months. Most were taken by a single diver.

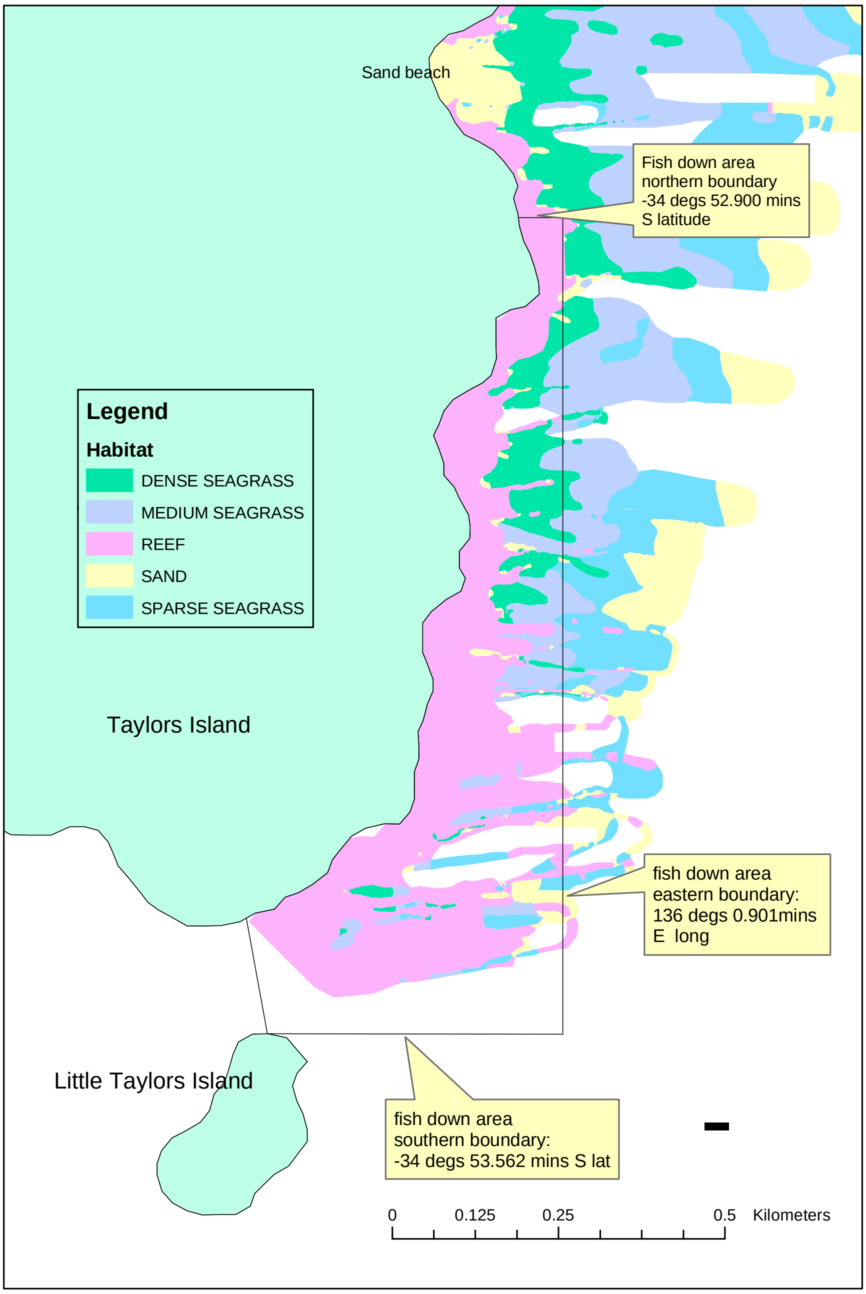

Figure 7.1. Map of the Taylor Island fish-down experimental study region distributed to commercial divers.

7.2.1. How Can Agreement Between Survey Difference and Numbers Removed be Determined?: A New Test Statistic

The two survey methods yielded estimates of legal-size greenlip abalone numbers, i.e. absolute population size, for the pre- and post-fish-down populations. Because they are based on a finite sample, the survey estimates have some uncertainty, due to sample variance. Confidence intervals (and more generally, a probability distribution) of likely estimates for mean legal density were obtained (1) using a 2-level bootstrap for the leaded-line method and

(2) using both a ratio estimator and a 2-level bootstrap for lower-bound levels of error in the timed-swim estimate. These bootstrap confidence ranges must be taken into consideration in deciding whether the survey estimate difference from before to after fish-down gives a reasonable level of agreement with the number of abalone actually removed.

As with all hypothesis testing based on confidence intervals, this can be done in two ways: (1) as a standard t-test comparing the observed difference in sample means (of legal absolute numbers from before to after the fish down) with the known (presumed without error) number of legal-size greenlip abalone removed, and (2) using a bootstrap.

7.2.1.1. Double-Difference Bootstrap

In this project we employed the bootstrap for two reasons: (i) the survey samples are non-normal, and (ii) the density counts were obtained using a 2-level sampling hierarchy which cannot be treated as identical and independent, but instead between- and within-sample variances should be accounted for explicitly. A bootstrap does not require that the data be described by a normal or any other known distribution, and a bootstrap algorithm can be constructed to accommodate the 2-level sampling design. For these reasons a (‘2-level’) bootstrap was used in Chapter 3 to generate the confidence intervals on the individual survey estimates of mean density. A new bootstrap algorithm, called a ‘double-difference bootstrap’, was developed for evaluating fish-down experimental outcomes.

This ‘double-difference’ bootstrap was used to quantify confidence intervals, and more generally, the probable range of change in absolute legal population size from two survey estimates run before and after the fish down. Therefore the double-difference bootstrap will underlie the statistical test of whether the tested survey methods, leaded-line and timed-swim, agree with known number of abalone removed.

The double-difference bootstrap was developed for calculating the expected range of probable survey difference in absolute legal greenlip numbers. It uses the 2-level bootstrap algorithm to quantify the uncertainty for pre- and post-fish-down surveys individually (Chapter 3), thus the name ‘double-difference’. This sample variance in the two survey estimates of mean legal density, each quantified by the 2-level bootstrap, is combined to quantify the overall survey-difference uncertainty. A double-difference bootstrap of 10,000 replicates was run.

The double-difference bootstrap algorithm for leaded-lines is summarised as follows: For each replicate (1) a 2-level bootstrap resample of leaded lines (at the primary level of sampling) and sides of each leaded line (secondary level) is drawn, as in Chapter 3. (2) This same set of randomly resampled leaded-line numbers and sides of each leaded line is used for both the pre- and post-fish-down surveys in each bootstrap replicate to simulate the experimental protocol of the same leaded-line locations being swum by divers for both pre- and post-fish-down surveys. (3) A survey estimate of absolute legal population size is calculated from the bootstrap resample using the 2-level stratified mean outlined in Chapter 3, one for pre- and one for post-fish-down survey data sets. (4) The two estimates of absolute legal greenlip population number were then subtracted, to obtain the difference, one predicted difference for each bootstrap resample. (5) The standard deviation of the full set of (10,000) bootstrap estimates quantifies the standard error on the estimated change in survey-estimated absolute density from before to after abalone removal by commercial divers. (6) The number actually removed by commercial divers is taken as a constant, known without error.

The double-difference bootstrap algorithm used for timed-swims was similar to that described above. The only difference was in step (2) where sampling at the secondary level was altered to resample from among the 4 10-minute timed swims at each site. Because, in timed swims, all abalone counted were also measured for length, only the legal numbers from each sample (each 10-minute count) were used in order to obtain a measure of legal population size.

7.2.1.2. Fish-Down Experimental Test Criterion

In order to formulate the fish-down experimental result as a statistical test, we must choose a test statistic and an acceptance criterion for agreement of survey difference with number harvested. A natural choice for the criterion of successful agreement between survey-estimated difference in absolute legal numbers and the actual fish-down number removed is obtained by specifying the percentage of probable observed confidence range that the double-difference bootstrap overlaps with the observed fish-down number removed.

Specifically, if we split the survey estimate probability evenly of success or failure, the statistical test criterion for successful agreement is that the number of abalone removed by fishers falls inside the 25%-75% confidence range of survey-predicted differences. This is the test statistic and test agreement criterion. If the known fish-down number falls within the 25%-75% confidence interval (specified by those quantiles from among 10,000 bootstrap survey replicates of the difference), the survey method is taken as yielding agreement under this fish-down experimental protocol.

This is a relatively strict criterion for success, since it is 50% probable that the true harvest number lies outside this confidence range, even if the survey method is, indeed, perfectly accurate (entirely unbiased). Non-bias is an underlying assumption in forming the double-difference bootstrap confidence distributions, just as it is assumed in forming any confidence interval from variance in the observed data. More to the point, given the observed levels of sample variance, the true value could fall outside the 25-75% range once out of every two fish-down experiments, on average.

7.3. Results

7.3.1. Fish-Down Experiments: Taylor Island

The predicted change in survey-estimated legal population size from before to after the fish down is shown for leaded lines (Table 7.1) and timed swims (Table 7.2). Also tabulated is the number of abalone removed (985) by fishers. The two leaded-line surveys estimated a 17% decline in legal numbers over that time. The timed swims estimated a 51% increase. In these tables (as elsewhere in this report), absolute population size (as numbers) is obtained by multiplying density (as numbers per m^2) by the area of the study region (m^2). For Taylor Island, we used the stratified mean density.

The percentage removed by fishers was calculated as a fraction of the pre-fish-down leaded-line survey estimate. The pre-fish-down stratified survey generated an estimate of 0.081 ±11.7% legal size abalone per m^2 (Table 3.3 of Chapter 3). Multiplying this survey-estimated abalone density (of approximately 0.08 per m^2) by the total area of the fish down study region (226,160 m^2) yielded an estimate of 18,300 legal size abalone. Thus 985 greenlip abalone harvested implies about 5% (4-6%) were removed in the fish down.

Table 7.1. Leaded-line survey estimates of change in population size in the Taylor Island fish-down experiment versus number removed by fishers.

	Area of study region (m^2)	Mean density: legal-size only	Estimated total legal-size abalone	SE-CV (from 2-level bootstrap)	Change from pre- to post-FD	Actual number of legal abalone harvested in the FD	Proportion legal
pre-FD	226,160	0.081	18,342	11.7%	-3165 (-17%)	-985 (-5%)	0.61
post-FD	226,160	0.067	15,178	22.4%			0.71

Table 7.2. Timed-swim survey estimates of change in population size in the Taylor Island fish-down experiment versus number removed by fishers.

	Area of study region (m^2)	Mean density: legal-size only	Estimated total legal-size abalone	SE-CV (assuming timed-swim area covered is known without error)	Change from pre- to post-FD	Actual number of legal abalone removed in the FD	Proportion legal
pre-FD	226,160	0.119	27,000	9.3%	+13,800 (+51%)	-985 (-5%)	0.80
post-FD	226,160	0.180	40,800	12.4%			0.85

The relative agreement of the two survey methods being evaluated with number harvested in the fish down is graphed in Figure 7.2. The hypothesis test criterion of 25%-75% confidence intervals from the double-difference bootstrap of probable change in legal population size from pre- to post-fish-down surveys are shown as boxes. The overlap of the leaded-line box with the line showing commercial number harvested implies agreement. That is, leaded-line surveys yielded an estimated change in legal numbers that, given known levels of survey sampling uncertainty, is consistent with a removal of 985 abalone over that time. Time swims, estimating a 51% increase in legal numbers, did not agree. Also shown (as the circle markers) are the 5% to 95% range of probable survey differences from pre-to-post fish down. For timed swims, the harvested number of -985 did not fall even within the 5%-95% confidence range and the timed-swim 5% lower limit of that range fell at an estimated increase in population size of 4000 abalone.

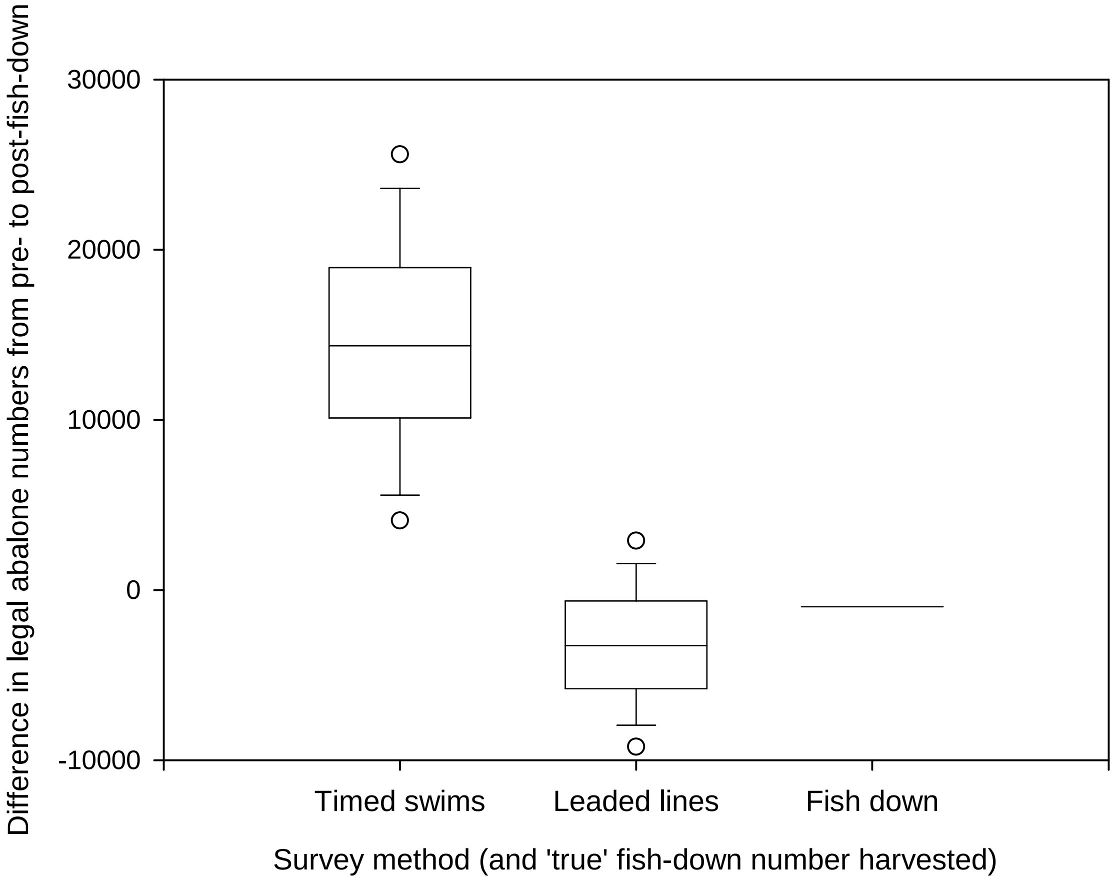

Figure 7.2. Survey differences and fish-down number harvested. Results of the statistical testing for agreement or not between survey measures of difference in absolute numbers of legal-size abalone between surveys run before and after the fish down harvest. Box-and-whisker plots show the ranges of the double-difference bootstrap replicates for the survey-estimated difference. The result for the two survey methods tested are shown alongside the number actually harvested in the commercial fish down. The 25% to 75% quantiles of pre-to-post-survey-estimated difference are indicated by the outer boundaries of the boxes. The line marking the median difference is shown at the middle of each box. The 10% and 90% quantiles are plotted as the limits of the ‘whisker’ error bars and the 5% and 95% confidence intervals by the open circle markers.

7.3.2. Length Frequencies

The length frequencies from the commercial fish down were plotted for comparison with a typical survey length-frequency sample, namely the pre-fish-down timed swim lengths (Figure 7.3). Note that the length mode of the commercial sample at 165-170 mm SL is 20-25 mm above the legal minimum length of 145 mm for WZ greenlip. Thus commercial divers avoided abalone that were 'close to the line' of legal minimum size to save time underwater by minimising the need to measure the lengths of individual greenlip abalone before prying them off the bottom and placing them in their collection bag.

