FRDC FINAL REPORT

LINKING FISHERY-DEPENDENT AND FISHERY-INDEPENDENT ASSESSMENTS OF ABALONE FISHERIES

Craig Mundy, Tim Karlov and Malcolm Haddon

July 2006

FRDC Project No. 2001/074

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Marine Research Laboratories

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Project Summary

2001/074 Linking fishery-dependent and fishery-independent assessments of abalone fisheries

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OBJECTIVES:

1. Establish the most appropriate fishery- independent index of relative abundance for a range of abalone habitats in Tasmania.
2. Develop methods of standardising abalone catch rate data that best relate catch rates to abundance.
3. Establish the optimum means for obtaining validated fishery-dependent data.
4. Synthesise all results so they can be included in the abalone stock assessment model currently under development.

NON TECHNICAL SUMMARY:

OUTCOMES ACHIEVED

- Recognition of fundamental flaws in logic of collecting fishery-independent abundance data on an annual basis.
- Development of a strategy for bi-annual monitoring of abalone density at key “indicator” sites rather than an extensive fishery wide survey program.
- Re-assessment of the data required for harvest strategy simulations using length-based models.

- Development of a new model that is not reliant on fishery-independent density data.
- Development of a new protocol for use of radial transect methods in marine environments, and the modification of theory for radial transect techniques as applied to abalone abundance surveys.
- Identification and progress towards an alternate approach for linking fishery-independent and fishery-dependent data using GPS technology.

The abalone fishery in Tasmania has experienced substantial management changes over the past two decades. These changes were based both on information from fishery-dependent data (catch and CPUE) and/or diver concerns that the stocks were declining. Globally, experience with abalone fisheries has shown that fishery-dependent data are poor indicators of stock abundance, with hyperstability in catch rates, often followed by sudden, rapid and unpredicted declines, which frequently lead to fishery collapse (Prince and Shepherd 1992). The collection of fishery-independent abalone abundance data is widely considered to be a crucial component of managing abalone fisheries (FRDC 98/170), permitting a more quantitative and independent process for assessing the sustainability of various management decisions.

Current harvest strategy simulation models (e.g. AbModeller, Gorfine et al 2005) require independent abundance and size frequency data in addition to catch-effort and commercial catch length-frequency data. Without fishery-independent data, the accuracy and utility of model predictions is thought to be significantly reduced. The collection of fishery-independent data should permit an unbiased assessment of trends in abalone abundance, and enable robust modelling of fishery performance and simulation of effects of management change through collection of density and size frequency data.

Fishery-independent surveys of abalone abundance have not previously been undertaken in Tasmania, with the exception of some basic trials undertaken in an early FRDC funded research program (Nash 1995). It was previously considered that abundance estimation of abalone in Tasmania was too difficult, and that variability among replicate sample units prohibited robust comparisons of abalone abundance in space or through time. Following a review of the literature relating to abundance estimation techniques in benthic habitats, the following sampling strategies were considered for investigation; 1) timed swims, 2) plotless density estimators based upon spatial statistics, 3) “variable area” transects (VAT) and 4) area-based sampling techniques (strip transects). Timed swims, whilst still used in a number of fisheries, including those in South Australia and New Zealand, have attracted considerable criticism in recent years (see section 4.3.4). Given the inadequacies identified from previous research (Hart *et al.* 1997a) this technique was abandoned following the exhaustive literature search process.

Initial field trials in this study concluded that plotless techniques had significant drawbacks or were entirely impractical in typical Tasmanian conditions. Computer simulations using the VAT technique showed that it too was likely to be impractical, and was subject to considerable statistical bias. Preliminary trials in typical South-East Coast abalone habitat (thick kelp, constant surge) with a radial transect technique were encouraging, and research was consequently focused on this method.

Prior to further field testing of the radial transect method, it became apparent that several theoretical issues with respect to radial sampling required attention. The first was that under existing radial transect protocols, survey sites were unevenly sampled, with progressive under-sampling of areas towards the perimeter of the circular site. The second was that the proximity of transects or portions of transects (towards the site centre) created a risk of spatial autocorrelation among replicates, potentially violating the assumption of independence implicit in random sampling theory. Investigations of these issues led to further questions concerning the optimal length of transects to achieve robust estimates of abalone density.

To address issues relating to unequal distribution of sampling effort within sites, and spatial autocorrelation concerns, algorithms were developed to improve spatial randomisation and representativeness of replicates within sites, thereby greatly reducing the pitfalls associated with existing protocols. The primary improvement in radial transect protocol was achieved by reducing the spatial bias inherent in the initial application of the technique through the application of increased sampling effort with increasing distance from the centre of the site, and by improving the resolution of bearings along which transects were oriented. An algorithm to generate coordinates for the modified radial transect technique was developed as an Excel spreadsheet macro (See APPENDIX on the attached CD-ROM) that allows the user to specify the size (in m) and shape (circular or semicircular) of the site, transect characteristics (length, spatial distribution pattern and minimum spacing) and the number of replicates required. The macro then uses Monte Carlo simulation techniques to generate a list of transect coordinates.

The investigations into determining the optimal transect length found that shorter transects were as accurate as longer ones, and provided abundance estimates with similar levels of precision. The optimal transect length for radial transects in Tasmanian habitats was estimated to be around 15m x 1m. This shorter transect length also proved to be of assistance in randomising transect placement within sites to ensure a more representative distribution of effort across the site.

Having developed the theory and identified an optimal transect length, the newly developed radial transect protocol was field tested. Initially, this was done in a small scale survey of 14 sites in south-eastern Tasmania. Because the performance of any technique is difficult to assess in areas of low abundance, sites used for initial tests had moderate densities of abalone abundance. These surveys revealed that the abundance of emergent abalone varied between approximately 700 and 17,000 abalone per hectare, and provided comparable levels of precision to abundance estimates in other published studies.

In practical terms, the modified radial transect procedure performed well, and was an efficient technique in all regions and habitats visited. Distribution and aggregation patterns of abalone in certain reef habitats (e.g. granite slabs) are likely to result in greater variance than boulder habitat areas with comparable abalone densities in the South-East, where the method was initially tested. Higher levels of replication may be required in areas where unusually large variation occurs among replicates. The method can be applied both to fully circular sites, or to sites which comprise one or more circular sectors. This provides a greater degree of flexibility in choice of sites than can be achieved by conventional radial transect protocols.

While the modified radial method has proven to be an effective and efficient method for obtaining robust estimates of abalone density, two key issues were identified that must be considered prior to implementation of a strategic fishery-independent abundance survey program in Tasmania. These are: 1) the cost-benefit limitations on diving in remote areas imposed by the Australian Scientific Dive Code, and 2) the degree to which variation in commercial fishing effort at survey sites masks longer term trends in abalone abundance and population structure obtained from survey estimates.