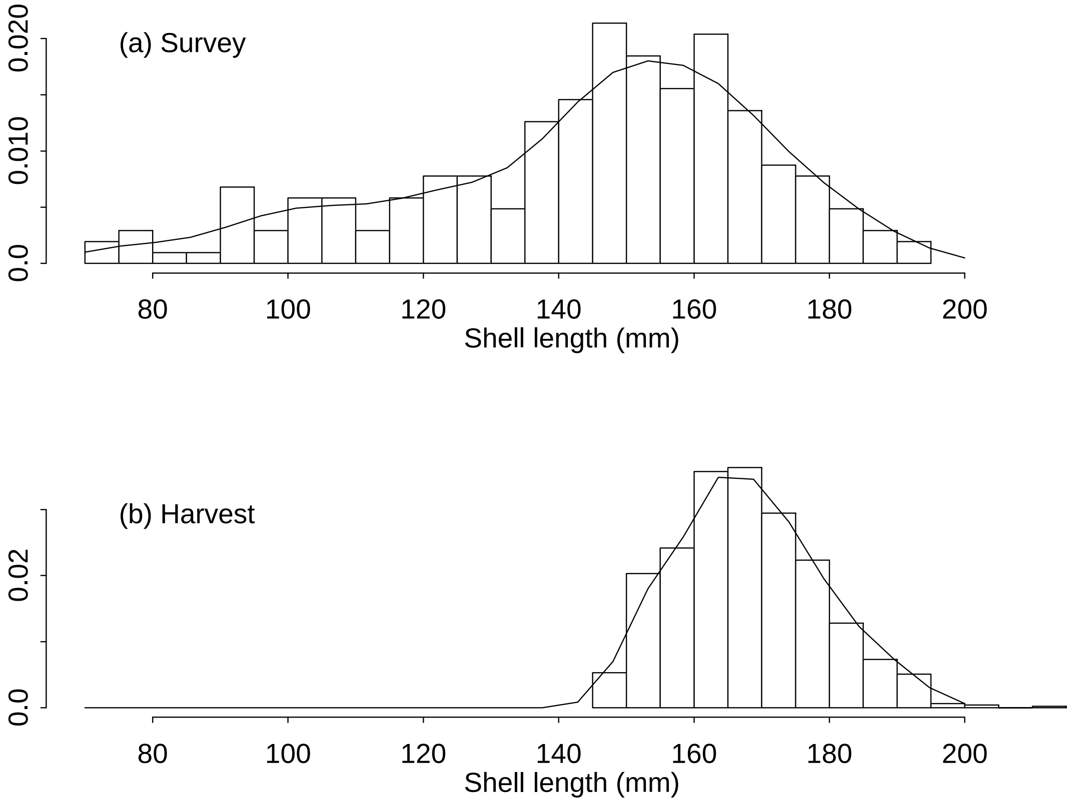

Figure 7.3. Shell lengths of fish from (a) pre-fish-down survey timed swims, and (b) the commercial harvest of 985 abalone removed in the Taylor Island fish down. These length-frequency distributions are plotted both as histograms with a 5-mm bin width and as smooth kernel density curves.

7.4. Discussion

With only 985 abalone removed in the fish down, representing a 5% reduction (assuming the stratified pre-fish-down survey provided an approximately correct estimate of absolute density), the number removed by commercial fishers was too small to be detectable. 95% confidence intervals, roughly double the SE-CV's, for individual surveys were 4 to 8 times that of 5% (Tables 7.1 and 7.2). Recall also that 2 surveys are needed to measure a difference, and the confidence uncertainty on the difference is roughly (slightly less than) double the confidence interval of each survey. However, a small harvest does not substantially impact on the quality of the fish-down experimental test since any known difference, including zero, from the first to the second survey can serve as the known target difference that the surveys seek to estimate.

Overall, the leaded-line method was successful. Moreover, the pre- and post-fish-down surveys were spaced apart by 4 months. During that time of high seasonal summer growth (December to mid-March), some additional abalone would have reached legal size. Natural mortality and changes in the habitat or behaviour making them more or less detectible could also have been acting to an unquantifiable extent. Thus, the leaded-line surveys did well to record a 17% decrease in absolute legal population size compared with the 5% of legal population harvested.

This was confirmed statistically by the success of leaded lines under the statistical test developed for this fish-down experimental procedure. Specifically, this statistical assessment of agreement for the fish-down experimental outcome is that the known number harvested fell within the 25%-75% confidence range for leaded-lines that was quantified using the double-difference bootstrap.

Timed swims performed relatively poorly, estimating a 51% increase in legal numbers over that time. Accepting that a 5% reduction (discounting all other sources of variation in numbers legal over the 4 month pre-to-post fish-down interval) is small enough to be ignored for this discussion, in effect, the two timed-swim surveys agreed with each other to about ±50%. Worse results have been known to occur in marine fishery surveys. Nevertheless, even if we ignore the seven important advantages for management and stock assessment that an unbiased measure of absolute density such as leaded lines provide (see Background) it appears, at Taylor Island, that leaded lines were also much better even as a relative measure of abundance, having predicted a modest decline in abundance over the fish-down interval rather than the large increase which timed swims estimate.

An approximate precision target of ±20% is reasonable for an abalone diver survey estimate of abundance. The SE-CV's for leaded-line stratified means of pre- and post-fish-down surveys were 11% and 22% respectively (Table 3.3). Thus, with these confidence intervals, and with respectable agreement to the fish-down number removed, the experimental results suggest that approximately ±20% precision was achieved by the Taylor Island leaded-line surveys in estimating absolute abalone density.

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CHAPTER 8. Tiparra Reef Fish-Down Experiments: A Measured Rise in Abundance

R. McGarvey, B. Davies

8.1. Introduction

This chapter reports the results of the two fish-down experiments on Tiparra Reef, namely in the two Tiparra study regions, at Coal Ground and West Bottom. As for all four fish-down experiments in this project, the performances of two survey methods are evaluated: time swims and leaded lines.

Survey outcomes, including estimates of abalone density and of proportion legal with associated confidence intervals were presented in Chapter 4. Spatial analysis of the Tiparra surveys was summarised in Chapter 5. In this Chapter 8, the change in legal numbers estimated from the two survey methods being tested, leaded-lines and timed-swims, run before and after the commercial fish-down harvest, are compared to the actual numbers of abalone removed by harvesters. Thus this chapter presents the results of the second and third of four fish-down experiments in this project.

8.2. Methods

8.2.1. Commercial Fish-Down Harvesting

The two Tiparra fish-down study regions, both 200x500 m^2, (Figures 8.1 and 8.2, inside corner points 1,2,3,4) were located in areas of high greenlip abalone density at the Coal Ground and West Bottom fishing grounds on Tiparra Reef. 'Study regions' were the areas inside which the mean densities before and after harvest were estimated by leaded-line and timed-swim survey, and inside which the fish-down harvest was confined.

Larger areas of 1000x500 m^2 at Coal Ground and 500x500 m^2 at West Bottom surrounding the fish-down study regions (Detail Areas #1 and #2 in Figures 1.8-1.10) had been closed to abalone fishing since 1 January 2003, the start of that quota year. Licence holders requested that the fish-down study region boundaries be marked to assist commercial divers from straying outside the study region. Fishing and surveys took place during late January and February 2003.

The research divers, commercial divers and project team (principal and co-investigators) met in Port Hughes on 4 February 2003 to outline and discuss the fish-down procedure. Research divers had previously completed the survey using the diver-survey protocol described in Chapter 4. Laminated (thus waterproof) maps showing the boundaries of the Tiparra fish-down study regions were distributed to all commercial divers. The GPS lat-long marks of the boundary corner points were also provided (Figures 8.1 and 8.2).

To demarcate the two fish-down study regions at the Coal Ground and West Bottom sites, SARDI divers deployed marking lines along the bottom, with floating flag ribbons attached to warn commercial divers doing fish-down harvest when they approached fish-down area boundaries. These 500 m lines (10 mm thickness) were laid E-W along the northern and southern boundaries (Figures 8.1 and 8.2). Sub-surface buoys were placed along the eastern and western boundaries, which harvest divers would encounter less often since they usually travel north or south (with or against the tidal current) when harvesting.

The decision at the Port Hughes meeting was to draw straws to determine the order that each of the six divers would enter Coal Ground and fish it. Because this harvest would count towards their annual quota (and respected the legal minimum length), divers at the Port Hughes meeting thought that the first diver or two would be achieving higher catch rates. Each diver was to fish inside the study region, twice, for one hour. Divers thought two hours each would be adequate to substantially reduce abundance. For the second set of 1-hour dives, the order among the six divers was reversed (to achieve fairness in overall catch-rate opportunity among divers).

In the event, the hour-in-order system broke down. Strong winds and mechanical failures disrupted the strict ordering. Catches greatly exceeded those anticipated by divers and the hours of fishing substantially exceeded the 12 hours originally planned. In spite of these obstacles, the rapid and timely removal of large numbers of greenlip abalone inside the study region boundaries points to the success of research-industry collaboration in the two Tiparra fish-down experiments.

Commercial divers kept all abalone shells from their fish-down harvest, separately for each fish-down experiment. They marked the date, diver and licence number, and dropped bags of all harvested shells at a collection point (generously provided by a diver, Steve Chamberlain).

A shell measuring machine (manufactured in Victoria) was loaned by the Abalone Industry Association of SA Inc. to the project and served effectively for measuring approximately 13,000 shells in the two Tiparra fish downs. All harvested shells were measured for length by SARDI researchers using the measuring machine.

8.2.2. Statistical Analysis: Double-Difference Bootstrap

Legal density was calculated by multiplying the leaded-line survey estimate of all-sizes (absolute) abalone density by the proportion of abalone that were of legal size obtained from the timed-swim length samples. Total numbers of legal abalone inside the two study regions (before and after each fish down) were calculated as the legal densities multiplied by the overall study region area (200m x 500m = 100,000 m^2).

The same bootstrap procedure described in Chapter 7 for the Taylor Island fish-down experiment was used in the two Tiparra fish-down experiments. Specifically, this algorithm (the ‘double difference bootstrap’) was used to statistically assess whether the probable range of estimated difference in survey numbers from before to after the fish down overlapped with the number of abalone actually removed by harvesters. This double-difference bootstrap was used for both leaded-line and timed-swim surveys.

For all survey estimates of absolute density in this project, bootstrap resampling explicitly accounted for both within-leaded-line and between-leaded-line variation. The same method (‘2-level bootstrap’) described in Chapter 4 for quantifying sample variance in the count densities of pre- and post-fish-down surveys was incorporated into the double-difference bootstrap used at Tiparra for quantifying the difference in legal survey population numbers before to after the fish downs.

At Tiparra, the 2-level bootstrap was modified from the Taylor Island version to account for the more highly spatially resolved counts of the Tiparra survey protocol at the secondary sampling level, that is, the within-leaded-line variation over both 2-m quadrats and 25-m transects. Thus sampling from the survey data first takes a bootstrap resample of leaded-lines, and then, at each leaded line, a bootstrap resample of 2-m quadrats and 25-m transects is randomly chosen.

In each double-difference bootstrap replicate, the same randomly chosen set of resampled leaded-line locations, and at each leaded-line, of resampled 2-m quadrat and 25-m transects, were used for the pre- and post-fish-down surveys. This simulates the actual survey protocol where the same leaded-line locations were used for pre- and post-fish-down surveys.

Likewise, for timed swims, a double difference bootstrap method identical to that described in Chapter 4 was employed. It also incorporated the 2-level bootstrap for simulating sample variance at the two levels of the timed swim sampling protocol, namely bootstrap re-sampling over swim locations and at each location, over the 4 10-minute timed swims.

The second modification to the double-difference bootstrap algorithm at Tiparra for estimating confidence intervals in survey legal population numbers for leaded lines, was to make explicit the variation due to randomness in the sampled proportion of abalone that were of legal size. Analysis showed this to be quite a large source of error at Taylor Island (Chapter 3) and was not explicit in the Taylor double-difference bootstrap (Chapter 7). Recall that for the Tiparra fish-down experiments, lengths were measured only in the timed-swim surveys, so proportion legal was inferred from these timed-swim length samples.

The sample variance in proportion legal for both pre- and post-fish-down surveys was modelled by incorporating, at the start of each double-difference bootstrap replicate, an additional stage of bootstrap resampling for the proportion legal. This added 2-level timed-swim bootstrap, applied to pre- and post-fish-down timed swim length samples, randomly chooses which specific timed swims to select for calculating the proportion legal in that double-difference bootstrap replicate. These randomly chosen length samples, were then used to generate the proportion legal in pre- and post-fish-down surveys. This proportion was then multiplied by the resampled absolute all-sizes abalone density (from the standard 2-level bootstrap leaded-line resample described above in this section and in Chapter 4) to obtain estimates for legal density, for both pre- and post-fish-down surveys, in each replicate.

The standard error of the estimate of survey change in legal population numbers was obtained from 1000 double-difference bootstrap replicates. Similarly, the confidence intervals needed for the assessment of each survey method (by the 25%-75% acceptance criterion, Section 7.2.1) were also calculated from the 1000 double-difference bootstrap replicates. These 5%, 25%, 50%, 75% and 95% double-difference bootstrap quantiles were also used in the boxplot of confidence intervals for the survey differences (Figure 8.3).

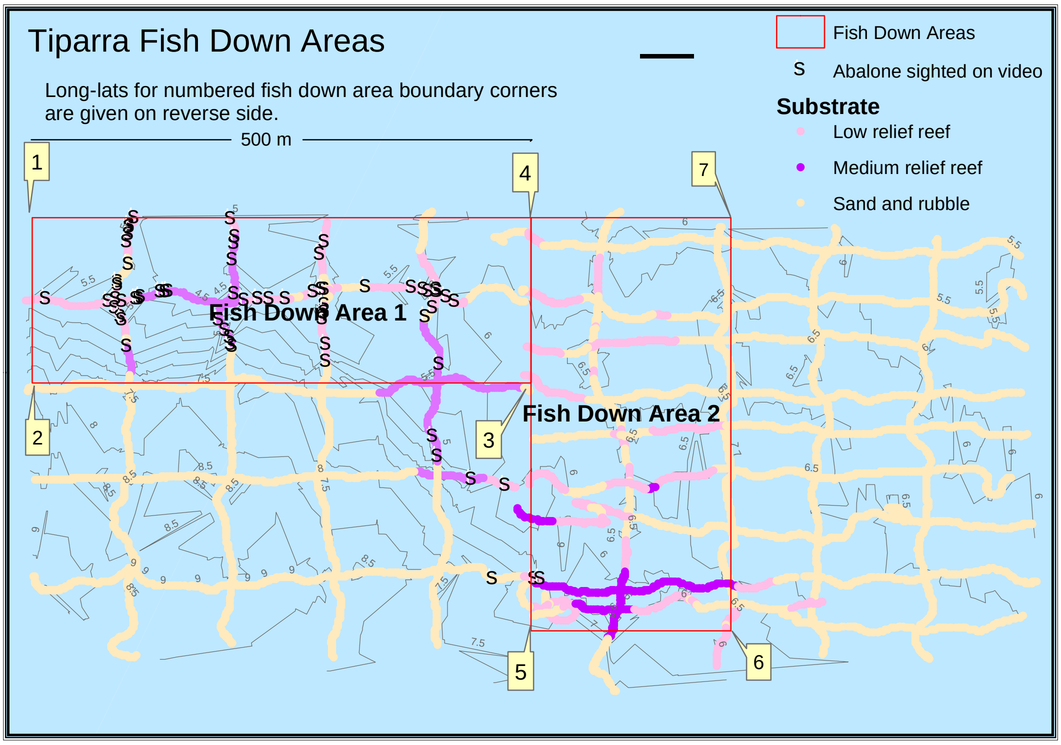

Figure 8.1. The fish-down study regions at ‘Coal Ground’ on Tiparra Reef distributed to commercial Central Zone abalone divers as waterproof-laminated maps. Only ‘Fish Down Area 1’ was used for fish-down experiment at Coal Ground. The GPS marks of the boundary corner points were included for divers and their boat-handlers on the reverse side.

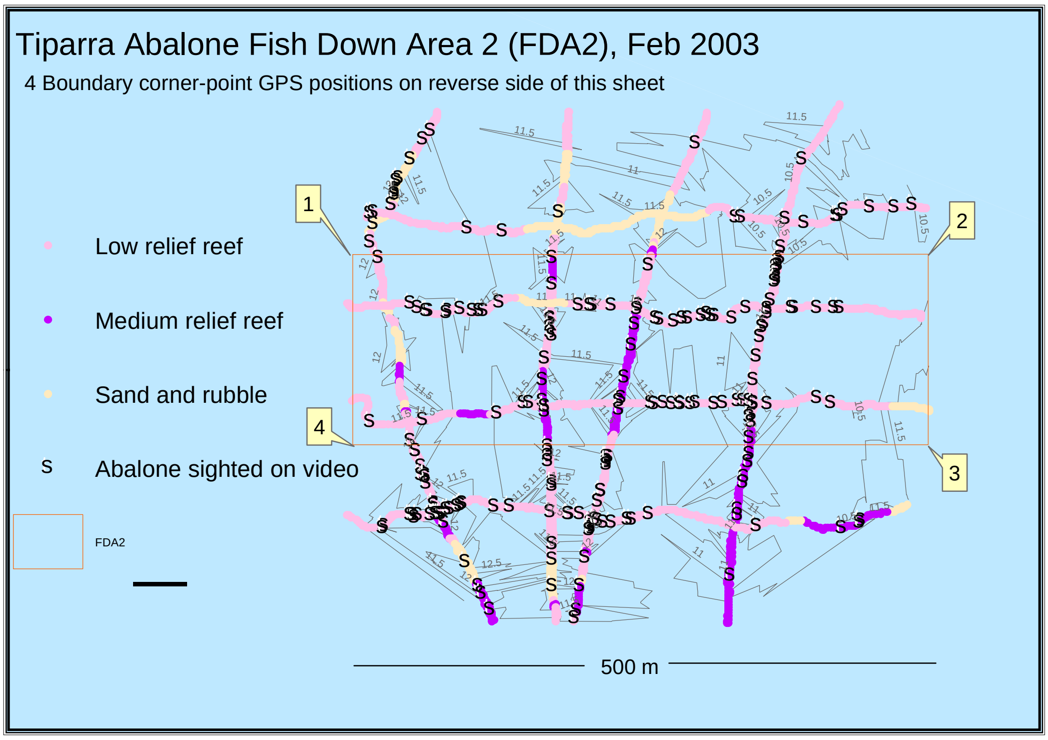

Figure 8.2. Map of the second fish-down study region at Tiparra Reef known as West Bottom (i.e. FDA2) distributed to Central Zone abalone divers. The GPS marks of the 4 boundary corner points were included on the reverse side of these waterproof maps.