Our conclusion is that while the modified radial transect technique can provide robust data on abalone density, a single annual survey of abalone density may provide an inaccurate estimate of stock abundance due to unpredictable temporal variation in fishing effort at each study site. This will lead to substantial variability among years that is not necessarily related to any actual variability in stock abundance. This is typical of fishery-independent survey programs elsewhere in Australia. One possible solution might be to conduct multiple (biannual) surveys at each site in each year, preferably at the beginning and end of the fishing season in that region if fishing is seasonal. This will however considerably reduce the number of sites that can be surveyed each year, and may mean that insufficient sites can be surveyed to provide meaningful input to length-based models of fishery performance.

Standardising abalone catch rates from some of the most important statistical catching blocks in Tasmania only led to minor changes in the trends described by the simple geometric means of catch rates. In all fitted statistical models there was little difference between the simple geometric means and the standardised catch rates. Despite large changes in catch rate occurring over the time period selected for this study, the standardisations would have an almost negligible effect upon any assessment. This surprising result may be due to a number of causes. It may simply be a confirmation of the often repeated refrain that catch rates in abalone fisheries contain little or no information about the stock status. However, the decline in catch rates, especially on the Tasmanian east coast, from 1996 to 2003 was very real and very marked; so clearly there can be some signal in the data. Alternatively, the divers may be so similar in their operations and fishing behaviour that implementing the standardisation is effectively unnecessary.

KEYWORDS: abalone, abundance, Australia, blacklip, fishery-dependent, fishery-independent, *Haliotis rubra*, radial transect, standardisation, surveys, Tasmania

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1. Background

This project was designed to determine the optimum methods for fishery-independent abundance estimation and standardisation of commercial abalone catch-effort information, and to develop a process for linking these two data sources. There are many environmental factors that may influence the performance of a diver during a particular day's fishing, and there have been many efficiency gains through time. This introduces a source of variation on catch-effort data in addition to variability in stock abundance. Standardisation of fishery-dependent data in theory will enhance the detection of trends in stock abundance by minimising unrelated "noise" from the data set.

A key issue requiring investigation is change in "catchability", or effort creep. Effort creep is a continuing problem in fishery assessments based on catch rates. One of the features of modern fisheries is that fishermen find ways to make their operations more efficient, and the Tasmanian abalone fishery has been no exception. If stock levels do not change, then efficiency increases mean that more abalone can be collected per unit of time now than in the past. This causes catch rates to rise without abalone abundance changing, or conversely, for catch rates to appear stable when in fact the stocks are declining.

The ability to obtain independent, objective and repeatable estimates of abalone abundance is central to many ecological and fisheries research questions relevant to the research needs of the Tasmanian abalone fishery. There have been few attempts in Tasmania to develop methods for estimating abalone abundance across a wide spatial scale. This reflected either an absence of a strategic plan for collection of data other than that relating to catch and effort, or insufficient resources to undertake a strategic collection of data, for the greater part of the history of the fishery. Nash (1995) attempted to use a strip transect technique in the late 1980s with transects running perpendicular to the shore. This approach was considered impractical in most field conditions, and was subsequently abandoned. Prince and Nash both conducted extensive population based studies in southern Tasmania (Prince 1989b, Nash 1995), where abalone abundance was monitored in large quadrats, however this approach while suitable for individual studies, is not appropriate for large-scale monitoring programs.

Finally, independent research data of all types must be collected from within the commercial fishing grounds, to ensure research outcomes are relevant to the fishery. Given the current spatial scale at which fishing activity is reported in Tasmania, appropriate choice of research sites is a key challenge for researchers, and is addressed in this study.

2. Need

Experience in other major abalone producing countries shows abalone stocks are vulnerable to localised depletion, followed by fishery collapse (Prince and Shepherd 1992). In Tasmania, the basis for stock assessments is generally an anecdotal interpretation of unstandardised commercial catch-effort data and sometimes, information on the size composition of the catch. This information is often combined, in an informal way, with research data to give an impression of the status of the stocks, and input from abalone divers on their perception of the difficulty of fishing. Most importantly, the sustainability of current catch levels is not known with any confidence. Meeting the guidelines from The Department of Environment and Heritage with regard to sustainability of fisheries requires a more formal assessment for such an important fishery.

The purpose of FRDC project 1999/116, to develop a national abalone model, was an attempt to answer the obvious need for a valid model. Currently, New South Wales and Victoria are the only states in which stock assessment models are being used as the basis for fishery management decisions. In Tasmania, the inputs currently available to stock assessment models include fishery-dependent catch-effort data, commercial catch length-frequency data, research length-frequency data, and estimates of biological parameters. The crucial data missing from the inputs to a stock assessment or harvest strategy model, is a fishery-independent index of relative abundance. There is thus a need to develop an optimum combination of fishery-independent indices of abundance that will have application in the full range of Tasmanian abalone habitats. In addition, Tasmania's raw catch-effort data must be standardised prior to its use in a formal assessment model because of the high variability in catch rates between divers, areas, season, and other factors.

The specific aims of this project were to:

(1) better determine the relationship between catch rate and abundance. This is needed for realistic standardisation of catch and effort statistics;

(2) improve our understanding of the differences between commercial size composition data and the actual size composition of the legal size abalone left after fishing (i.e. selectivity versus availability). Such data are a key ingredient of stock assessment models;
(3) assess the accuracy of diver logbook data. This will help ensure that the data requested via industry logbooks focuses on the most appropriate questions and will assist with appropriate standardisation.

It is expected that the information gained will underpin the development of credible, realistic fisheries models for abalone, which will consequently improve the confidence with which abalone fisheries can be managed.

3. Objectives

1. Establish the most appropriate fishery-independent, index of relative abundance for a range of abalone habitats in Tasmania.
2. Develop methods of standardising abalone catch rate data that best relate catch rates to abundance.
3. Establish the optimum means for obtaining validated fishery-dependent data.
4. Synthesise all results so they can be included in the abalone stock assessment model currently under development.

4. Sampling Designs and Methods for Estimating Abalone Abundance.

4.1. Fixed vs random sampling designs for Tasmanian habitats

4.1.1. Practicality of using completely random versus permanent sites

A fundamental requisite for achieving unbiased estimates of abundance is random sampling, either of individuals (e.g. in conjunction with distance-based methods), or through the random spatial allocation of sample units (e.g. transects). Ideally therefore, any abundance monitoring program would involve spatial randomisation of sample units, either across the entire study area or smaller strata therein. In practice however, several factors conspire to make completely random sampling impractical in a broad-scale abalone monitoring program in Tasmania. Patchiness in the distribution of both suitable habitat and abalone, occurs at a variety of scales (from sub-metre to hundreds of kilometres). Consequently, where the allocation of sampling effort is randomised across broad areas in each year, a large number of sample units (or sites) would not contain abalone or abalone habitat, thus preventing precise estimates of the status of abalone stocks. In this situation therefore, completely random sampling exacerbates the problem of separating real temporal change from background spatial variation. This would in turn make temporal trends in abalone abundance impossible to detect given any realistic level of resourcing (Green 1993, Van der Meer 1997).