8.3. Results

8.3.1. Fish-Down Experiments: Survey Estimated Change and Fish-Down Harvest Numbers

The fish-down experimental results are presented for Coal Ground and West Bottom. This assessment of the extent of agreement between survey difference and numbers harvested is presented for both of the diver-based abalone survey methods being assessed in these experiments, namely timed swims and leaded-lines.

Fishers carried out the fish-down harvests as agreed and provided close logistic support. Participation levels by Central Zone divers at Tiparra were high and cooperation was excellent.

8.3.1.1. Coal Ground

At Coal Ground, both survey methods, timed swims and leaded lines, yielded agreement between survey-estimated change in legal numbers and the number of greenlip abalone fishers actually harvested.

Boxplots (Figure 8.3a) show this graphically. The boxes show the 25%-75% ranges of confidence for survey-estimated change in legal abalone numbers that we have chosen as the statistical criterion for acceptance (in Sub-section 7.2.1), i.e. of successful survey agreement with number harvested. Two box-and-whisker plots are given for leaded lines, illustrating the outcome for two ways of calculating the confidence intervals, namely without or with the variation in proportion legal explicit, the latter denoted 'LL %legal'. The principal outcome in Figure 8.3a is that the 25%-75% boxes overlap with number actually harvested in the fish down for both survey methods, timed swims and leaded-lines.

In addition, Figure 8.3 shows the extent to which variation in proportion legal widens the confidence intervals. For Coal Ground, making explicit the sample variation in proportion legal has a quite noticeable effect. The relative contributions of sample variation due to proportion legal and density to the overall confidence intervals are summarised in Table 8.3. At Coal Ground, SE-CV's of 15% and 9% were about 3/5ths or half of those due to density counts.

Tables 8.1a and 8.2a summarise the Coal Ground experimental results in terms of absolute number of legal abalone. The number of greenlip harvested in the Coal Ground fish-down by 6 Central Zone divers was 7323. The leaded-line surveys measured a decline of 9,200 abalone, with confidence intervals shown in Figure 8.3a. Timed swims, in this experiment, obtained a very close measured decline of 7,100 abalone.

8.3.1.2. West Bottom

At the West Bottom fish-down experiment, both leaded lines and timed swims estimated an increase in abalone abundance from before to after the fish down. Figure 8.3b shows the outcome as a boxplot. Timed swims estimated an increase of 61% in legal numbers, about double that of leaded lines (32%).

At West Bottom, the confidence intervals were not substantially widened by adding variation in proportion legal to the double-difference calculation of confidence intervals, shown by comparing the box marked ‘Leaded-lines’ with the one marked ‘LL %legal’ in Figure 8.3b. This is explained by the fact that the sample variance in proportion legal was less at West Bottom than Coal Ground, giving bootstrap-estimated SE-CV’s of 7% and 6% (Table 8.1), about a third of the SE-CV’s obtained for the measure of density.

Possible causes for the relatively poor result of leaded lines and very poor result of timed swims at West Bottom (both estimating higher numbers of legal abalone subsequent to the fish down) is further examined in Discussion.

Table 8.1. Summary of outcomes for the two Tiparra fish-down experiments: using leaded-line survey counts.

	Leaded-line survey density (abalone m^{-2}): all sizes	Confidence interval as SE-CV from variance in density counts (by 2-level bootstrap)	Area of study region (m^2)	Proportion legal (from timed swim)	Confidence interval as binomial SE-CV on % legal	Survey density (abalone m^{-2}): legal-size (>130 mm SL) only	Estimated total legal-size abalone	Confidence interval as SE-CV (combining variances from counts and % legal)	Survey-estimated change from pre- to post-FD	Actual number of legal abalone removed in the FD
a. Coal Ground (Leaded-Line Survey)										
pre-FD	0.636	19.1%	100000	44.5%	3.5%	0.283	28,300	22.6%	-9,200	-7323
post-FD	0.588	16.0%	100000	32.4%	4.6%	0.191	19,100	20.6%		
b. West Bottom (Leaded-Line Survey)										
pre-FD	0.469	20.3%	100000	41.8%	3.5%	0.196	19,600	23.8%	6,300	-4435
post-FD1	0.538	16.7%	100000	48.1%	2.9%	0.259	25,900	19.6%		
post-FD2	0.651	9.6%	100000	48.1%	2.9%	0.313	31,300	12.5%	11,700	

Table 8.2. Summary of outcomes for the two Tiparra fish-down experiments: using timed-swim survey counts.

	Area of study region (m^2)	Mean density: legal-size only	Estimated total legal-size abalone	SE-CV (assuming timed-swim area covered is known without error)	Change from pre- to post-FD	Actual number of legal abalone removed in the FD	Correlation coefficient of density vs. proportion legal
a. Coal Ground (Timed-Swim Survey)							
pre-FD	100000	0.246	24,600	16.2%	-7,100	-7323	-0.25
post-FD	100000	0.175	17,500	15.0%			-0.31
b. West Bottom (Timed-Swim Survey)							
pre-FD	100000	0.269	26,900	10.4%	16,300	-4435	0.08
post-FD	100000	0.432	43,200	10.0%			-0.21

Table 8.3. Two-level bootstrap standard errors for the four timed swim surveys (from which proportion legal was inferred). These estimated confidence ranges are given as relative percentages, that is, as coefficients of variation ('SE-CV', the standard error divided by the mean) for (1) proportion legal, (2) absolute all-sizes abalone density (or equivalently, of absolute population numbers), and (3) legal survey density combining these two sources of error.

	SE-CV: Proportion legal		SE-CV: Abalone density (all sizes)	SE-CV: Legal density
	Estimated by 2-level bootstrap	If estimated as a simple random sample	Estimated by 2-level bootstrap	Estimated by 2-level bootstrap (combining proportion legal and density)
a. Coal Ground (Timed-Swim Survey)				
pre-FD	15%	3%	25%	35%
post-FD	9%	5%	19%	24%
b. West Bottom (Timed-Swim Survey)				
pre-FD	7%	4%	22%	25%
post-FD1	6%	3%	18%	20%

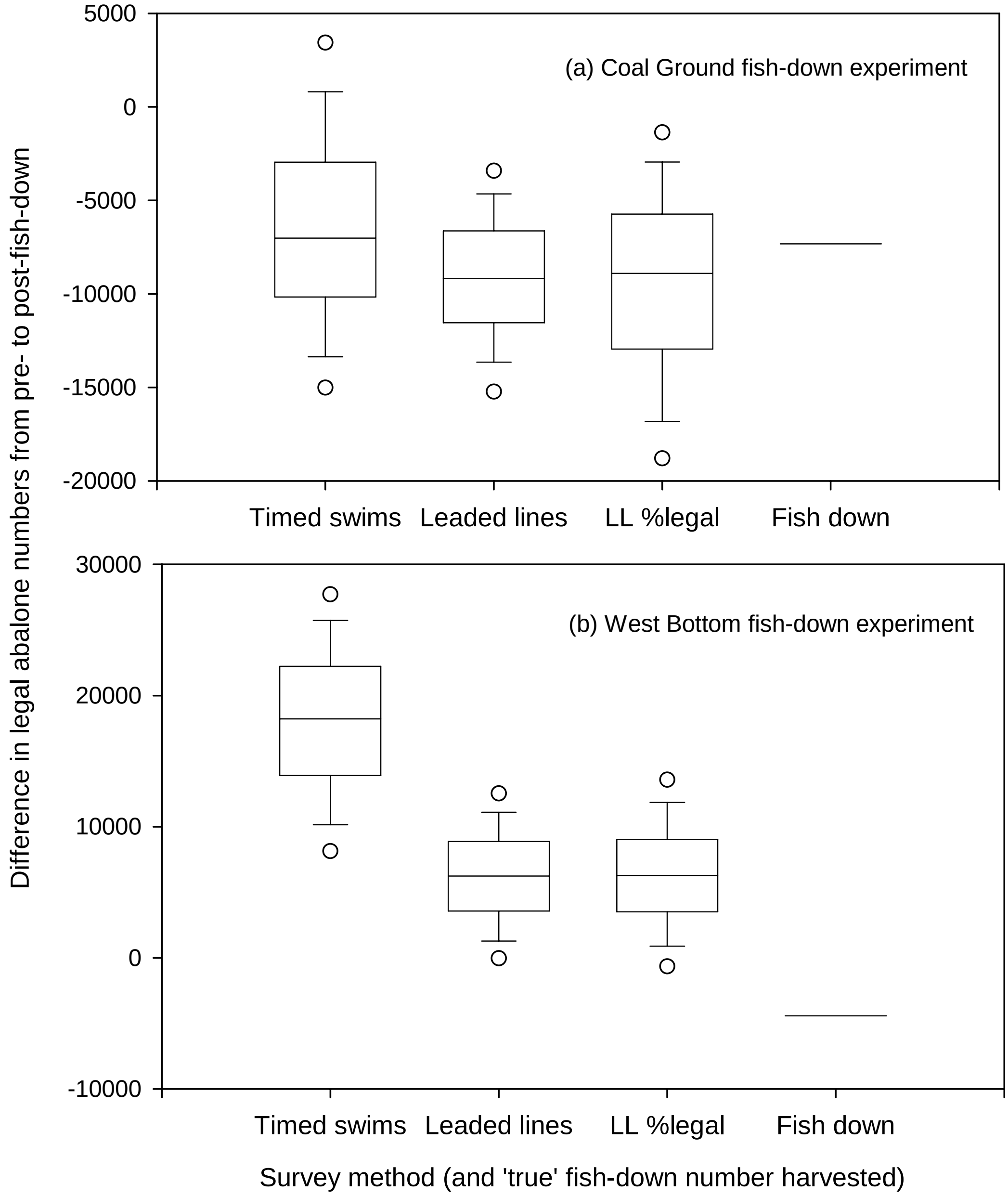

Figure 8.3. Boxplots of agreement or not between survey measures of difference and the fish-down number harvested. Box-and-whisker plots show the ranges of the double-difference bootstrap replicates for the predicted difference in number of legal-size abalone from surveys run before and after the fish-down harvest. The result for the two survey methods tested are shown alongside the number of greenlip abalone fishers actually removed. The 25% to 75% quantiles of pre-to-post-survey-estimated difference are indicated by the outer boundaries of the boxes. A line marking the median difference is shown at the middle of each box. The 10% and 90% quantiles are plotted as the limits of the 'whisker' error bars and 5% and 95% quantiles are marked by open circles. The confidence intervals for the boxplots denoted 'Leaded lines' incorporate only error due to sample variation in density. Those denoted 'LL %legal' incorporate, in the double-difference bootstrap, the additional leaded-line estimate uncertainty due to variation in proportion legal.

8.3.2. Length Frequencies of Harvest and Survey

The length frequencies from the commercial harvest were obtained from a measurement of all greenlip abalone harvested (n = 7323 at Coal Ground, and n = 4435 at West Bottom, Table 8.1 or 8.2). Along with these commercial harvest length frequencies were plotted the pre-fish-down survey lengths (Figure 8.4). This shows the abalone sizes that commercial divers harvested compared with the sizes they would have seen as they searched over the same study area that research divers sampled in these surveys (Chapter 4).

The first observation (Figure 8.4) is that the abalone were larger at Coal Ground. This was evident comparing either survey lengths or commercial harvest lengths on these two important Central Zone fishing grounds of Tiparra.

It is also clear (Figure 8.4) that harvesters shied away from taking abalone near the legal limit. This reflects both (a) a careful intent by commercial divers to avoid any risk of taking undersize abalone, of prying them off the bottom and have them be thrown back by the sheller which risks significant probability of handling and release mortality; (b) fishers clearly can find enough of the larger abalone well above the legal limit (130 mm SL); and (c) in 2003 fishers in the Central Zone had informally agreed among themselves to harvest only greenlip abalone larger than 135 mm SL.

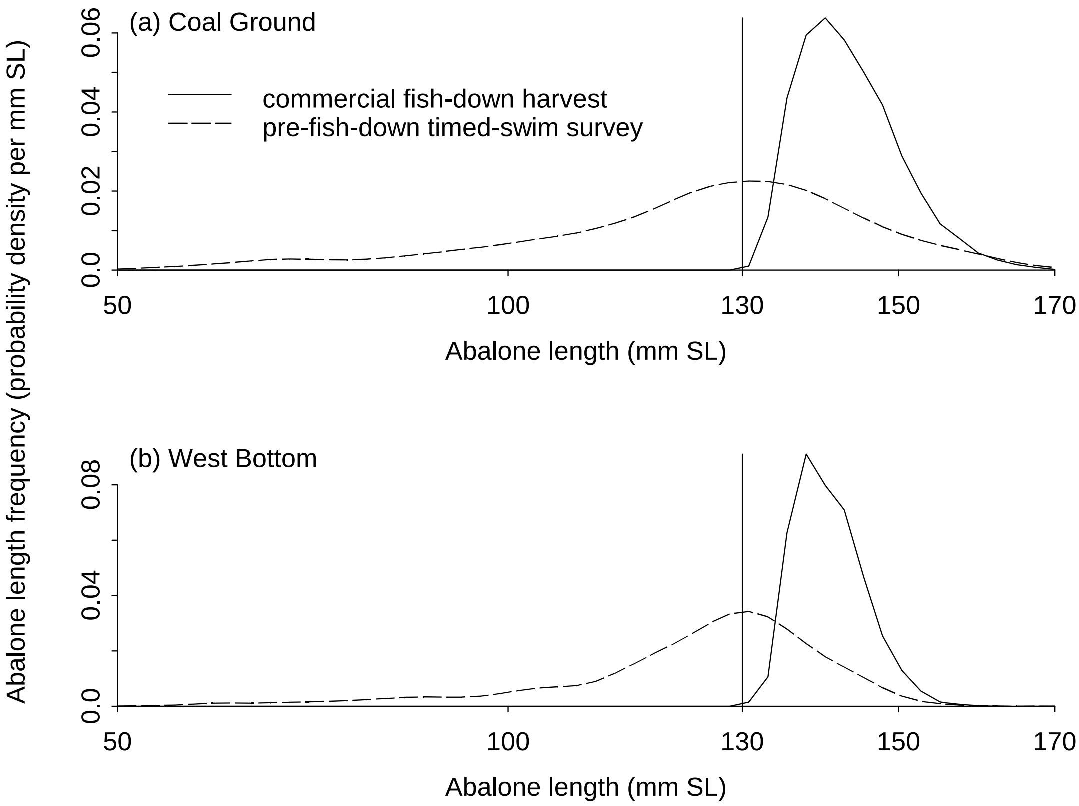

Figure 8.4. Length frequencies of (pre-fish-down) survey and commercial harvest from the two Tiparra fish-down experiments. These are (S-Plus) kernel probability density plots of length frequency (which sum to 1 under each curve).

8.4. Discussion

Thus, at Coal Ground, both survey methods found agreement with number removed, whereas at West Bottom, both estimated an increase rather than a decrease in density, with timed swims estimating by substantially greater increase.

8.4.1. Why Measured Density Increased at West Bottom?

The unexpected rise in estimated density at the West Bottom site merited closer inspection. Error in survey estimates of legal density is contributed by both factors, proportion legal and all-sizes density. We first examine all-sizes density estimated by leaded-lines.

Examining the counts from individual leaded lines before and after (Figure 8.5b) shows that density counts were about the same at 3 of the 8 West Bottom LL's (2, 5, 8), lower at 2 of the leaded-lines (1, 6), and higher in the post-fish-down leaded-line survey at 3 leaded-lines (3, 4, 7). The extent of randomness is shown in Figure 8.5 and the chance of an observed rise does not look improbably small. The two leaded-lines that gave large increases were LL4 and LL7. If just one of those two leaded-lines had yielded before and after samples that resulted in a decrease over the time of the fish down, then the West Bottom estimate would have declined a bit and the survey estimate would have been close to the small decline that occurred.

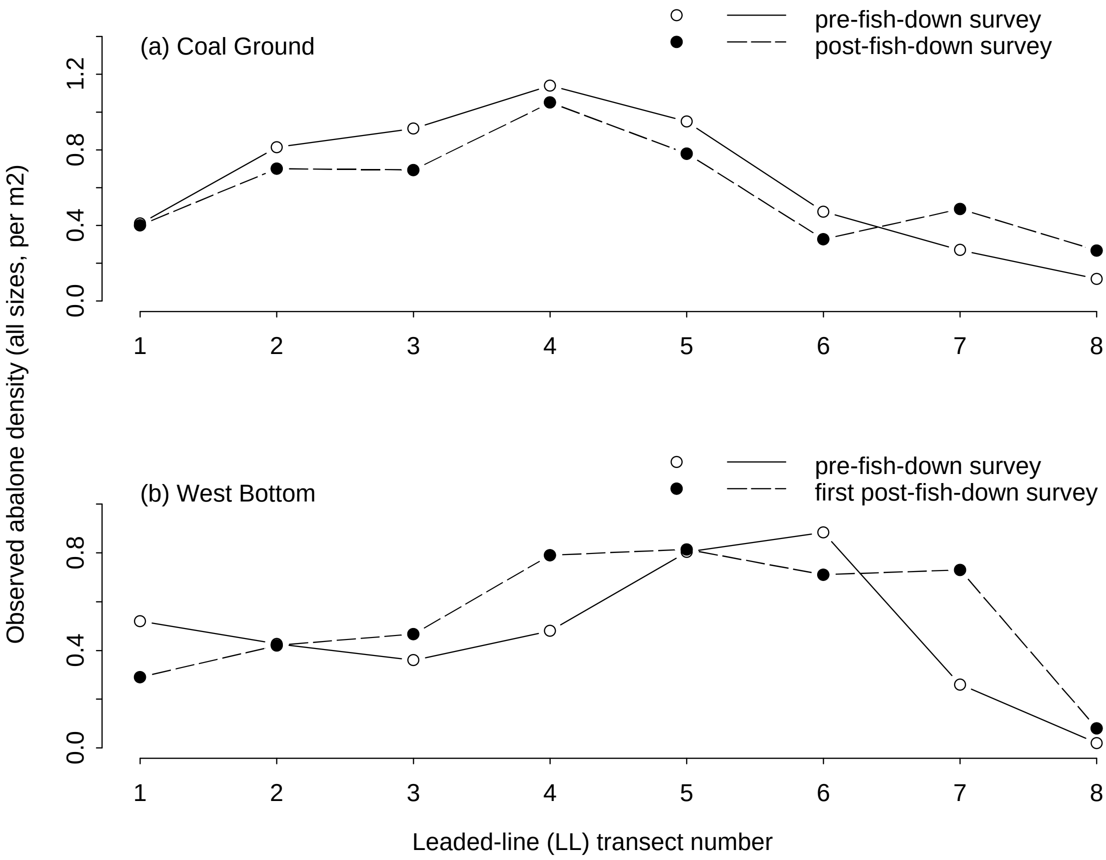

Figure 8.5. Diver-count densities by leaded-line from the two Tiparra study regions, before and after fish down.

A statistically precise measure of how likely an observed rise was, given measured levels of sample variance, is shown in the bootstrap histograms for West Bottom (Figure 4.10). These show the distributions of possible mean (all-sizes) density values, based on the spread of the data in each of the 3 surveys. A value, for example, of 0.6 m^{-2} would not have been an unlikely mean density from any of the surveys. So, to this extent, it is statistically possible that this rise from pre- to post-fish-down was just a random occurrence.

However, in addition to leaded lines, timed swims also estimated an increase in all-sizes density. The timed swims, in fact, saw a much larger increase (Tables 8.1 and 8.2). Moreover, both forms of the leaded-line survey, 2-m quadrats and 25-m transects, which were independent since they were swum over different bottom, saw a rising trend. So, in effect, not one, but three independent surveys all recorded a rise. This suggests that there may have been some non-random cause for the observed increase in density, such as higher detectability of greenlip abalone at the time of the second survey, or emergence of abalone from cryptic habitat.

8.4.1.1. Error in Proportion Legal (Again)

This source of survey error, in the proportion of abalone that are of legal size, was also found to be a larger than random error for Taylor Island (Section 3.4.5).

At West Bottom, the length-frequency distributions (Figure 4.13), gathered in timed swims, exhibited an increase in relative abundance specifically only for legal sizes, again the opposite of what one might have expected. The proportion legal should decline since only legal-size abalone were removed. It can be shown that this measured rise in relative proportion of legal-size animals in the length samples (from 41% to 48%, Table 8.1) explains slightly more than half of the estimated increase in leaded-line legal numbers reported at West Bottom (Table 8.1 and Figure 8.3). Moreover, it can be shown that if the proportion legal had instead declined as it did at Coal Ground (and all the other fish downs), say, for example, if the proportion legal had instead declined from 41% to 33% (in Coal Ground the decline was greater, namely from 44.5% to 32.4%, Table 8.1), then the outcome for leaded-line estimated change in legal numbers would have been a modest decline, thereby giving close agreement to fish-down harvest numbers.

The SE-CV's shown under 'If estimated as a simple random sample' (Table 8.3) are those that would be obtained if abalone lengths were random in the sampled population. That these binomial-based SE-CV's were, in fact, half to a fifth of the bootstrap-estimated values, shows that proportion legal varies in a non-random fashion. This higher than expected levels of variation in proportion legal were discussed in Sections 3.4.2 and 6.3.3. Thus, as with Taylor Island, the error in proportion legal is larger than expected from a random sample.

For this reason, in future, care should be taken in survey design to limit the error due to high random variation in proportion legal.

Sample sizes of abalone measured for length in the surveys were quite large (of 1000 to 1300 in each timed-swim survey). Therefore the 'effective sample size' is plainly much smaller than the actual number of abalone measured. This very high level of sample error in length-frequency measurements is common to many fish stocks and was the principal focus of a series of papers by Pennington and colleagues (Pennington and Vølstad 1994; Pennington et al. 2002).

In designing the leaded-line survey protocol for the fourth and last fish-down experiment at Waterloo Bay, we sought to reduce this source of error by measuring for length all of the abalone that were counted. This reduces error in proportion legal (and more generally, any error due to length sampling) in four ways: (1) It completely eliminates the dependence of the estimate of legal density on sublegal numbers detected. As discussed in Chapter 3, when all abalone that are counted are also measured for length, only the count of legals from each transect (or quadrat) is used in estimating legal density. Therefore random variation in measured sublegal numbers would have no effect on the estimate of legal density. This separation of sublegals from legals is not possible if the lengths are obtained as a subset of the counts, or if lengths are obtained in separate dives from the counts. (2) It increases the sample size of lengths measured. (3) Perhaps most importantly, measuring lengths at all leaded-line sample locations assures that the locations of sampling for lengths are as uniformly spread across the study region as possible. Leaded-line sample locations are already being chosen with this objective in mind. Coupling length sampling with counts assures that the lengths (like the counts) are sampled representatively. (4) Lastly, the lengths from each leaded line will automatically be weighted in the overall length-frequency sample in proportion to the abundance (the all-sizes density) at each sample location; i.e. these length samples are self-weighting.

This improvement in the quality and precision of length samples will also improve the precision of estimates of absolute biomass used in quota setting. Biomass is estimated by combining length frequencies and a length-weight relationship with the survey estimates of absolute density.

8.5. References

Pennington, M. and Vølstad, J. H. 1994. Assessing the effect of intra-haul correlation and variable density on estimates of population characteristics from marine surveys. Biometrics 50: 725-732.

Pennington, M., Burmeister, L.M., and Hjellvik, V. 2002. Assessing the precision of frequency distributions estimated from trawl-survey samples. Fishery Bulletin 100: 74-81.

8.6. Acknowledgements

The Tiparra fish down experiments were made possible by contributions of time, resources and advice of the Central Zone abalone divers and licence holders. In particular, we thank Steve Chamberlain, who permitted us to use his driveway for survey boat storage and maintenance and shell measurement, and who assisted in fish-down project coordination.

CHAPTER 9. Waterloo Bay Fish Down Experiment: Identifying Spatial Patterns of Exploitation

R. McGarvey, P. Preece, J.E. Feenstra, S. Mayfield

9.1. Introduction

In this Chapter, we present the results from the fourth fish-down experiment at Waterloo Bay. The experimental protocol was adopted with modifications from previous fish-down experiments. Here we report principally (1) survey-estimated change in absolute abalone numbers from before to after the fish down, compared with the number harvested, and (2) spatial maps of fish-down harvest catch rate and mean length, for comparison with the corresponding survey maps of density and mean length in Chapter 6.

The principal experimental extension in the Waterloo Bay fish-down was in the spatial and temporal resolution of the harvest reporting by fishers. At Waterloo Bay, fishers reported the time and GPS position of every bag of abalone brought to the surface. Also, the lengths from each bag were kept separate from others, thus providing point-specific length information. From these, data maps were constructed of fish-down CPUE and fish-down mean length inside the Waterloo Bay study region. These will be compared with corresponding survey maps of density and mean length (above 130 mm SL) presented in Chapter 6 that were constructed from the pre- and post-fish-down leaded-line surveys.

This chapter also summarises, for the timed-swim survey design, the principal fish-down experimental outcome of estimated change from pre- and post-fish-down surveys in Waterloo Bay compared with the number of greenlip abalone harvested.

9.2. Methods

9.2.1. Project Brief

A Project Brief for the fish-down experiment (Appendix 9.1) was submitted to the Minister for Primary Industries and Resources of South Australia in obtaining approval (1) to open the closed area of Waterloo Bay for two weeks for experimental fishing, (2) for the additional allocation of research limit (experimental greenlip harvest in the Waterloo Bay fish down experiment), and (3) a lower minimum length of 130 mm SL (from the current greenlip legal limit of 145 mm SL in the Western Zone). This Project Brief facilitated extensive planning and approval discussions with commercial divers and licence holders, the Abalone Research Steering Committee, PIRSA fishery managers and compliance officers, and the industry peak body, abalone processors. It was distributed to all stakeholders prior to the fish down. The Project Brief is included as Appendix 9.1.

9.2.2. Spatial Harvest Data

Information on the commercial catch obtained included (1) a complete count of the catch, (2) the lengths of 62% of the landed abalone, (3) the GPS position where every bag of abalone catch surfaced (each bag, sent up by the abalone divers from the bottom and retrieved by shellers driving the boat), (4) the time of surfacing of every bag, and (5) the total time divers spent in the water. Thus the harvest data set included the abalone counts and lengths, and the GPS position and time from every individual bag that surfaced.

This is possible because of the detailed information that fishers, and specifically on-board shellers, provided (sometimes, with the help of a second on-board crew member) for all boats that participated, that is, all licences in the Western Zone fishery. Participation levels were low for the first Western Zone fish-down experiment at Taylor Island. One principal difference at Waterloo Bay was that all greenlip taken were in addition to yearly quota, so the financial incentive to participate was substantial. Regardless of reason, the best data set of the four fish-down experiments was obtained from Waterloo Bay where fishers provided details on the time and location of each individual bag of harvested abalone.

Maps were generated for two important features of the greenlip populations in Waterloo Bay, namely abalone density and mean length. The input data for spatial analysis of the commercial fish down were the (1) bag-specific catch rate, i.e. numbers of abalone per minute of harvesting in each bag, which is taken as a proxy for density, and (2) the measured lengths of abalone in a majority of the bags, which provide mean length in those bags whose lengths were measured. Thus, because fishers recorded the GPS position of each bag of abalone harvested, these bag-specific measures of abalone density and size inside the study region can be used to draw maps of those population characteristics. Thus, the input data are point-specific measures of density (approximated as catch rate) and mean length.

Abalone in two-thirds of the bags harvested (190 of 283) were measured for length. Of these (140 of 190) were usable for spatial analysis because full spatial information was available. (For some bags, either GPS was not reported, or tags were lost in the transfer from fishers, to processors, to researchers.) The abalone count from the 140 harvested bags usable for spatial analysis and measured by researchers for length was 11,712, yielding about 99% agreement with the number of abalone, 11,838, reported on the corresponding fish-down catch forms.

As at Tiparra (Chapter 5), two statistical methods were used to draw regions of similar density and mean length inside the study region. Two methods were used because each approach makes assumptions about how density and mean length vary in the areas between data points. These two ways to achieve a similar spatial-data-analysis objective were both carried out using ArcView 8.0 GIS. The first method is more direct, and makes fewer assumptions, namely TIN contouring, which effectively draws lines between points assuming a linear change in values between observed points. Kriging is a more sophisticated statistical approach which assumes the influence of a particular data point should decrease with increasing distance from that point. Kriging is an unbiased minimum variance interpolator and should therefore give optimal accuracy and precision when all of its assumptions are satisfied.

9.2.3. *Commercial Fish Down*

The fish-down experiment proceeded in 11 stages: (1) SARDI Abalone research team carried out the pre-fish-down surveys by both leaded-line and timed-swim (29 September to 15 October 2003). (2) Based on the estimate of absolute greenlip abalone numbers from this pre-fish-down leaded-line survey, the quota for the fish-down harvest was set at 30% of the estimated biomass to permit a good chance of detecting a change from pre- to post-fish-down survey. (3) A project brief was prepared and submitted to all stakeholders (4) Planning meetings were held with PIRSA managers and compliance, and with industry representatives on the Research Steering Committee. (5) A submission was prepared by PIRSA managers Merilyn Nobes, and the Director of Fisheries, Will Zacharin, to the Minister of PIRSA for approval to enter the closed area of Waterloo Bay for experimental fishing. (6) A presentation and discussions were held with industry participants at a Western Zone meeting in Port Lincoln. The importance and implications of measuring absolute abalone abundance and details of the Waterloo Bay fish-down protocol were discussed in detail. (7) The Waterloo Bay harvest fish down was held 17-28 November 2003. Fishers each harvested 540 kg of greenlip abalone, 130 mm SL and larger, inside the study region. (8) Abalone were landed whole and shelled by participating processors, and all shells from each bag that surfaced in the fish down were transferred into individual collection bags. (9) SARDI divers returned to carry out post-fish-down leaded-line and timed-swim surveys. (10) Data from the forms returned by fishers were processed and ArcView GIS maps generated of survey and fish-down spatial information. (11) Shells were picked up from processors and two-thirds of the abalone were measured for length. (12) The counts and length samples from the leaded-line surveys were analysed (Chapter 6).

20 10-minute timed swims were run at 5 sites, at leaded-line transect location numbers LL2, LL8, LL17, LL4, and LL11 (Figure 6.1).

The total number of abalone (greenlip only) harvested (as reported on the fishers' experimental data sheets) was 25,378 (Tables 9.1 and 9.2) and a random sample of 15,659 harvested abalone were measured for length.

9.3. Results

9.3.1. *Calculating the Experimental Harvest Allocation*

A fish-down harvest of 30% was set, confined to abalone inside the study area which left some inshore dense populations in Waterloo Bay unexploited. The estimate of number available for harvest ($\geq$ 130 mm SL) was based on the mean density estimate from the pre-fish-down survey of 0.0686 abalone per m^2. Total area of the study site was 1,343,235 m^2 calculated from the boundary coordinates in ArcView, i.e. roughly 1 square km. The total estimated population of greenlip abalone ($\geq$ 130 mm SL) was 92,138.

A take of 30% implies 27,641 animals. Mean weight of harvested animals was assumed to be 0.45 kg whole weight. This yielded a total greenlip abalone biomass for fish-down harvest of 12,438.56 kg, or about 12 tonnes. Dividing this among the 23 licences in the Western Zone abalone fishery, equalled 1201 abalone per licence.

Assuming an average whole weight of 0.45 kg per abalone, a research limit of 540 kg whole weight was set by PIRSA fisheries. This harvest limit was set as a whole weight because the abalone were landed in shell to permit researchers the ability to measure all of the shell lengths after landing.

9.3.2. Experiment Description

The fish down was completed in the first week. 19 of 23 vessels in the Western Zone fishery went into Waterloo Bay on the first day of the fish down (17 November 2003) and all of those caught close to their research limit of 540 kg whole weight. All boats came back to complete their research limit on a subsequent day, once they knew precisely the whole weight of their first day's catch, to avoid exceeding their whole weight limit of 540 kg. Weather was very good on the first two days, with nearly no swell or wind on the first day, and low swell and moderate wind on the second day. The SARDI Principal Investigator was present and commercial vessels stayed inside the line for all time observed (observing from the beach, the water by boat, or from a house overlooking the Bay).

9.3.3. Spatial Abalone Distributions by Density And Mean Length

9.3.3.1. Density

Fishers achieved higher catches and tended to concentrate their fishing in one specific area of the Waterloo Bay fish-down study region (Figure 9.1). This area was located near and south of the end of the jetty. The majority of the fish-down harvest came from a wide strip of higher catches and catch rates that started at the fish-down boundary near the end of the jetty, and extended southward (Figure 9.1). Two secondary patches of higher-than-average catch rates were also identified by the kriging interpolation (Figure 9.1b) in the northern half of the study region. One of these secondary patches was located over or near the large 'sand hole' (plainly visible in the aerial photograph of Figure 6.1) which was an area of high catches in previous fish downs (Shepherd, pers. comm.). Few abalone were found just inside the Bar, another area where abalone were abundant in the 1980's (Shepherd, pers. comm.).