A stratified sampling approach may theoretically be used to reduce sample variance. However, detailed knowledge of the physical distribution of abalone and abalone habitat is not available at the relatively small scales necessary to stratify in a meaningful way. Furthermore, such information is unlikely to be obtained in the immediate future given the sheer physical scale of the fishery, as the fieldwork required would far exceed the capacity of the field resources.

4.1.2. Sampling of spatially-fixed sample units within permanent sites

In theory, repeated sampling at fixed positions can provide precise information on temporal changes of populations, and such methods have been frequently used in ecological monitoring, particularly of sessile invertebrates (Edgar and Barrett 1999, Sweatman et al. 2001, Worthington et al. 1997). The primary advantage of fixing the position of sample units is that spatial variability is reduced, leading to a concomitant increase in the sensitivity of the surveys to detect temporal change.

For patchily distributed species such as abalone, where spatial variation in abundance is high, failure to fix sample positions tends to result in statistical models being “swamped” by spatially derived variance. This frequently obscures temporal trends, such that only very large temporal differences can be detected (Green 1993). In the context of an abundance monitoring program therefore, where interpretation of temporal trends is the principle goal, the use of fixed survey positions is attractive (Green 1993, Nelson 1996, Van der Meer

1997). However, this approach is dependent on researchers being able to re-locate and re-survey the same area during each sampling event.

Fixed position samples have been used extensively for monitoring benthos and benthic organisms, including abalone. For example, Sweatman et al. (2001) used fixed position video transects in conjunction with point-sampling to estimate percentage cover of corals and other sessile benthic organisms, and Sims (1992) used fixed strip transects to estimate abundance and population characteristics of the black-lip pearl oyster, *Pinctada margaritifera*. In the New South Wales blacklip abalone fishery, sampling of fixed reference areas forms the basis of a broad-scale fishery-independent monitoring program (Worthington et al. 1997). Here, natural features such as reef walls and gutters are used rather than, for example, quadrats or transects, to avoid potential problems associated with locating arbitrarily positioned and/or shaped sample units (Andrew et al. 1998). Fixed transects were also established for Western Australian greenlip abalone surveys (Hart et al. 1999), and their application has been discussed in relation to Californian abalone fisheries (Anonymous 2005)

However, repeated sampling at fixed sites carries with it a number of disadvantages (Nelson 1996). Arguably the most important issue is confounding of small-scale spatial effects with temporal change, i.e. where the path of “fixed” sample units has an associated component of spatial imprecision. A second potential disadvantage is the loss of time series data that arises when a fixed transect position is lost (due for example, to damage or theft of markers, or sand inundation). Given the paucity of easily locatable and unmistakable natural features (such as distinct gutters) in much of the Tasmanian fishery, and the risk of human interference and natural impacts on artificially marked sites, transect position movement and loss were considered to be substantial risks in the context of an ongoing abalone monitoring program.

Several other disadvantages of using fixed sample units within sites also exist. These included effects on fisher behaviour of using clearly marked survey positions, and loss of operational efficiency by surveyors spending dive time searching for individual fixed sample units (Nelson 1996). In the context of dive surveys, the use of fixed sample unit positions generally also requires familiarity on behalf of the researchers, to be able to identify and locate these with reasonable precision. Where turnover in the research team is rapid or synchronous, this familiarity can be lost, leading to problems with continuation of sampling, particularly if documentation of positions is incomplete, inaccessible, or difficult to interpret for researchers unfamiliar with the surveys. This has been the case in the NSW *H. rubra* fishery, which experienced a period of rapid and complete staff turnover (Worthington, *personal communication*). Furthermore, because fixed sample units only provide estimates of density relating specifically to the area that they occupy, there is a considerable risk that data thus obtained may not be representative of the broader fishery(Green 1993). This problem could be ameliorated somewhat by increasing replication, however this not always possible.

To determine the practicality of using spatially-fixed sample units within permanent sites, study sites were established at three locations in south-eastern Tasmania (George III Rock, Sterile Island and Actaeon Island). For the purposes of these initial trials, the positions of these transects were marked with car tyres filled with concrete and iron, and chain was laid between these to facilitate their location by research divers. Theft of the chain soon after placement at one site and movement of the tyres (almost certainly because of swell) at another led to a re-assessment of the advantages and disadvantages of fixed transects. Consequently, fixed sample units within sites were considered inappropriate for monitoring of Tasmanian abalone stocks.

4.1.3. Sampling of randomly positioned transects within permanent sites

An alternative to re-sampling fixed individual sample unit positions is to randomise the position of sample units within permanent sites during each sampling event. This design represents a compromise between full spatial randomisation and the opposite extreme of spatially fixing individual sample units, and incorporates the benefits and disadvantages of both. Random allocation of sample units offers several advantages over the use of spatially-fixed sample units. Any spatio-temporal confounding of error terms due to small positional changes of the fixed site is likely to be minor, as this will occur only at the edges of the site (provided that temporal site "movement" is small relative to the size of the site). This allows less precise methods of spatial positioning, such as GPS or reference to physical features, to be used thereby improving the operational efficiency of the method.

Sampling several transects at one site can also reduce the amount of unproductive field time spent travelling between locations, deploying and retrieving divers and equipment, and preparing for dives. As is the case with fixed sample units, the potential still exists that trends in abundance within these sites will not be representative of those in surrounding reef systems. However, because the estimate from a fixed site relates to a much greater area (e.g. 0.25 ha to 1 ha) than that from a fixed transect (e.g. 0.01 ha), this risk is reduced. Given these considerations, this design was deemed to be the most appropriate for a potential fishery-independent *H. rubra* monitoring program, and consequently formed the basis for all further investigations. A similar design was described by (McShane et al. 1993) for monitoring algal coverage in association with abundance surveys of *Haliotis iris*.

4.2. Relative versus absolute abundance

Once an unbiased estimate of abalone abundance is obtained, this can be used to follow trends in relative stock abundance, and if assumptions of representativeness are met, the data can be extrapolated to provide an estimate of absolute abundance. Estimates of absolute abundance are highly attractive because they allow managers to determine the harvestable biomass for a given location, in a particular year (McGarvey et al., unpub). Additionally, the method used to gain an estimate of abundance is not important, providing that the method returns an accurate estimate of abundance at each site sampled. However, absolute estimates of abundance assume some level of spatial homogeneity of stocks in the area of interest, and that sampling is unbiased and completely random (Sutherland 1996). If the stocks occur as meta-populations whose locations are patchily distributed, the level of sampling required (in terms of sites sampled) to determine absolute abundance becomes significant. Because of the highly patchy nature of abalone stocks in Tasmania and the lack of knowledge on location and area of suitable abalone habitat, the resources required to estimate absolute abundance for the Tasmanian abalone fishery with any reasonable degree of precision are considered unobtainable.