The location of this principal area of high catches and catch rate is consistent with the area of high density identified by the surveys. Both pre-fish-down and post-fish-down surveys found high densities in essentially the same area south and near to the jetty (Figures 6.7 and 6.8) where fishing was concentrated (Figure 9.1). Thus, the surveys appear to have successfully identified the areas of abundant greenlip abalone, confirmed by the fish-down bag-specific commercial catches and catch rates. The surveys also appear to have identified the secondary areas of harvest in the northern half of the study region (Figures 6.7 and 6.8), with somewhat less precise agreement between surveys and fish-down in the location of these secondary patches (Figure 9.1).

The post-fish-down survey also estimated significant decreases in abalone density in this primary harvest patch south of the jetty by comparison with the pre-fish-down survey. This constitutes a second form of agreement since we know that most harvested abalone were removed from this location.

Overall, agreement in the spatial disposition of abalone, and in the spatial disposition of change in density from before to after fish down, exceeded expectations. Together, these two forms of agreement at Waterloo Bay suggest that leaded-line surveys express a relatively high ability to quantify the spatial dynamics of greenlip abalone inside a study region like this one, of about 1 km^2, using 32 pairs of 100-m long transects.

The kriging routines in ArcView 8.2 (using the Geostatistical Analyst package) also allowed us to generate a map of the uncertainty as standard error (Figure 9.3a) in the krigged map of catch rate (Figure 9.1b).

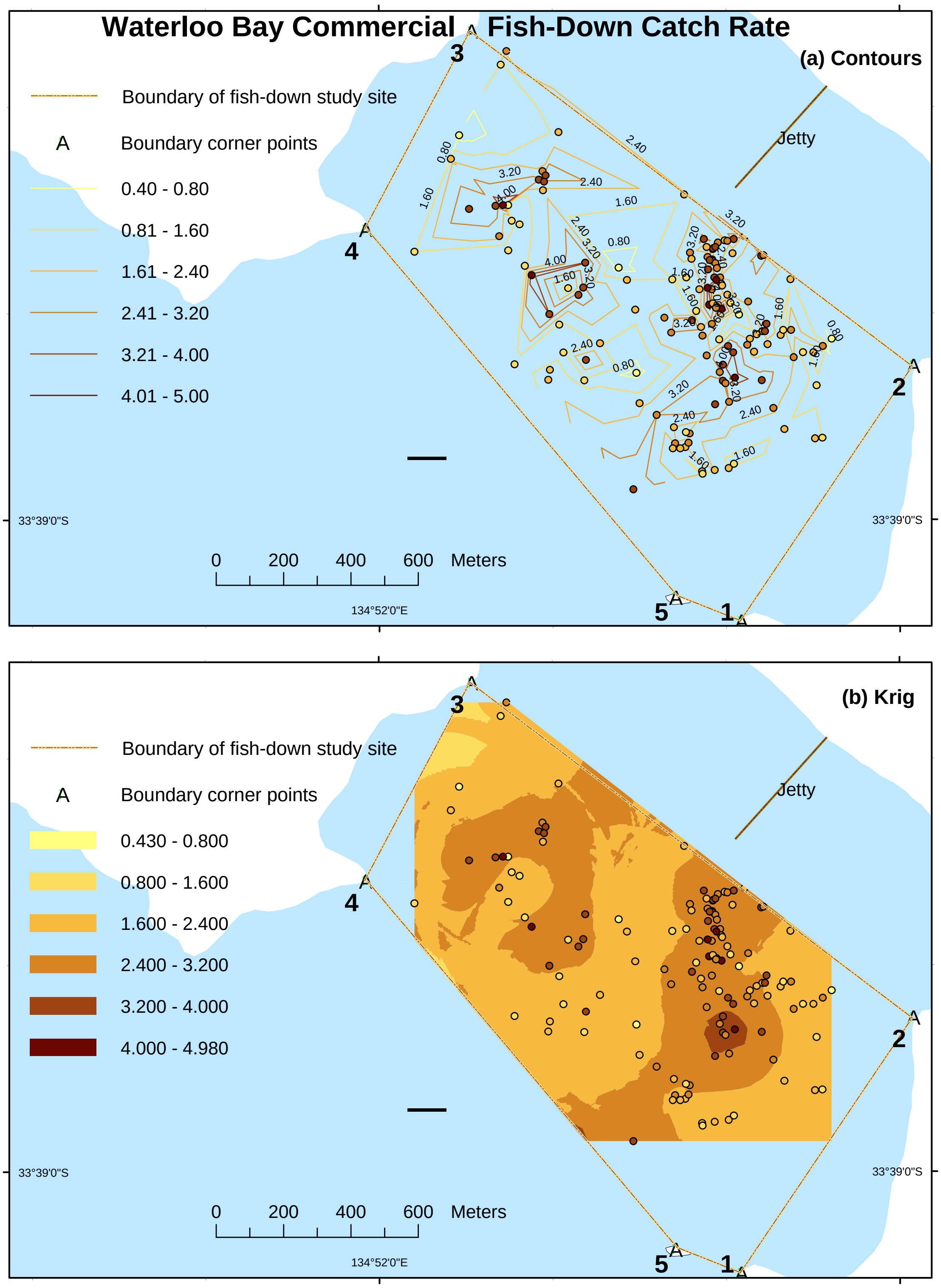

Figure 9.1. Maps of catch rate (greenlip abalone per minute) from the Waterloo Bay fish down. Points (n = 140) represent location and catch rate of individual bags of harvested abalone. The same point-location data set of abalone numbers divided by the harvest time (in minutes) is used for both maps, where the method of interpolation is (a) raw contours, or (b) kriging. For kriging only, the corresponding map of standard errors is presented in Figure 9.3a.

9.3.3.2. Mean Length

The same procedure employed in the section above for abalone density can be used comparing survey and fish-down maps of abalone length. Again, because we measured the abalone lengths for about half of the bags harvested (140 of 283), a satisfactory measure of the spatial distribution of the sizes of harvested abalone on a bag-specific basis was obtained. The interpolated maps of mean abalone length using the two methods are shown in Figure 9.2.

The survey sample size is reduced for spatial analysis of mean length because no information is obtained from the leaded-line locations where a zero count of abalone was recorded. These are identified as stars (rather than circles) in Figures 6.9 and 6.10. The survey measure of mean length includes only harvestable sizes ($\geq$ 130 mm SL) for comparison with mean length in the harvest.

As with density, both pre- and post-fish-down survey maps of mean length (Figures 6.9 and 6.10) show generally good agreement with the fish-down map (Figure 9.2). There appears to be a core area in the central basin of Waterloo Bay where abalone are smaller in size. Outward from this central basin, in roughly all directions, mean abalone length increases. This central basin is the area of generally greatest depth in Waterloo Bay.

One noticeable difference is that the area of smallest mean length from both survey maps (Figures 6.9 and 6.10) lies just west of the end of the jetty, while from fishers' bag-specific catches, it lies more directly opposite the end of the jetty. This difference is, at least in part, explained by the fact that there was only one reported bag from the area just to the west of the jetty, so no data are available on catch length from this area, identified by the surveys as the area of smallest abalone size.

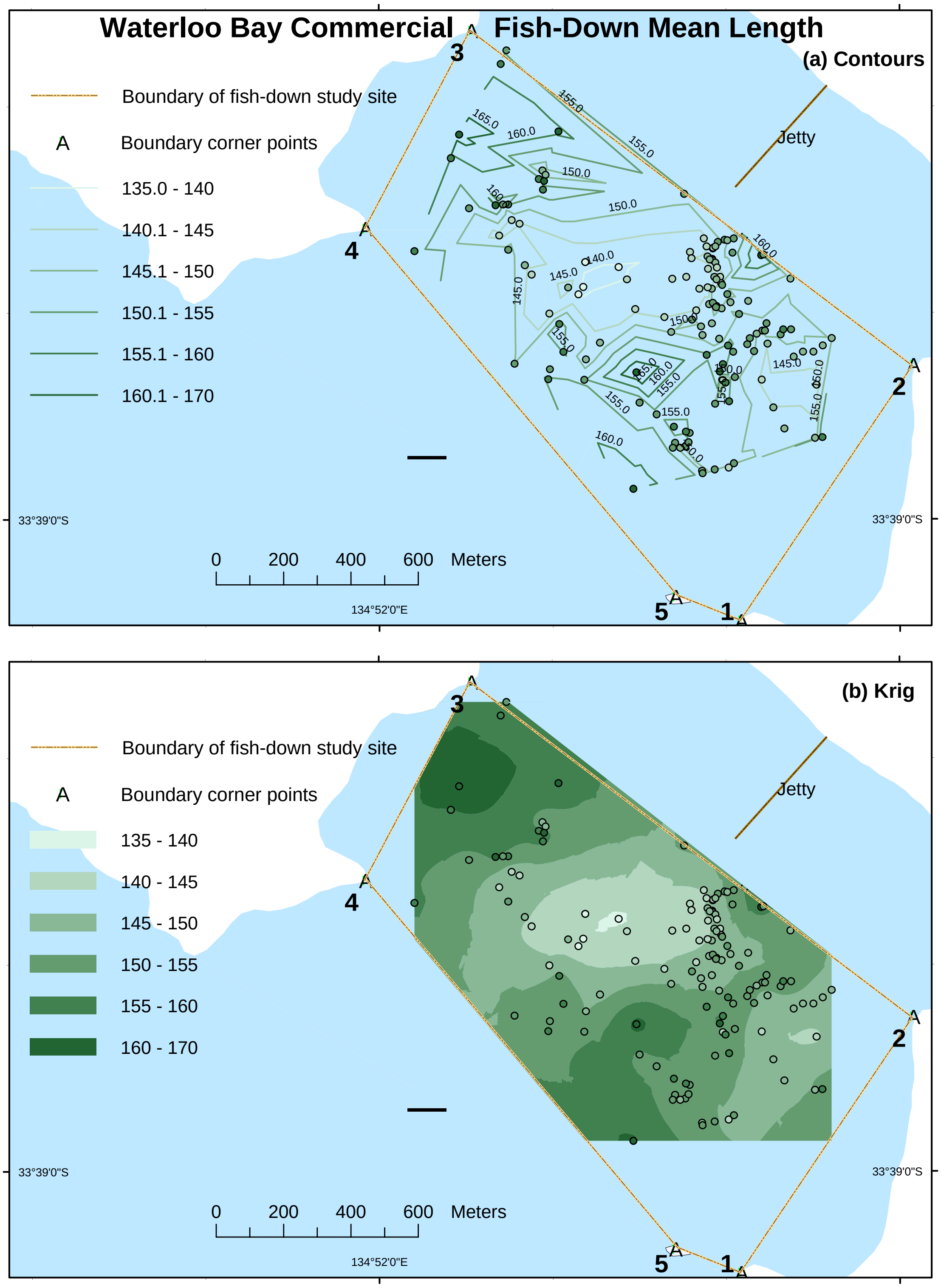

Figure 9.2. Maps of mean length (mm SL) of harvested abalone from the Waterloo Bay fish down, with each point (n = 140) a harvested bag of abalone as in Figure 9.1, where the method of interpolation is (a) raw contours or (b) kriging. For kriging (b) only, the corresponding map of standard errors is shown as Figure 9.3b.

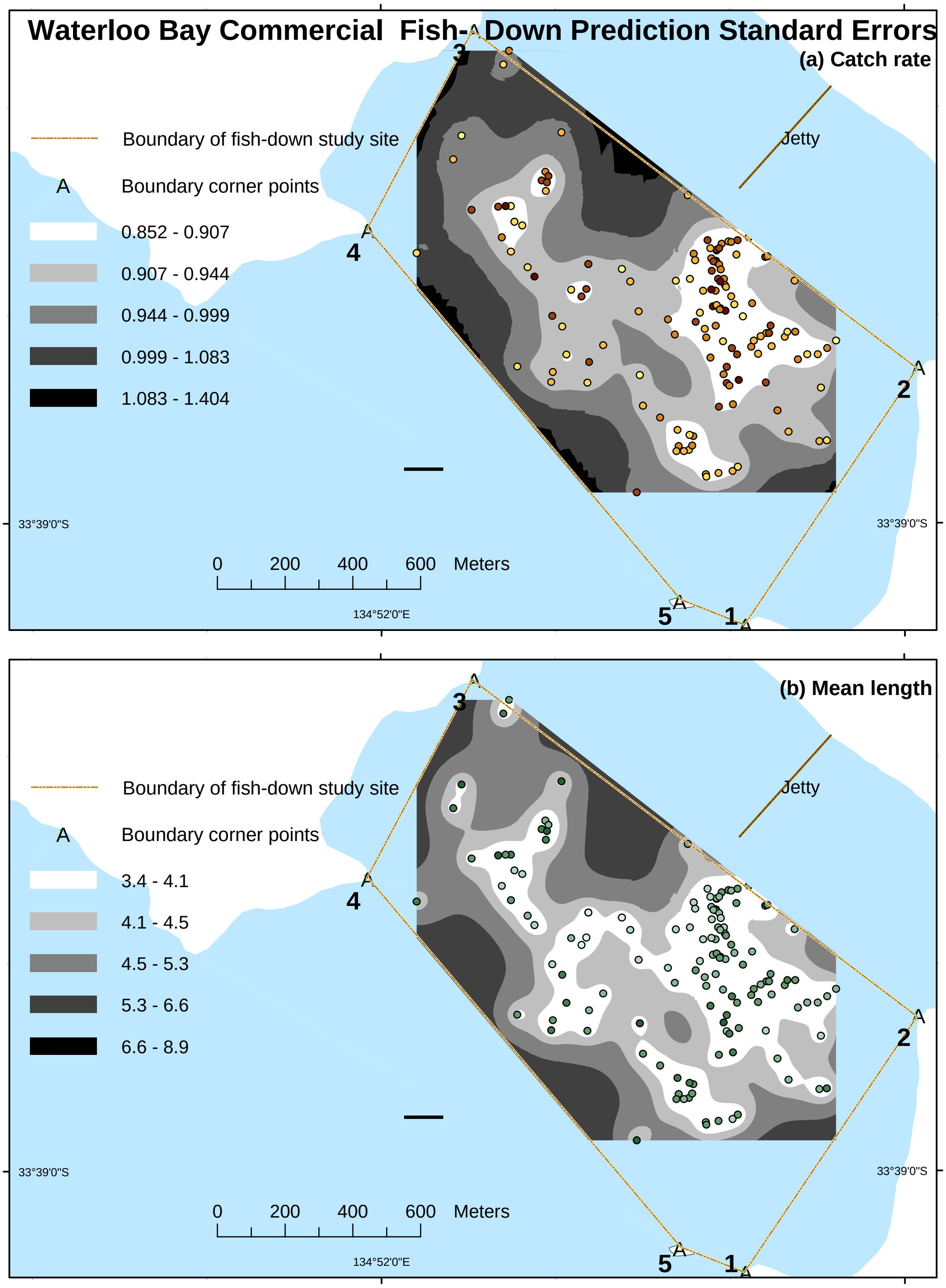

Figure 9.3. Maps of kriging as standard error are shown for (a) abalone catch rate as abalone caught per minute (Figure 9.1b), and for (b) mean lengths (mm SL) of abalone caught in the commercial fish-down (Figure 9.2b). These standard error maps provide a quantification of reliability in the kriging interpolated values at each location in the prediction surface.

9.3.4. Leaded-Line and Timed Swim Survey Design Comparison

9.3.4.1. Leaded-Line Survey Method

The fish-down experimental results showed generally good agreement of leaded-line estimates of population change with actual number removed by fishers (Figure 9.4). Confidence intervals (CI) were relatively wide, for both the double-difference bootstrap measure of change in absolute population size (Figure 9.4) as well as for the individual surveys, especially the pre-fish-down survey, which had a bootstrap confidence interval as SE confidence ratio of $\pm$31% (Table 9.1).