4.3. Evaluation of potential abundance estimation techniques

The method with which the fixed sites were to be sampled was investigated in considerable detail. Following a review of the literature relating to abundance estimation techniques in benthic habitats, alternative sampling strategies selected for investigation included plotless density estimators based upon spatial statistics, “variable area” transects, timed swims, and area-based sampling techniques, both conventional and novel.

4.3.1. Use of electronic DiveTracker® to collect spatial data on abalone distribution and abundance.

When FRDC Project 2001/074, “Linking fishery-dependent and -independent assessments of abalone fisheries” was initially proposed, it was envisaged that much of the work would be based on data gathered using the DiveTracker® underwater positioning system from Desert Star Systems. The system is designed to provide three-dimensional position information underwater, using a combination of sonar triangulation and depth sensors. The intention was to determine the precise position and size of all emergent abalone that occurred within defined areas at a variety of locations. Computer simulation trials using the spatial data could then evaluate various survey techniques. In practice, however, the system proved prohibitively unreliable in field applications.

In early tests on the Tasmanian east coast, position data generated using DiveTracker® were found to be affected by the presence of dense kelp, complex rocky topography , and the diver’s own bubble stream (Anonymous, 1998). Haloclines and suspended particles can also affect communications between the hydrophones and sensors. These factors led to a frequent and substantial attenuation in the positional precision of the system. Because the system employs position averaging, imprecise positional information meant that not only were maps based on data generated by the system potentially inaccurate, but that survey times were greatly increased as divers found it necessary to wait for impractically long periods for positional error to diminish. The problem was so great that it was frequently impossible to obtain any precise positional information. Outright failure of the equipment on several occasions further exacerbated the problem. New Zealand abalone researchers have used similar equipment to monitor aggregations of paua (*H. iris*), and also reported technical problems (Andrew et al. 2000a) After committing considerable time and effort (both in the field and base) without producing any useful results, the use of the DiveTracker® system was finally abandoned.

4.3.2. Plotless sampling techniques.

The absence of spatial data restricted the theoretical and simulation based investigations into plotless sampling and associated distance-based statistics. The ability to validate and optimise field-based distance sampling was limited, since without data on abalone size and position, it was not practical to explore a detailed range of alternative sampling strategies, such as ordered-distance and angle-order methods (Krebs 1999), for various size classes of abalone.

Line transects have been used for abalone surveys in South Australia (Shepherd et al. 1999, Dowling et al. 2004), and were trialled in Victoria (Officer, *pers. comm.*) and Tasmania (TAFI unpublished data). However, a number of factors, including frequently rough conditions, variable and often limited through-water visibility, varying patch size, highly irregular benthic topography and variable and often complete algal cover makes the method impractical for assessment of *H. rubra* abundance under Tasmanian conditions. Furthermore, earlier work undertaken in Tasmania (Nash et al. 1995) found that the assumption of 100% sighting probability at zero distance (Seber 1982) is violated for blacklip abalone surveys.

It is well established that for aggregated organisms, distance-based statistical methods generally give biased abundance estimates (Batchelor 1971, Delince 1986, Engeman et al. 1994, Krebs 1999). The direction and magnitude of the bias depend on the particular estimator being used. For example, Diggle (1975) reported that abundance was *under*estimated for aggregated organisms using random point to organism distances, and *over*estimated when using nearest neighbour distances between organisms. Distance-based abundance estimation has been trialled for assessment of blacklip abalone on at least one occasion (Anonymous ca. 1982). In this study, the distances between “random” points and the five nearest abalone were used, and it was deemed (by comparison to other methods), to overestimate abundance.

Compound estimators, which incorporate several simple distance estimators have been shown to be more robust to aggregation than the simple distance estimators alone, with the estimator γ^* proving to be fairly robust to aggregation (Diggle 1975, 1977). Simulation work based on a real blacklip abalone population from Point Cook, Victoria (Officer et al. 2001b), suggested that compound distance methods may be feasible for abalone abundance assessment. They showed that this estimator gave good estimates of abalone abundance for the Point Cook population, although more than 400 measurements (i.e. 200 point-abalone and 200 abalone-abalone) were required to constrain variance to an acceptable level.

A simple field trial was conducted using an analogous distance-based estimator: the angle-order, or point-centred quadrant method (Cottam et al. 1953, Pollard 1971). This method involves selecting a series of random points (e.g. along a transect), dividing the area around the point into segments (in this case, four 90^o quadrants) and then measuring the distance to the r^{th} nearest abalone in each of the quadrants. The technique proved impractical for several reasons. The complex benthic topography and heavy algal cover made it difficult, and thus time consuming to determine which abalone was actually closest to the reference point. This also made accurate measurement of distances difficult. In moderate swell conditions typical of abalone habitat, where the diver and measuring line are pushed about, the accurate collection of information using this technique proved to be very difficult. Desktop investigations into the sensitivity to inaccurate measurement of this and related techniques revealed high sensitivity to small measurement errors. Finally, substantial search effort is required at each reference point, due to a largely unavoidable but considerable repeat searching of the search area. Searching is conducted in a series of concentric annuli, the boundaries of which must overlap to ensure that the area is completely searched. Furthermore, when several abalone are of roughly similar distance to the reference point, it is often difficult to determine which is the nearest individual (Parker 1979), and in such cases it is frequently necessary to recheck measurements.

South Australian researchers attempting distance-based estimation of greenlip abalone under more benign conditions (lower algal cover and less complex topography) came to similar conclusions regarding the practicality of such plotless methods (McGarvey, pers comm). The key issue with plotless or distance-based methods is that complex benthic topography, and extensive kelp canopy, swell surge, the relatively small size of abalone and the limitations of diving make searching and locating abalone, measuring distances greater than one arm span very difficult. Consequently, identifying the nearest, or r^{th} nearest neighbour is difficult, particularly when the nearest individual is more than one metre away. Accordingly, investigation into such estimators was abandoned, although one novel distance-based estimator, the variable area transect method (Parker 1979) was considered further using simulation techniques.

4.3.3. Variable Area Transects.

The variable area transect method combines distance-based statistics with a practical methodology analogous to that associated with strip transects. The technique involves the use of randomly positioned strip transects, the widths but not the lengths of which are fixed. The distances between the start of the transects and the r^{th} abalone are then used to derive an estimate of density with associated confidence intervals (Parker 1979).

The benefit of the variable area transect over other related plotless density estimators is that searching is conducted in only one direction. This is in contrast to most other point-based distance estimators such as nearest-neighbour, ordered-distance, T-square and angle-order sampling, where the r^{th} nearest organism must be found by searching in ever-increasing concentric bands (Krebs 1999). As such, the variable area transect method is in many ways, a much simpler technique in terms of practical application.

As with other distance-based survey methods, density estimates of non-randomly distributed organisms obtained using variable area transects are known to be biased (Engeman et al. 1994). The magnitude of such bias decreases where the distance measured is not that to the nearest organism, but to the r^{th} organism, where $r>1$. In general, the greater the value of r, the lower the bias. An additional benefit of using $r>1$ is that precision also increases with increasing *r* (Pollard 1971). The body of literature relating to variable area transect sampling is limited, but of the few papers that do exist, at least two have used *r*=3. However, Engeman and Sugihara (1998) showed using simulated populations, that reductions in bias of variable area transects diminished beyond *r*=6 or 7, with gains in precision diminishing beyond *r*=5 or 6 (in reality, the optimum value of *r* would be dependent on the characteristics of the particular populations under survey). Their recommendation for variable area transects, was that the minimum value of *r* to use should be the greatest number practical that is less than or equal to six.

4.3.3.1.Comparison of VAT and strip transect techniques

4.3.3.1.1. Methods

The performance (precision and bias) of variable area and standard strip transect techniques were compared using Monte Carlo simulations. The two techniques were tested using simulated populations that varied with respect to their density and degree of aggregation. Three different population densities were simulated (0.25 abalone m^{-2}, 1.5 abalone m^{-2} and 3 abalone m^{-2}), with five patterns of simulated abalone distribution: one random and four levels of aggregation (Figure 1). To generate the aggregated populations, cluster locations were randomly positioned throughout a 100m x 200m virtual site, and a given number of individuals (four or nine) were located around each of these points by randomly sampling a bivariate normal distribution of specified standard deviation (0.5m or 1.0m). These populations were then sampled with a range of sample units and levels of replication for each technique (Table 1). Each combination of population, sample method and sampling scheme was run 500 times. Precision was calculated as the coefficient of variation (standard deviation ÷ mean) of the 500 sample means, and relative bias as:

$$\text{Relative Bias} = \frac{D_{est} - D_{actual}}{D_{actual}}$$

Where: D_{est} = estimated density

D_{actual} = actual density

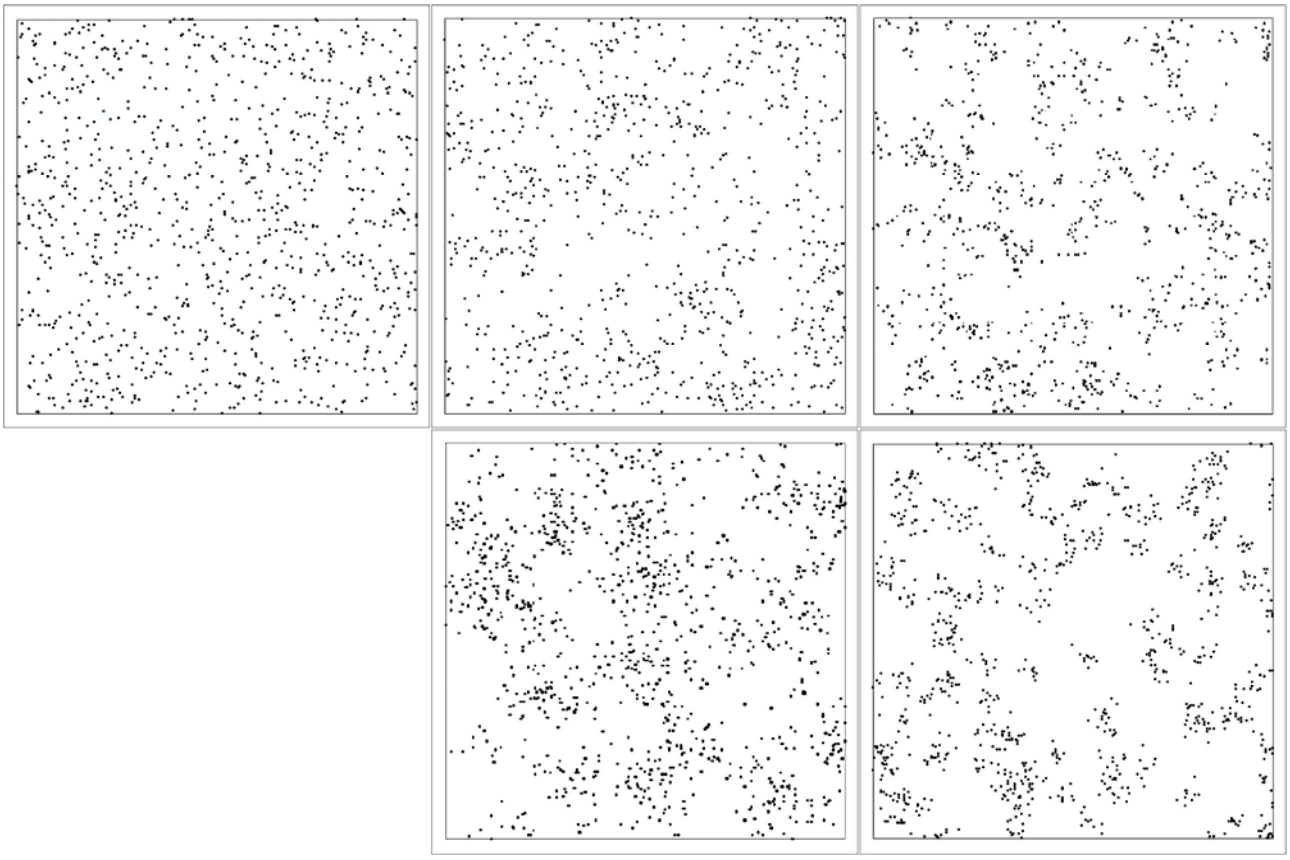

Figure 1. *Visual representation of simulated abalone populations used in Monte Carlo analyses. Aggregated populations were generated by specifying a ratio of the number of clusters to the number of individuals within each cluster. Positions of individuals within aggregations were selected using a bivariate normal distribution, with a specified standard deviation (SD). The distributions are (clockwise from top left): random; ratio 1:4, SD 1.0m; ratio 1:4, SD 0.5m; ratio 1:9, SD 0.5m; and ratio 1:9, SD 1.0m. Each square represents a 25m x 25m block, and the density in all blocks is 1.5 abalone m*$^{-2}$.

Table 1. Sampling regimes used in Monte Carlo simulations for variable area and strip transects. N = sample size, *r* = number of abalone counted per variable area transect and L = strip transect length (in metres). Both the variable area and strip transects were 1m wide.