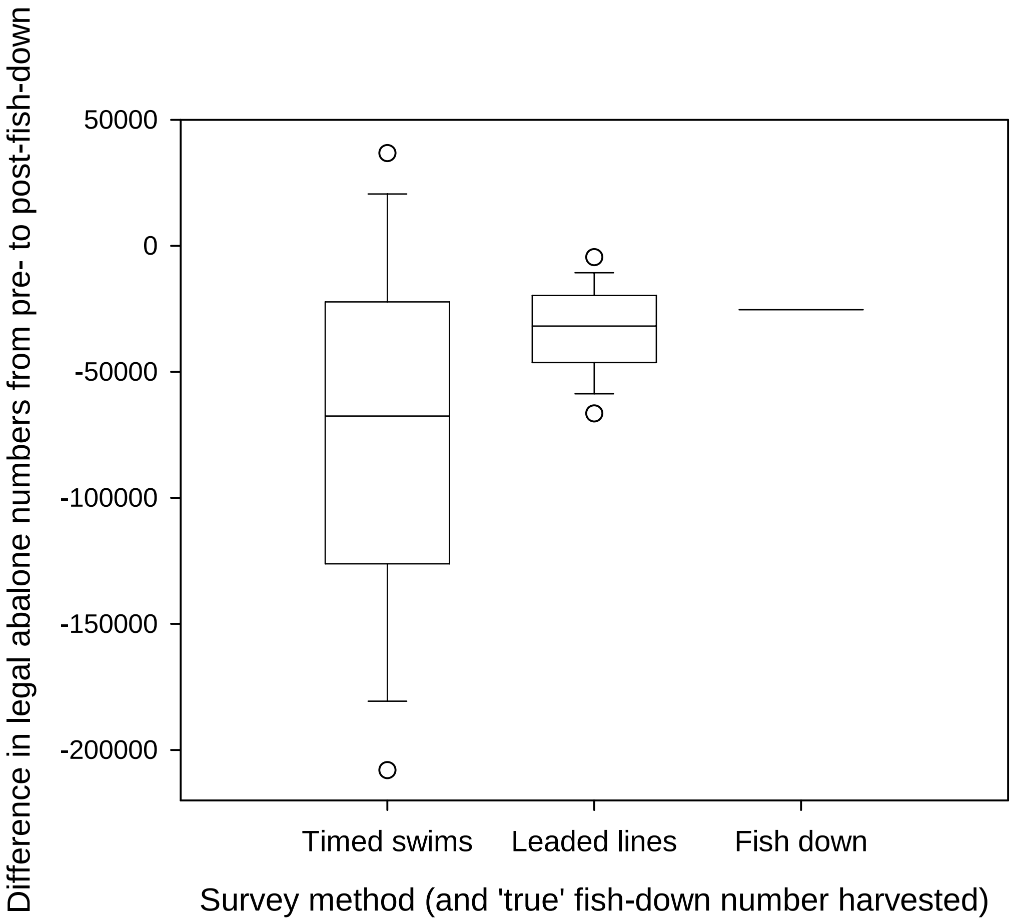

Figure 9.4. Waterloo Bay fish-down experimental results. Boxes show distributions of survey estimated differences in legal population numbers quantified by the double-difference bootstrap. The 25% to 75% quantiles of pre-to-post-survey-estimated difference are indicated by the outer boundaries of the boxes. A line marking the median difference is shown at the middle of each box. The 10% and 90% quantiles are plotted as the limits of the 'whisker' error bars and 5% and 95% quantiles are marked by open circles.

Table 9.1. Waterloo Bay fish-down experiment statistics for the leaded line survey method: Area, numbers, densities, and difference in leaded-line-survey estimated numbers from before to after the fish down versus commercial fish-down number removed. (FD ≡ fish down, and 'fishable-size' signifies abalone of shell length ≥ 130 mm).

	Area of study region (m^2)	Mean density: fishable-size only	Estimated total fishable-size abalone	SE-CV (from 2-level bootstrap)	Survey change from pre- to post-FD	Reported number of abalone removed in the FD	Proportion legal
pre-FD	1,343,235	0.0686	92,100	30.8%	-33,581 (-36.4%)	-25,378 (-27.5%)	0.51
post-FD	1,343,235	0.0436	58,600	24.5%			0.49

9.3.4.2. Timed-Swim Survey Method

Two features of the estimates from timed swims were observed: (1) The mean estimated difference was well within the 25-75% confidence intervals (Figure 9.4) of the double-difference bootstrap, and (2) the double-difference estimates of confidence interval were unusually wide (Figure 9.4).

The estimated levels of absolute population size (140,000 and 100,000) for pre- and post-fish-downs respectively (Table 9.2) are higher than those from the theoretically unbiased estimates by well-defined transect counts obtained from the leaded-line survey of 92,000 and 57,000 (Table 9.1). By contrast, at Tiparra, the timed-swim-survey legal population estimates were lower than the estimates from leaded-lines by larger factors of difference (Tables 8.1 and 8.2).

Table 9.2. Waterloo Bay fish-down experiment statistics for the timed-swim survey method: fishable-size (≥ 130 mm SL) greenlip abalone

	Area of study region (m^2)	Mean density (m^{-2}): By ratio estimator	Estimated number of fish-down-size abalone	SE-CV (assuming timed-swim area covered is known without error)	Change from pre- to post-FD	Actual number of legal abalone removed in the FD	Proportion legal
pre-FD	1,343,235	0.104	139,100	27.3%	-38,400 (-28%)	-25,378 (-27.5%)	0.56
post-FD	1,343,235	0.075	100,700	16.7%			0.58

The uncertainty on timed-swim estimates of mean density is, in fact, calculated two ways. Both methods assume that the variation in the area covered by each timed swim search is given exactly by the Shepherd formula (Section 3.4.1). The mean-of-ratios method implicit in the double-difference bootstrap, gave much higher values for the timed swim estimated mean densities of 0.140 abalone per m^2 (not shown) versus 0.104 (Table 9.2) and 0.084 (not shown) versus 0.075 (Table 9.2) for pre- and post-fish-down timed swim surveys respectively. It is widely accepted on statistical grounds (Cochran 1977; Rice 1995) that the ratio estimator is the more precise of the two. For this reason, the large differences between ratio and mean-of-ratios estimates, especially for the pre-fish-down survey (of 0.104 versus 0.140), probably represents a case where the ratio estimator provides substantially better overall estimates of mean abalone density when analysing data from a timed-swim survey design. Formulas were presented for calculating the ratio estimate of mean density from timed-swim counts in Section 3.4.1.

Note that the SE-CV's given in Table 9.2 are taken from a ratio estimator, while the double difference bootstrap error bars about the estimate of timed-swim population difference from pre- to post-fish-down in Figure 9.4 is more similar to a ratio-of-means confidence interval, for the purpose of combining uncertainty from both pre- and post-fish-down timed-swim absolute population estimates, to get the overall uncertainty in the difference from pre- to post-fish-down.

9.3.5. Length Frequencies

The majority of abalone harvested in Waterloo Bay fell into the size range 130-175 mm SL.

In the 1998 and 1999 Waterloo Bay experimental fish downs organised by Dowling and Shepherd (Dowling 2002, Chapter 3), the size range of harvesting was limited to 125-145 mm SL to investigate the hypothesis of fishery-selective removal of faster growing abalone. The idea was to remove the 125-145 mm greenlip abalone in order to target the presumed slower growing abalone and thus attempt to reverse the growth selection for faster growing animals. (One problem with this approach would be that some abalone in this 125-145 size range might be simply younger rather than slower growing; a second potential factor is that artificial selection over more than one generation would normally be required for such an effect to be incurred on the overall population genome of the Waterloo Bay population.). The plot provides no obvious visual evidence of removal restricted to the 125-145 mm SL size range in April 1998 and April 1999, 4.65 and 5.65 years prior to the November 2003 fish down, which probably reflects growth variation and other factors.

Comparing the survey and commercial fish-down length samples, it is clear, as usual, that fishers generally avoided the abalone of size near to the declared fish-down limit of 130 mm SL, taking abalone in rough proportion to the previous size range only above about 145 mm, the regulation greenlip size limit in the Western Zone.

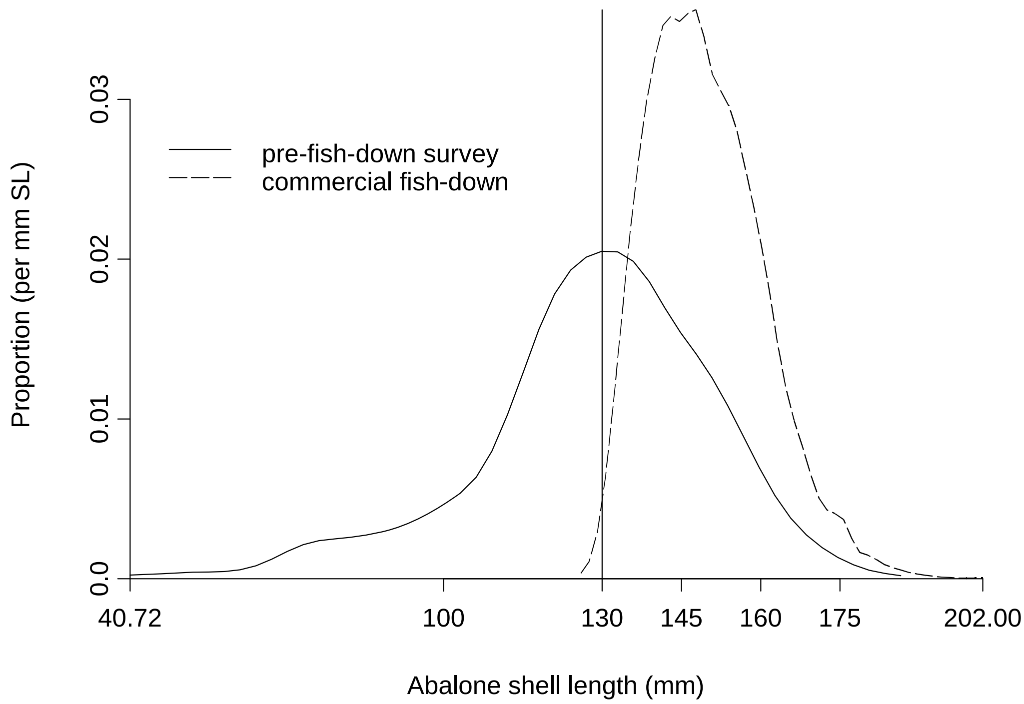

Figure 9.5. Length frequencies from the commercial fish down and, for comparison, from the pre-fish-down leaded line survey (the latter also shown in Figure 6.5).

9.3.6. Hourly Catch Rates

As noted, fishers provided times of surfacing of each bag and the number of abalone harvested in each bag for calculating an hourly catch rate over the 10 days of 10-hour fishing days (8:00 am to 6:00 pm) of the Waterloo Bay fish down. The results are plotted as a scatterplot, each point representing the catch rate from a single bag of abalone. This catch rate is quantified as number of abalone in the bag divided by the time taken to harvest that bag. The time used to harvest was, in turn, computed as the time (in minutes) from either (1) the beginning of the harvesting dive to the time of the ascent of the first bag or (2) for all subsequent bags in that dive, the time (in minutes) since the previous bag surfaced for that licence.

We tested for a decrease in hourly catch rate over time. A declining catch rate assumes that catch rate is dependent on abalone abundance, which, in turn, declines with the number of hours in the fish down that fishers have been harvesting (Figure 9.6). The outcome was that, while a decline was suggested (for the linear least squares fit, with a negative slope of -0.009), this decline in catch rate over time was slow and not statistically different from no change in catch rate with time.

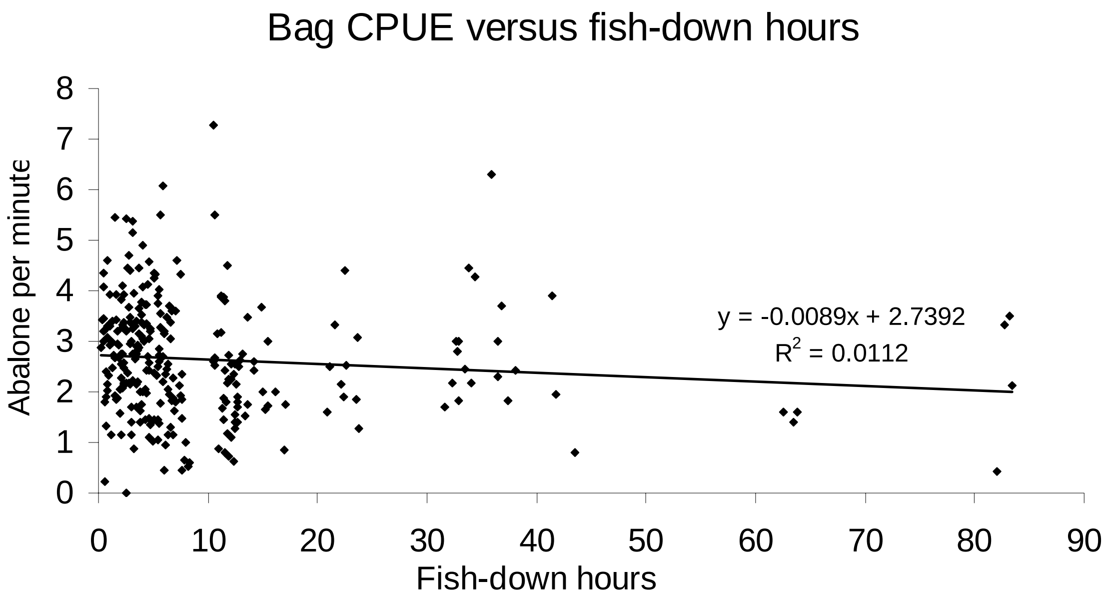

Figure 9.6. Hourly commercial catch rate (CPUE) in the Waterloo Bay fish-down, from reported abalone per bag sent to the surface by abalone divers. Points represent numbers of abalone divided by the time taken to harvest each bag.

The reason for the failure to detect a significant change in catch rate over the two-week time span of the fish down is apparent in Figure 9.6, namely very wide variability in individual bag-specific catch rates. The variation as CPUE, namely a SD = 1.14, is approximately 100 times larger than the slope of 0.009 abalone per minute. The overall drop in CPUE over the approximately 85 hours of fishing, assuming the linear trend line is a reasonable approximation of the change in CPUE, was about 28%.

The Waterloo Bay fish-down experiment protocol permitted a direct test of CPUE as a time-dependent index of abalone population size because the bag-specific catch reporting provides a measure of change in absolute abundance over time (Figure 9.7). The starting level of absolute abundance is provided, as an estimate, by the pre-fish-down leaded-line survey. The change in (absolute) abalone numbers in the study region over that time is given directly by the reported numbers harvested in the fish down. Thus, fish-downs allow us to compare CPUE with a true measure of decreasing abundance. It is quantified by the decline in population number from the bag-by-bag catch forms, reporting the time and numbers taken, that all 23 fishers returned for all bags harvested.

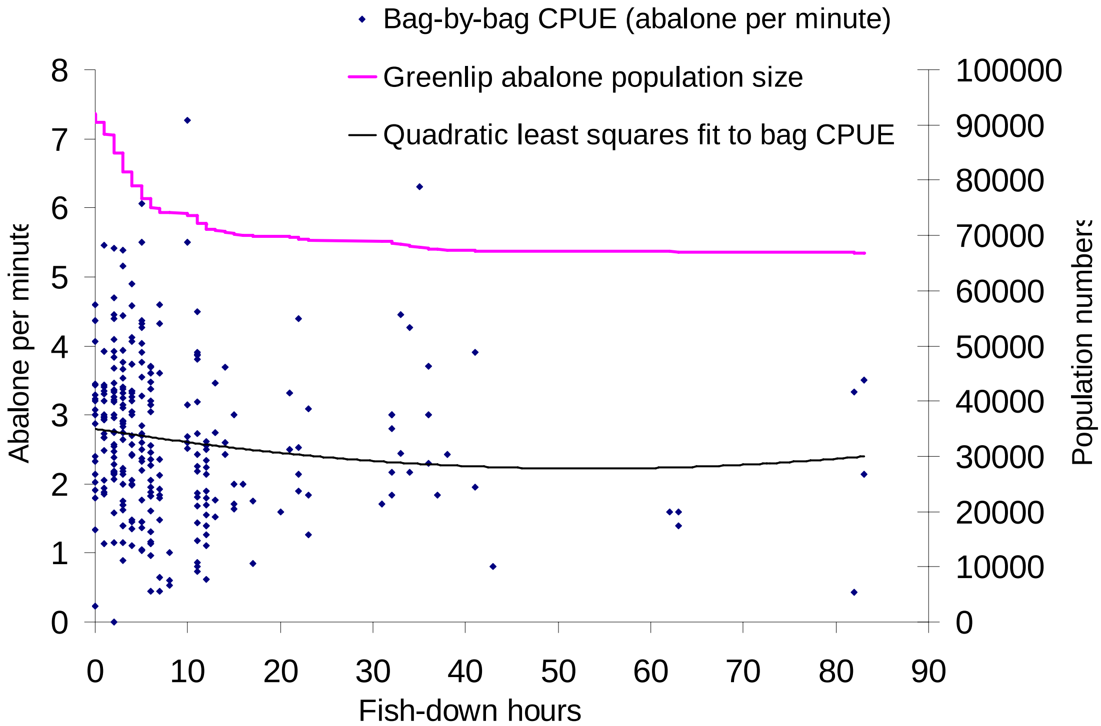

Figure 9.7. Bag-specific CPUE data as in Figure 9.6, with estimated population size now shown, calculated from pre-fish-down survey and bag-by-bag depletion. A quadratic trend line replaces the linear trend line of Figure 9.6.

The change in population size is known because fish-down numbers on a bag-by-bag basis are reported with negligible error compared with other sources of error. A total of about 25,000 greenlip abalone were harvested. There is uncertainty in the assumed total number of abalone inside the 2003 Waterloo Bay fish-down study region at the start of the fish down. This estimate was obtained from the pre-fish-down leaded-line survey, which had a mean and standard error of 92,000 ± 31% (Table 9.1).