Variable area transects		**Strip transects**	
N	***r***	**N**	**L (m)**
30	3	5	25
60	3	10	25
30	6	5	50
60	6	10	50

4.3.3.1.2. Results from VAT simulations..

Strip transect sampling was unbiased for all densities, spatial patterns, levels of within-sample replication (sample size) and lengths of transect (Figure 2). Bias estimates were a little more variable at lower population densities, reflecting the lower precision with which such populations were sampled. Precision, measured as the 95 percentile spread of density estimates (Figure 2) and CV (Figure 3) improved with increases in replication, transect length and population density, but decreased with increasing aggregation. Both 250m^{-2} samples (ten replicate 25m transects and five replicate 50m transects) performed similarly.

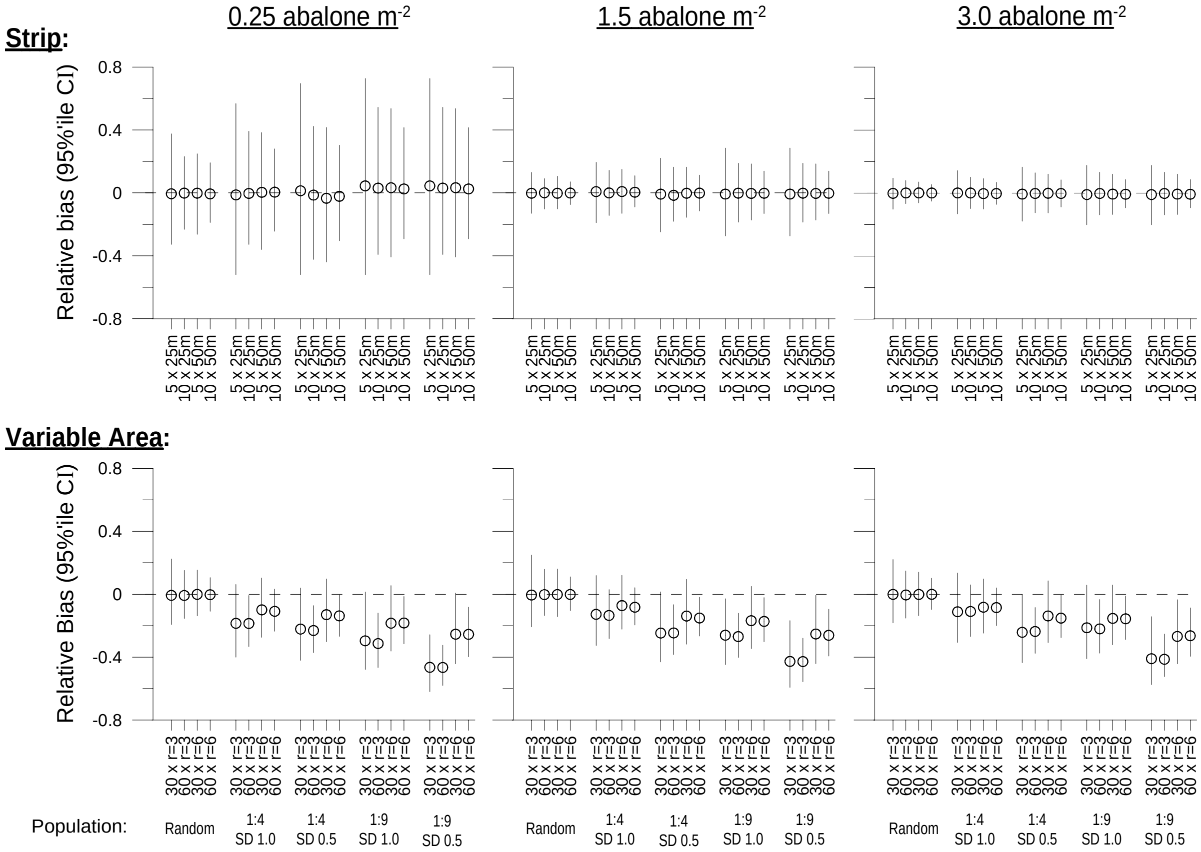

Figure 2. *Mean relative bias and 95 percentile confidence intervals from Monte Carlo simulations of strip transect and variable area transect sampling (500 iterations). The horizontal axes show the four different sampling strategies used: the labels describe the number of replicates per sample (e.g. 5x, 30x etc.), and either strip transect length (25m or 50m), or number of abalone counted per variable area transect (r=3 or 6). The ratios shown on the population labels relate to the ratio of number of clusters, to number of individuals per cluster; the standard deviation (SD) on these labels describes that of the bivariate normal distribution used to generate positions of individuals within each cluster and has units of metres.*

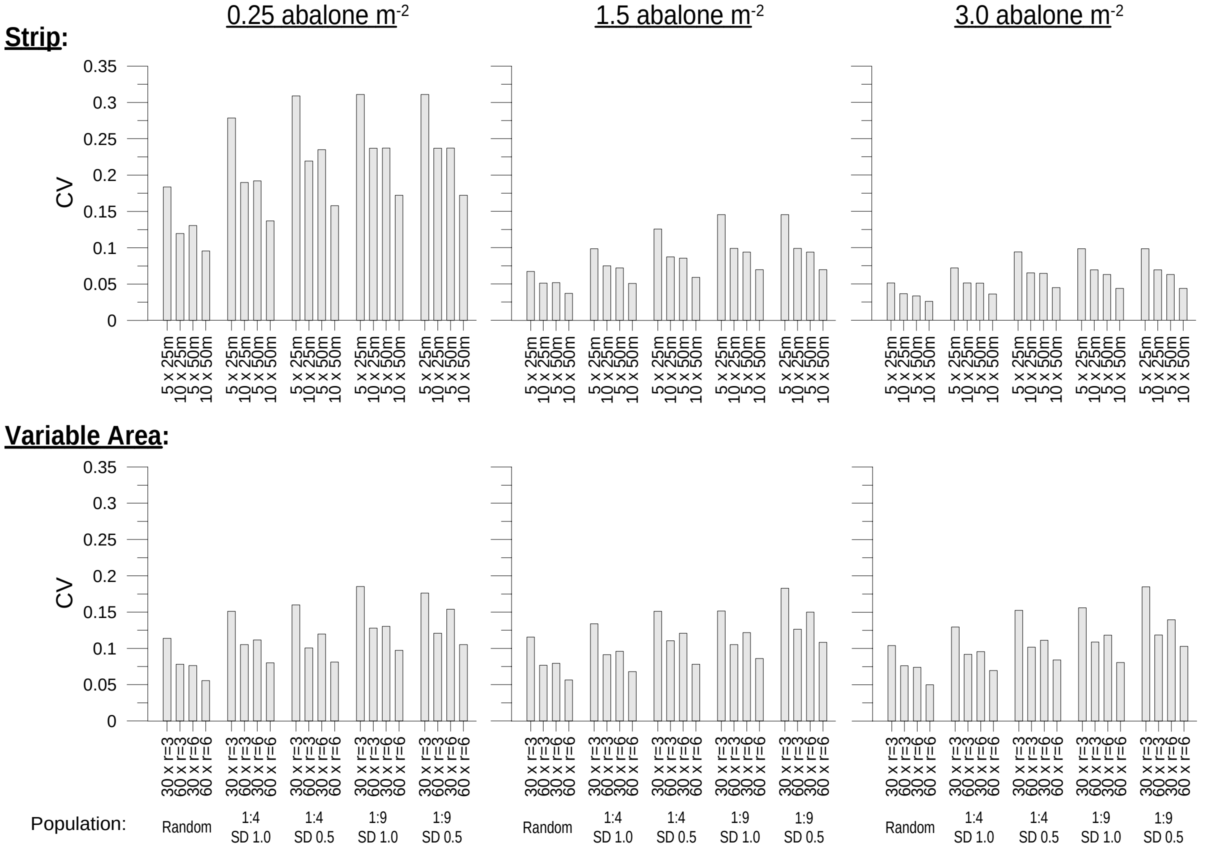

Figure 3. *Coefficients of variation from Monte Carlo simulations of strip transect and variable transect sampling (500 iterations). The top row of three plots relate to strip transects, and the bottom row to variable area transects. The horizontal axes show the four different sampling strategies used: the labels describe the number of replicates per sample (e.g. 5x, 30x etc.), and either strip transect length (25m or 50m), or number of abalone counted per variable area transect (r=3 or 6). The ratios shown on the population labels relate to the ratio of number of clusters to number of individuals per cluster; the standard deviation (SD) on these labels describes that of the bivariate normal distribution used to generate positions of individuals within each cluster, and has units of metres.*

For variable area transects, density estimates were unbiased for randomly distributed populations, but negatively biased in all aggregated populations (Figure 2). The magnitude of this bias increased with increasing degree of aggregation, and for a given level of aggregation, bias decreased as *r* was increased from three to six. Doubling sample size from 30 to 60 replicates had no noticeable effect on the magnitude of the bias. Similarly, the level of the bias inherent in the technique was not sensitive to abalone density (Figure 2). The precision of density estimates (measured by CV) improved with sample size for all population distributions, but unlike strip transects, was not sensitive to population density (Figure 3). Precision also improved with the number of abalone counted per transect (*r*), but tended to decrease with increasing aggregation.

The average area searched per variable area transect sample depended not only on the number of abalone counted per transect and sample size, but was negatively correlated with density (unsurprisingly) and positively correlated with aggregation (Figure 4). For samples from the randomly distributed population, the average area of variable area transect samples doubled with a doubling in the number of abalone counted per transect (from three to six). However, the magnitude of this difference decreased with increasing aggregation.

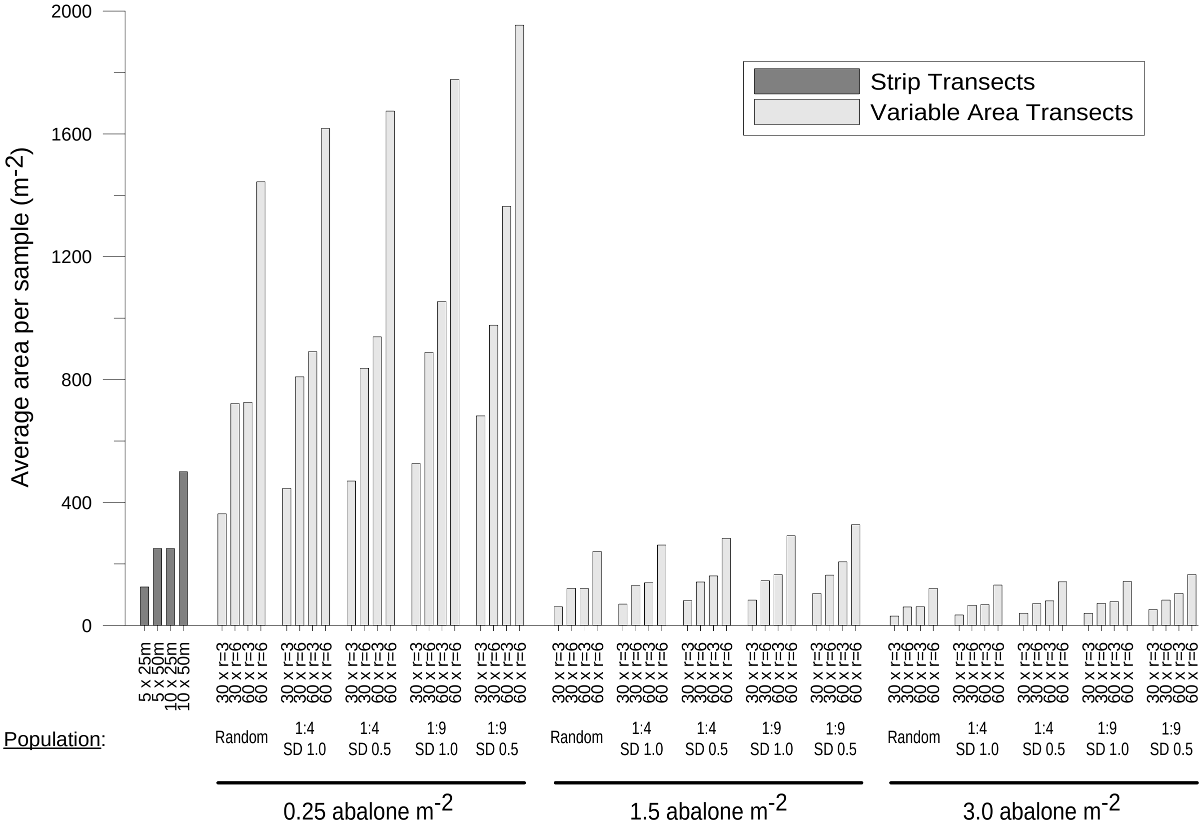

Figure 4. *Average area "searched" in 500 Monte Carlo strip and variable area transect samples of simulated abalone populations. The horizontal axis labels show the number of replicates per sample (e.g. 5x, 30x etc.), and either strip transect length (25m or 50m), or number of abalone counted per variable area transect (r=3 or 6), and are grouped according to population distribution and density. The ratios shown on the population labels relate to the ratio of number of clusters, to number of individuals per cluster; the standard deviation (SD) on these labels describes that of the bivariate normal distribution used to generate positions of individuals within each cluster (in units of metres). The area of strip transect samples is independent of all population densities and distributions.*

4.3.3.1.3. Discussion of simulated VAT and strip transect techniques and recommendations.

It is difficult to make quantitative comparisons of the relative effort required to sample strip and variable area transects based on these simulations, given the dissimilarities between the two methods. General conclusions as to their relative performance and potential as survey techniques, can however be reasonably drawn.