This result is fully consistent with previous studies of abalone catch rate as a measure of abundance. While the outcome does show weak evidence of a declining catch rate, it is swamped by the differences in catch rate among divers, and among bags harvested for each diver. Thus, in this Waterloo Bay fish down, it is clear that as a predictor of abundance, the noise in the signal being two orders of magnitude larger than the signal itself means that catch rate provided a highly imprecise but, by this example, relatively unbiased measure of abalone abundance, after the first day.

9.4. Discussion

9.4.1. Leaded-Line and Timed Swim Survey Design Comparison

The last of four fish-down tests of the two survey methods at Waterloo Bay showed relatively good agreement between leaded-line survey difference from before to after and the actual numbers removed in the fish down. The two leaded-line surveys measured a change in population number of 36% and the true fish-down removal was 27% (Table 9.1). Confidence intervals on the survey change were $\pm 31\%$ and $\pm 25\%$ so the true value of population change fell comfortably within the expected probable range estimated by the leaded-line survey method. Thus, to this level of confidence, it appears that leaded-line surveys provided an accurate estimate of the absolute harvestable population numbers, with confidence intervals that are realistic.

In predicting the absolute change in population size, timed swims also performed fairly well, predicting a change of 38,000 rather than the 33,000 of leaded lines, compared with the true numbers removed of 25,000 (Tables 9.1 and 9.2). The very wide double-difference bootstrap confidence intervals shown in Figure 9.4 exaggerate the timed-swim estimate uncertainty because the double-difference bootstrap does not, by its nature, incorporate the ratio-estimator. Ratio estimates were, however, presented in Table 9.2, and these confidence intervals are smaller, of $\pm 27\%$ and $\pm 17\%$. Considering all four fish-down experiments, for three of four fish-down experiments, leaded-lines gave better agreement with fish-down numbers removed.

However, while the differences between pre- and post-fish-down agree fairly well, for both survey methods, the absolute levels of abundance show less consistency. At Waterloo Bay, timed swims gave substantially higher estimates of both pre- and post-fish-down greenlip abalone population number than leaded lines. Given that leaded lines represent a method that is known to be unbiased, while timed swims do not, and knowing that the confidence intervals of Table 9.2 quantify none of the potential bias, it is likely that the true levels of population size are better estimated by the unbiased survey method, of leaded lines. For the pre- and post-fish-down surveys, timed-swim estimates of absolute (fishable-size) population numbers were 52% and 72% higher than leaded-line estimates.

At Taylor Island, timed-swim pre- and post-fish-down survey estimates were 47% and 167% higher respectively. At Coal Ground, timed-swim and leaded-line estimates essentially agreed, with timed swim estimates a bit lower by–13% and –8%. At the West Bottom fish down experiment, timed-swim estimates were, as usual, higher by 37% and 67%. Thus, in general, timed-swim estimates of absolute abundance appeared to overestimate compared to the unbiased measure from leaded-lines, except at Coal Ground, where they effectively agreed, and where both survey methods agreed with fish-down numbers removed.

9.4.2. Hourly Catch Rates

The outcome for comparing bag-specific CPUE versus known (fish-down) total numbers was surprising in that CPUE did appear to roughly track the actual change in abalone population size. The quadratic fit matched population size for times after the first day when most abalone were removed. Moreover, a fourth-order polynomial fit (not shown) gave a much steeper trend line, and thus a much better agreement with population size, for the first day (up to 10 hours) than did the quadratic fit plotted in Figure 9.7; this is also visually evident by close examination of the wide scatter of points varying from 1 to 6 abalone per minute obtained from the first day. This general agreement of change in CPUE and change in true population size could have been coincidence (due simply to both being small) but leaves open the possibility that catch rate is related in some meaningful way to abundance. It can, at least, be concluded that the results at Waterloo Bay, apart from the first day, do not refute catch rate serving as an index of abundance.

9.4.3. Spatial Abalone Distributions by Density and Mean Length

9.4.3.1. Density

The agreement spatially of survey density with fish-down catch rate was clear and encouraging. Subject to further testing, this implies that a spatially uniform coverage of leaded-line transects can define areas of high and low abalone abundance, to a resolution comparable to the distance between transect locations.

This, in turn, may have two important ramifications for the use of leaded-line survey in (1) spatial stock assessment, and for quantifying the environmental effects of fishing on abalone distributions, and in (2) stratification for future surveys.

Shepherd et al. (2002) and Shepherd and Rodda (2002) postulate that spatial contraction preceded decline to unfishable levels in several Western and Central Zone greenlip populations. Thus, one of the principal questions for South Australian abalone management is whether and by how much the spatial distribution of abalone populations expands or contracts over long times. The outcome at Waterloo Bay suggests that the leaded-line diver-survey method can quantify abalone spatial contraction and expansion. The extent of spatial agreement between survey and fish-down locations were, it appears, in Waterloo Bay, adequate to meet that objective.

Secondly, the identification of areas of high, medium and low density should permit the drawing of survey strata in future years, based on spatially resolved survey results from previous years. A program of yearly, or multi-yearly refinement of these strata, should allow increasing levels of survey precision in estimates of overall density inside any given study region of management interest. Stratification was discussed in sections 3.4.3 for Taylor Island and 4.4.1 for Tiparra. Knowledge of where abalone occur in high, medium and low density, (or optionally, just high and low) would require spatial resolution sufficient to identify areas for each stratum not smaller than that needed to allow at least several leaded-line transects to be run inside. Thus, the spatial resolution obtained at Waterloo Bay, based on the spatial resolution of agreement obtained between fish-down and survey, approximately that between two leaded-line transect locations, say about 100 m, would be sufficient to draw future survey strata. In particular, the results of the contouring (by kriging or RBF) could be used directly to define future stratum boundaries.

Thus, for example in Waterloo Bay (Figure 6.7b), the RBF contours of 0.000-0.050 abalone per m^2 could define the low-density stratum, that of densities >0.150 could define the high density stratum, and everything in between can be taken to define medium density. Because the measure of abundance given by leaded-lines (or any transects or quadrats that cover the study region randomly or uniformly) is absolute density, the survey design can be altered, and in particular, the strata boundaries can be redrawn as further information on spatial distributions comes to light in future surveys.

9.4.3.2. Mean Length

The spatial distribution of mean length inside the Waterloo Bay study area, found the smallest greenlip abalone (above legal size) in the deeper central basin of the Bay. This was observed in the length samples from both surveys and from commercial divers.

This spatial distribution has at least one plausible hypothesis. It may be explained by the prevailing spatial pattern of settlement and subsequent movement. Shepherd and Partington (1995) examined the spatial patterns of recruitment in Waterloo Bay and found that recruitment was correlated with slower water movement and depth. The maps of Shepherd and Partington (1995, Fig. 4) confirm that the regions of greatest depth were in this central area where we found greenlip with the smallest mean length. The trajectories of drogues released in Waterloo Bay, also mapped by Shepherd and Partington (1995, Fig. 4) tended to move more slowly and showed more curvature in their movement above and near this basin of deeper water, implying a greater probability of free-floating abalone spat settling in this area of the Bay. Thus, slower water movement, and more curvature in the flow, would permit more time for water to pass over this deeper basin, allowing the opportunity for more abalone spat to settle into this deeper water habitat.

Shepherd (1986a) provided evidence that the movement direction of greenlip abalone inside Waterloo Bay was towards the swell, that is, towards the open sea. Clavier and Chardy (1989) and Prince (1989) also recorded movement of abalone to locations where water movement was stronger. Shepherd (1986b) showed that the greatest tendency for directed movement was of larger-size abalone, notably mature adults.

Thus, it is at least plausible that the pattern of smallest abalone in the deeper central basin, and larger abalone, on average, in directions away from this basin is explained by a general spatial pattern of higher recruitment to the deeper central basin, and then, over long times, movement of adults, either towards the open sea or to the edges of the Bay. The spatial patterns in density and mean length observed were consistent with this hypothesis.

The one notable difference in the results presented in the Chapter with those of Shepherd and Partington (1995) was the low greenlip densities we found in the areas just inside the Bar (a shallow reef separating Waterloo Bay from the open sea) at the seaward mouth of the Bay. Instead, the spatial patterns of both density and mean length, under this settlement and movement hypothesis, suggested less purely seaward directed movement, and instead, a more broadly directed movement in all observed directions away from the deeper central basin. We have no survey or fish-down data for the inner Bay (inside the study region, to either side of the jetty), and so we have no information about whether abalone moved farther inward, or how about the size of abalone in these inner shallows of Waterloo Bay.

9.5. References

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Appendix 9.1

This Appendix (the next 7 pages) is a copy of the Project Brief submitted to PIRSA, the Fishery Management Committee, and the fishers to summarise the proposed fish down experiment. PIRSA permitted a lower-than-legal size limit and approved the additional research allocation that fishers received via participation in the fish-down experiment.

SARDI *Aquatic Sciences*

Project Brief

Testing Survey Design through a Fish-Down Experiment in Waterloo Bay under FRDC Project 2001/076, "Assessing survey method for greenlip abalone in South Australia"

Prepared by
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SARDI Aquatic Sciences

5 November 2004

Introduction

Currently SARDI and the abalone industry are collaborating on an FRDC project to develop and test survey designs for estimating absolute abalone density. Measuring absolute density would permit estimates of the total fishable biomass of abalone in a given area, which is valuable information for resource management decision making, notably for setting quota.

The principal method for testing diver-survey designs proposed in this FRDC project is through 'fish-down experiment'. This combines surveys by researchers with intensive fishing by commercial divers. The method is to undertake a diver survey using the design to be tested prior to fishing. Both the absolute density and the length frequency distribution of the abalone populations are measured. Commercial fishers then remove a significant portion (~30%) of the abalone, sufficient in number to be measurable by the survey method. The total number and the lengths of all harvested abalone are recorded. Thereafter, the second 'post-fish-down' survey is undertaken using the same survey design. The survey design is validated if the number of legal-size abalone removed equates to the difference in total estimated numbers from the pre-fish-down to post-fish-down surveys.

Currently Waterloo Bay is closed to abalone fishing. The purpose of this brief is to outline the procedure under which harvest of greenlip abalone may be permitted, through allocation of a research limit, to allow the fish-down experiment to proceed. Similar 'fish-down' experiments, with an associated research limit, were also undertaken at Waterloo Bay in 1998 and 1999.

This Waterloo Bay experiment will be the fourth of four fish-down survey design testing experiments for greenlip abalone (*H. laevigata*) contracted with Fisheries Research & Development Corporation (FRDC) under FRDC Project 2001/076, "Assessing survey methods for greenlip abalone in South Australia". The six specific proposed outcomes of the fish-down experiment are:

1. To estimate, by diver survey, the absolute density of harvestable abalone in the fish-down area prior to the commercial fish down.
2. To sample length frequencies of abalone prior to the fish down.
3. To harvest 30% of the estimated total fishable biomass in the commercial fish down and an accurate count.
4. To measure the shell lengths of all (or a large sample) of the harvested abalone.
5. To estimate the absolute density of harvestable abalone in the fish-down area after the fish down.
6. To sample length frequencies of abalone after the fish down.

Discussions between the abalone industry, SARDI, the Research Steering Committee of the AFMC, and PIRSA Fisheries have led to the development of an experimental protocol. The outcomes that have flowed from these discussions including a detailed description of the study area, timing of the experiment and the 'fish-down' procedure are provided in the remainder of this brief.

Study Site

An area comprising about two-thirds of Waterloo Bay is proposed for the fish-down experiment (Figure 1).

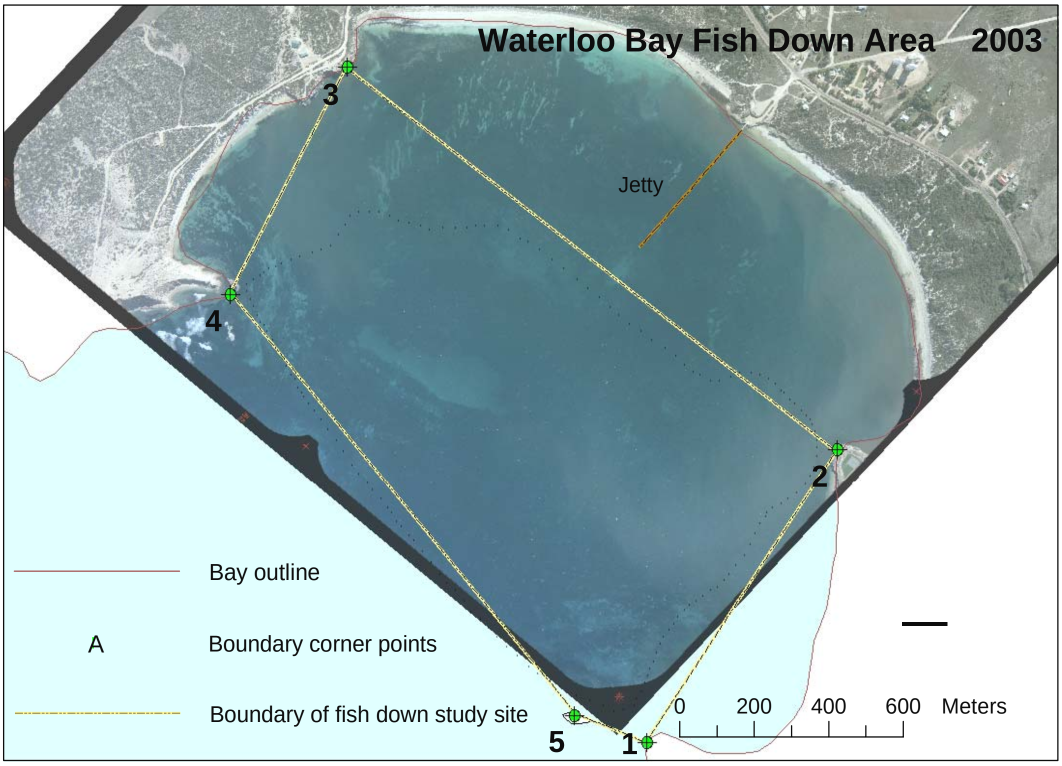

Figure 1. Waterloo Bay with an aerial photo superimposed. The boundaries of the fish-down study area inside which fishing would be permitted are shown in yellow.

Latitude-longitude coordinates (GDA94 datum) of the five corner points defining this study area are, as numbered in Figure 1:

	Decimal degrees		**Degrees decimal minutes**		**Degrees minutes decimal seconds**	
Corner	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
1	-33.65273°	134.87827°	-33° 39.164'	134° 52.696'	-33° 39' 9.8"	134° 52' 41.8"
2	-33.64584°	134.88378°	-33° 38.751'	134° 53.027'	-33° 38' 45.1"	134° 53' 1.6"
3	-33.63684°	134.86965°	-33° 38.211'	134° 52.179'	-33° 38' 12.7"	134° 52' 10.7"
4	-33.64217°	134.86626°	-33° 38.53'	134° 51.975'	-33° 38' 31.8"	134° 51' 58.5"
5	-33.65209°	134.87617°	-33° 39.125'	134° 52.57'	-33° 39' 7.5"	134° 52' 34.2"

Harvest of the proposed research limit will be confined to within the fish-down study area. To aid commercial fishers in remaining within the study area (1) a line of buoys will be placed by SARDI between points 2 and 3 to mark the inshore line just seaward of the jetty and (2) the location of the seaward boundary of the study area was selected to coincide with a shallow reef (the bar) that provides a natural boundary across the mouth of Waterloo Bay.

This study area excludes (1) the area to the northwest of the jetty that was also closed to fishing during previous 'fish-down' experiments in Waterloo Bay (April 1998, April 1999) and (2) the two side regions NW and SE of the study area. These areas are shallow and fishing would be unlikely to occur there.

Timing of the 'fish-down' experiment

Dates are of the fish down are still to be finalised, and are, in part, weather dependent. However, it is anticipated that the proposed 'fish-down' will occur between 17 and 28 November 2003.

'Fish-Down' experiment procedure

Harvest of the proposed research limit will be restricted to weekdays only, 8:00 am to 6:00 pm over a two-week period. Only greenlip abalone will be harvested.

Size limit

The proposed minimum size limit for the 'fish-down' experiment in Waterloo Bay is 130 mm shell length (SL, the measured distance across the abalone shell at its widest extent). This is lower than the current minimum size (145 mm SL) applicable in the Western Zone. The proposed reduction in size limit to 130 mm for the 'fish-down' experiment strengthens the scientific merit of the experiment because the size limit in the two previous fish-down experiments of this FRDC project, undertaken in the Central Zone abalone fishery at Tiparra Reef, also had a minimum size limit of 130 mm SL. There will be no maximum size limit.

Harvest Information Reporting

Co-operation from fishers and processors will be required to ensure the success of this experiment. This is because substantial catch and effort data, along with the shell from every abalone harvested needs to be recorded. To ensure that this occurs:

1. Fishers will be issued a kit containing (1) pencils, (2) a set of numbered waterproof harvest bag tags, (3) a map of the fish down area (Figure 1 above), (4) GPS coordinates of the fish down boundary corner points, (5) waterproof data sheets for recording catch and effort data, and (6) reply-paid envelopes.
2. Fishers must complete dive-by-dive catch-data sheets (see Appendix 2) at the conclusion of each dive. Data to be recorded include (1) date, (2) diver name, (3) Western Zone abalone licence number, (4) the name of the processor (who will place the shells in bag once meats are shucked), (5)

the dive number (sequential on each day), (6) the datum of the GPS used, (7) the time of start and end of the dive, (8) time every catch bag of harvested abalone reaches the surface, (9) number of abalone in each bag, (10) GPS position at the start of the dive and where each bag was brought to the surface, and (11) the number printed on the tag to be placed in each bin (one catch bag to a bin) and (12) the total number of abalone harvested during that dive.

3. The dive-by-dive catch-data sheets must be returned in the stamped envelope addressed to SARDI.
4. One waterproof tag, with pre-printed licence number and tag number, must accompany each bag of harvested abalone. If the contents of a single bag exceed a storage bin, the same tag number for that bag must be recorded on a separate blank tag and included with the abalone in the second bin.
5. All abalone are to be landed in the shell.
6. At the processors, all shells and the accompanying tag from each bin must be placed into separate collection bags (provided by SARDI). All shells from each bin must go into a single collection bag. If the shells from a bin exceed the collection bag, the same tag number for that bag must be recorded on a separate blank tag and included with the shells in a second bag.
7. The shells will be collected and measured by SARDI.

Outcomes

Copies of the FRDC final report documenting the findings of the study will be submitted to PIRSA Fisheries and the Abalone Fishery Management Committee by 30 June 2004.

Appendix 1: List of Processors

By the specifications of the exemption, abalone from the Waterloo Bay fish down (only greenlip may be taken) can be sold to only one of the following four processors:

Western Abalone Processors Pty Ltd
attn: Jim George
30 Proper Bay Road
Port Lincoln SA 5606
Ph: (08) 8682 4665

Yorkshell Pty Ltd
T/as Australian Southern Seafood
attn: Huia Groen
48 Proper Bay Road
Port Lincoln SA 5606
Ph: (08) 8682 5859

Smoothpool Nominees pty Ltd
T/as Blancheport Fisheries
12 Alfred Terrace
Streaky Bay SA 5680
Ph: (08) 8626 1161

Australian Bight Seafoods Pty Ltd
attn: Terry Richardson
Pine Freezers Road
Port Lincoln SA 5606
Ph: (08) 8682 2333

Appendix 2: Catch and effort form for the Waterloo Bay fish down

A catch data sheet will be used by Western Zone abalone licence holders to provide dive-by-dive catch and effort information when fishing in the Waterloo Bay fish down experiment. An example of this form follows on the next page.

Commercial Greenlip Abalone Catch and Effort Return Form for <u>Waterloo Bay Fish Down</u>

Date:

<u>South Australian Research and Development Institute</u>

* Fill in this form using **<u>PENCIL</u>** only

Processor name:

Dive number:

License Number:

Cage used? Y / N

Diver:

GPS Position

Time in water:	33° 3	S
	134° 5	E

GPS datum:

Tag number:		Time of first bag:		No. abalone:		GPS position:	33° 3 S / 134° 5 E
Tag number:		Time of second bag:		No. abalone:		GPS position:	33° 3 S / 134° 5 E
Tag number:		Time of third bag:		No. abalone:		GPS position:	33° 3 S / 134° 5 E
Tag number:		Time of fourth bag:		No. abalone:		GPS position:	33° 3 S / 134° 5 E
Tag number:		Time of fifth bag:		No. abalone:		GPS position:	33° 3 S / 134° 5 E
Tag number:		Time of sixth bag:		No. abalone:		GPS position:	33° 3 S / 134° 5 E

Time out of water:

Total abalone on dive:

Signature

Total weight of abalone:

<u>On completion *this form should be returned* (in reply-paid envelopes supplied) to:</u>

Dr Rick McGarvey, SARDI, PO Box 120, Henley Beach, 5022, SA
08-8200 2460 or 0422 008 212

Benefits

The principal outcomes of this project are new abalone survey outputs delivered to managers for stock sustainability, and exploring new ground for fishery expansion. Information about absolute density, spatial distributions, and clustering are provided, notably for greenlip abalone in South Australia. These are not measured by current abalone surveys in Australia and New Zealand.

Having a direct measure of abalone biomass in any surveyed region has now shown itself to permit immediate quota decision making. A range of quota options are presented to managers in a 'decision table', permitting them to choose the level of risk that biomass is overestimated, and to choose the fraction of survey-estimated biomass to allocate for harvest.

With surveys that measure relative abundance, it takes approximately 5 years for a time series to become informative to managers.

The leaded-line design, because it measures an absolute quantity that does not depend on the particular survey protocol utilised, can be modified and improved over time. This is not possible for relative measures of abundance which must maintain an unchanging sampling protocol for the time series to be self-consistent.

Thus management can request information on total biomass available for harvest in any given survey study region, in any year.

We elaborate the benefits of this new abalone survey design in the two sub-sections below.

Advantages of Measuring Absolute Abalone Density

To date in Australia, abalone survey designs have divers returning to fixed sample locations yearly, at designated locations along the coast. Fixed sample sites are used in NSW and Victoria, and were the method investigated in a recent FRDC project in Tasmania. The advantages of the alternative abalone survey design we propose, of measuring absolute abalone density in diver surveys are as follows: (1) They provide a direct measured estimate of harvestable-size abalone biomass, the information most needed for quota setting. (2) They are ideal for finer-scale spatial management, increasingly called for and applied in Australia, because these survey estimates of biomass and size structure can be obtained from any bounded survey region, large or small. (3) Not being fixed in space, managers can select where and when abalone surveys are deployed, presumably directing this capability to areas of management interest or sustainability concern. Recent boat-tracking technologies that provide information on spatial distribution of effort, notably those developed in the recent Tasmanian FRDC project, are ideal for identifying where surveys might be needed, and this method and Tasmanian hardware, were used to identify survey stratum boundaries in the most recent of 3 Cowell leaded-line surveys (Carlson et al. 2006). (4) Unlike with fixed sites, which yield only a relative measure of population abundance, with surveys designed to measure absolute density, sampling methods or technology can be improved in the future and the time series of abundance is not disrupted. (5) Relative abundance surveys require 3 or 4 years to establish a baseline for comparison with future years before they become informative for stock management. With information on absolute biomass, even a single survey is sufficient to permit managers to set (usually, as a first go, conservative) quotas, using the decision table approach developed subsequent to and extending this FRDC project for South Australian management applications of the (‘leaded-line’) survey method in Waterloo Bay (McGarvey et al. 2005) and Cowell (Dixon et al. 2004; Carlson et al. 2006; Mayfield et al. 2006). (6) Most model assumptions and prior-assumed rate inputs, such as natural mortality, growth, and commercial capture selectivity, are not needed to estimate survey biomass, thus eliminating these potentially large sources of error, but (7) when a model is available, survey measures of absolute length-specific population density taken as survey data input, would enhance, sometimes greatly enhance, the precision and accuracy of model estimates of absolute biomass. (8) Maps of abalone density and mean size can be generated within the survey region boundaries. (9) Direct survey measures of absolute density and clustering offer new performance indicators for risk assessment and stock management. In particular, they should permit comparisons among reefs which were sustainably productive over long times with those that showed evidence of decline (or increase).

Each of these advantages of absolute density surveys could alone arguably be sufficient to favour their use for stock management. Taken together, the enhanced quality of information provided for managing abalone resources, for given number of hours of dive time, are overwhelming. Fixing sample locations permanently for all future time permits no flexibility in where and how abalone research surveys are undertaken in the future and, as noted above, means foregoing vast amounts of important survey information which absolute survey measures can provide. The Waterloo Bay and Cowell applications of the leaded lines survey design have shown that the survey objectives of absolute abundance estimation can be achieved in practice.

Carlson, I.J., Mayfield, S., McGarvey, R., and Dixon, C.D. 2006. Exploratory fishing and population biology of greenlip abalone (*Haliotis laevigata*) off Cowell. Report to PIRSA. SARDI Aquatic Sciences Publication No. RD04/0223-2. SARDI Research Report Series No. 127. 35 pp.

Dixon, C.D., Mayfield, S. and McGarvey, R. 2004. Exploratory fishing and population biology of greenlip abalone (*Haliotis laevigata*) off Cowell. Report to PIRSA. SARDI Aquatic Sciences Publication No. RD 04/166. 24 pp.

Mayfield, S., McGarvey, R., Carlson, I., Turich, S., Chick, R., Foureur, B. and J. Feenstra. 2006. Distribution, abundance and biomass of greenlip abalone (*Haliotis laevigata*) off Cowell. Report to PIRSA. SARDI Aquatic Sciences Publication No. RD04/0223-3. SARDI Research Report Series No. 180. 21 pp.

McGarvey R., Mayfield, S., Feenstra, J.E. 2005. Biomass of greenlip (*Haliotis laevigata*) and blacklip (*H. rubra*) in Waterloo Bay, South Australia. SARDI Aquatic Sciences Publication No. RD05/0024-1.

Advantages of the Leaded-Line Survey Design

There are five advantages of the leaded line survey design for measuring absolute abalone density: (1) It affords research divers swimming along the bottom no choice about where to search in counts of abalone, which was known to have been a major source of bias and random variation in relative abundance surveys, especially timed swims, but also with surveys (all previous designs) where divers themselves swim out the cable which marks each transect. (2) Individual 2-m quadrat counts (when recorded) along each leaded-line transect permits short-scale spatial clustering of abalone to be quantified. This may prove to be a critical indicator of stock sustainability because one hypothesis for the high collapse risk of abalone is that divers target aggregations, and only tightly knit aggregations, of abalone within a meter apart, can successfully reproduce, since males and females must be close to successfully fertilise eggs in the water column during spawning events. (3) The leaded-line survey length-frequency samples are highly representative, being from a uniform spread of sample locations, and obtaining a self-weighted sample at each sample location, whose weighting is proportional to abalone density at each location. (4) The time research divers spend underwater deploying a line and recovering it is saved, permitting more bottom time for population measurement, counting and measuring abalone. (5) A long thin sampling geometry reduces spatial autocorrelation, providing a more representative sample of abundance (and length) at each sample location.

Further Development

Application in South Australia

Greenlip abalone: One of the important components of the fishery assessment program for abalone in South Australia are the regular fishery-independent surveys. Changes in the spatial distribution of greenlip abalone catches have necessitated implementation of additional survey sites to ensure that the key stocks are appropriately monitored. These new survey sites are Anxious Bay, Flinders Island and Avoid Bay (Western Zone) and Hardwicke Bay (Central Zone). Each of these sites is now surveyed using the leaded-line method, as opposed to the more traditional timed-swim approach. Additional survey sites are planned for Avoid Bay and one of the most important fishing areas in the South Australian abalone fishery, Tiparra Reef.

Blacklip abalone: The principles underpinning this method have also been used in the development and implementation of surveys for blacklip abalone in the Western Zone (Sheringa, Hotspot, Drummond Point, Ward Island and Highcliff) and Southern Zone (Middle Point, Gerloffs Bay, Ringwood Reef, Jones Bay, Cape Northumberland and Douglas Bay). We also anticipate that these approaches will be extended to the survey of blacklip abalone populations in the Central Zone (principally around Kangaroo Island) in coming months.

Cowell: The collaborative research program undertaken off Cowell since 2004 has involved fishery-dependent and fishery-independent components, to explore and develop a new fishery subregion. During the first stage, systematic exploratory fishing by commercial divers over 1,100 km^2 identified a subregion of reef with high densities of greenlip abalone, covering ~19 km^2. This area was surveyed using the leaded-line method, with survey outputs including estimates of greenlip abalone density, length-frequency and bled-meat-weight (the unit by which quota is decremented) biomass in a risk analysis framework. The framework was used to inform development of harvest strategies that culminated in a substantial increase in the TACC for greenlip abalone in the Central Zone in 2006. High catch rates in the most recent fishing in May 2006 confirmed the potential, first quantified by this two-stage study, for the area to support a commercial fishery. The estimates of population size in all three years were in agreement.

Waterloo Bay: In a similar manner, increasing interest from commercial abalone fishers to access the abalone stocks in Waterloo Bay led PIRSA to request SARDI to re-survey a defined region of the bay in 2005. The leaded-line survey method was applied, and represented the first time it was used to estimate the biomass of greenlip and blacklip abalone simultaneously. Estimates of harvestable biomass were small but consistent with previous estimates. This information assisted decisions regarding future management arrangements for the area, it being resolved to extend the current closure and to use Waterloo Bay, as had been done previously, for collaborative fish-down experiments with controlled commercial harvest in future years.

Further Research

One additional task, of quantifying measurement error, could be of value in assessing uncertainty. This would require repeated swims by different divers of the same 100-m leaded line transect. Components of the search error that can be differentiated include (1) legals and sublegals; (2) different days, and (3) swimming in different directions. These studies have begun for blacklip, directed by R. Chick.

Modifications to the leaded-line survey design could improve survey precision by spreading out the transect area searched. Currently, the two transects at each leaded line location lie immediately adjacent along either side of the leaded rope line. One possible modification (Section 3.4.3) would be to space two 100-m transect lines by, say, 5 m, thus sampling a more representative area at each leaded-line location. A second possibility would be to extend the length of the leaded line to, for example 180 m, and swim only one side of the line.

Planned Outcomes

The planned outcomes of this project were to develop and test a greenlip abalone survey design that met 10 design objectives: (1) Measure absolute abalone density in each survey stratum; (2) be unbiased; (3) quantify confidence intervals; (4) quantify clustering. Statistical requirements of rigorous survey design should be satisfied, notably (5) randomisation and (6) stratification. For application to abalone management, additional objectives were that the design (7) allow managers choice in designating yearly locations where abalone density is to be measured, (8) that the survey design can permit improvement over time, (9) that it provide length-frequency samples, and (10) that the spatial distribution of abalone density be mapped inside each study region.

The results of the fish-down experimental tests of the leaded-line method imply that all of these 10 survey design objectives were met.

The other essential requirement, that research divers are comfortable and confident about the new design has also been attained, principally through extensive involvement and contributions by SARDI researchers/divers in its development, testing and implementation.

Conclusions

Objective 1. To field test the precision and practical applicability of diver survey methods for greenlip abalone.

The leaded-line transect survey design met effectively all of the objectives of an abalone diver survey first set in the project proposal. As emphasised elsewhere in this report, many of these advantages were achieved because a more ambitious survey measure of stock abundance was sought from the outset: absolute density, as simply abalone per m^2.

Three of four field tests, as fish down experiments, proved that the leaded-line method proposed does provide an accurate measure of abalone density, having successfully estimated the number removed by harvesting within a level of precision quantified by the survey-measure of variability (via the 2-level bootstrap).

SARDI divers have adopted the leaded-line method, implicitly confirming its practical applicability. It has been applied or is planned for use in several South Australian greenlip stocks, and could replace timed swims over the next 2 or 3 years.

Objective 2: To present for industry approval, survey protocol specifications for adoption in South Australian abalone assessment.
On 3 December 2004, the South Australian Abalone Fishery Management Committee met and the principal investigator presented this survey design, and the results of the project. Steve Mayfield, a co-investigator and Sub-Program Leader for abalone stock assessment in South Australia, also spoke on its behalf and recommended its adoption. The new leaded-line survey design is now approved and adopted for use in SA, and is being broadly applied in SA abalone stock assessment. For details of where and how it been used to date, see Further Development above.

Appendix 1: Intellectual property

The FRDC's share of intellectual property, based on inputs, is 57.36%.
Intellectual property is not protected.

Appendix 2: Project Staff.

SARDI Aquatic Sciences: Richard McGarvey, John Feenstra, Stephen Mayfield, Peter Preece, Brian Foureur, Thor Saunders, Brian Davies, Michael Brickhill, David Miller, David Fleer. Additional diving and shell measuring were provided by Coby Matthews, Kate Rodda, Bob Delaine, James Brook, and Shane Penny. Rob Day, Cameron Dixon, and Sylvain Huchette of the University of Melbourne ran the Central Zone abalone density-dependence project which collaborated closely with us in the evaluation of the point-nearest neighbour method (Chapter 2).

Critical statistical advice, notably in identifying bias in point-nearest neighbour and suggesting transects as an theoretically unbiased alternative was provided by the statistician on this project, Karen Byth. Additional statistical input was provided by Mike Pennington (IMR, Bergen, Norway).

The habitat mapping methodology and advice were provided by the Tasmanian Fisheries and Aquaculture Institute: Miles Lawler visited for several days and guided our implementation of that system. The director of that team, Alan Jordon provided advice and the Seabed Mapper software.

Bob Pennington, Bill Ford and Michael Tokley of the Abalone Industry Association of SA Inc. provided advice and input from the industry component. Michael Tokley and the Abalone Industry Association of SA Inc. provided the shell measuring machine used in the Tiparra and Waterloo Bay fish down to measure the commercial harvest.