The comparison is arguably most difficult to make when sampling populations with high density. Where populations are dense, variable area transects are shorter and hence require less searching effort (Figure 4). The length of strip transects on the other hand is fixed, and so sampling effort per transect is independent of population density at best,, or may even show a positive relationship (e.g. if the abalone are measured, then higher population densities mean there are more abalone to measure). However, the precision of abundance estimates made with strip transects improves with density, allowing fewer transects to be surveyed; this is not the case for variable area transects where variance is independent of density.

Because it is logistically difficult and time consuming to randomly position transect start points throughout a dive site, and for divers to locate and travel between these, it is likely that the advantage of reduced search area offered by variable area transects in dense populations is at best nullified, and probably outweighed by the high number of random positions required. As such, at high densities (1.5 and 3 abalone m^{-2}), where the area searched by variable area transect is relatively low, the sampling effort required for this method might at best be comparable to that required to sample strip transects. However where abalone occur at a density of 1.5 abalone m^{-2}, there is more variability associated with variable area than strip transect samples (Figure 3). Given that densities much higher than this are likely to be encountered only infrequently (unpublished data), strip transects are probably the preferred method for such populations. That the variable area transect method is sensitive to small inaccuracies in measurement at relatively high densities, adds weight to this conclusion.

At moderate population densities (0.25 abalone m^{-2}), the distinction between the two methods is even clearer. The area that must be searched using variable area transects is considerably larger than for conventional strip transects, and underestimates actual density, despite the greater area searched (Figure 4). The need to randomly position a larger number of individual transects further adds to the challenge of variable area transects.

An additional difficulty associated with the use of variable area transects in low density populations arises from the extended length of the transects. Abalone have particular habitat preferences, and suitable habitat is patchy. In many instances, it would not be possible to physically accommodate relatively large numbers of long transects, and assure the assumption of independence of replicate sample units on which the estimates rely. Additionally, *a priori* selection of random start positions for such transects is problematic, as the distance that must be maintained between these positions to prevent the transect paths from overlapping cannot be determined until after the length of the transects is known.

The variable area transect method belongs to the family of plotless density estimators which were developed for forestry applications. Abalone represent quite a different case from this however, in that they are relatively small, often difficult to distinguish from their background, occupy complex three-dimensional habitat, and are often found under heavy algal cover. That searching occurs in the logistically challenging underwater environment, where for example the physical movement of researchers is restricted, visibility is variable and researchers are subjected to the forces of current and swell, adds to the difficulties. As a result, searching tends to be a relatively difficult and time consuming component of abalone surveys. The complexity of randomly positioning a large number of transect starting points and the high resource cost of searching large areas when abalone occur at all but very high densities easily outweighs any possible advantage of higher precision offered by variable area transects at these rarely encountered densities.

Finally, abundance estimation for multiple size classes is problematic when using variable area transects, requiring either more replicate transects be sampled (a set for each size group), or a much larger number of individuals to be counted on each transect (in order to encompass enough individuals from each size class of interest). Furthermore, members of particular size classes might represent only a small subset of the entire population, and as such occur only in relatively low densities, thus exacerbating the problems associated with sampling long transects.

Given all of these considerations, and the bias that is inherent in the method, variable area transect sampling was deemed inappropriate for abundance assessment of *H. rubra* in Tasmanian waters.

4.3.4. Timed swims

Timed swim protocols have been a popular choice for abalone abundance estimation for many decades, and have been applied to abalone surveys throughout the world including the Channel Islands (States of Jersey) (Forster et al. 1982, Anonymous 2004a), British Columbia (Wallace 1999, Lessard et al. 2002), California (Anonymous 2005), South Africa (Fielding 1995), and New Zealand (McShane et al. 1996, Breen and Kim 2004). Timed swims have also been used extensively in some Australian states including Victoria (McShane and Smith 1989) and South Australia (Shepherd et al. 1999), for both blacklip and greenlip abalone.

In general, timed swim methods involve divers visually searching reef habitat, with searches being timed either from the beginning of a dive, or from the sighting of the first abalone, and continued for a set period of time (usually five or ten minutes). Depending on the specific protocol used, divers may search either emergent (Shepherd and Baker 1998) or cryptic (McShane 1995, Findlay and Willerton 1996) habitat (e.g. by rolling boulders). Divers may either count (Andrew et al. 2000a) or collect individuals (McShane 1994), or estimate patch sizes (McShane 1995); and generally use their knowledge of abalone distribution to target suitable habitat (Shepherd 1985, Nash 1995, Andrew et al. 2000b). Timed swim abundance measures are relative (i.e. number of abalone per unit of time) (Wallace 1999), although numerous attempts have been made to extrapolate to a density by incorporating estimates of diver power (e.g. area searched, handling time per abalone) (Shepherd 1985, McShane 1995).

The attractiveness of timed swim methods lies in their relative efficiency and ease of operation (Shepherd 1985, McShane 1995). For example, (McClanahan and Muthiga 1992) and (Shepherd 1985) found timed swims to be around twice as efficient as transect methods, whilst (McShane 1995, 1998) reported an approximate fourfold difference in efficiency. It has also been suggested that timed swim methods can be applied in conditions that are too rough for conventional transect sampling (Shepherd 1985, McShane 1994). A further advantage of these methods is that they can be used to provide data on patch size and frequency, which may provide important additional information on the state of fished stocks (McShane 1995, Shepherd and Partington 1995). Most other survey methods do not easily provide such information.

Despite the apparent advantages of timed swim methods, the potential problems associated with such surveys are both numerous and well documented. For example, individual divers differ in the efficiency with which they can locate, and where appropriate collect, abalone (Shepherd 1985, Nash et al. 1995, Gorfine et al. 1998), and these between-diver differences may not always be consistent. Diver standardisation can be done, but is not trivial, requiring either ongoing comparative tests of diver performance, or several years of survey data from each diver (Gorfine et al. 1998) which may not always be possible to obtain (due, for example, to staff turnover). The efficiency with which a given diver can locate abalone will also vary temporally, and may be affected by factors such as visibility, swell, algal cover and topography, as well as less overt factors such as increasing experience or the diver's state of health and mind (McShane 1995, Nash et al. 1995, Hart and Gorfine 1997, Gorfine et al. 1998). This not only increases the temporal variability of such data, but confounds attempts to standardise diver performance.

Because divers generally target aggregations and optimal habitat during timed swims, abundance estimates tend to suffer from the same hyperstability that besets commercial catch-effort data (Hart et al. 1997b, Gorfine et al. 1998). That is, divers may quickly swim from patch to patch without wasting time searching between these, and so the relationship between search time and abundance is confounded (ideally, divers should swim at constant speed, however this may not always be the case).

A related problem with timed swims lies in the relationship between the abundance of the target organism and "handling" time (which here, includes the time taken to count, as well as that to measure individuals). This relationship is asymptotic: because handling time is finite, the more abalone encountered during a survey, the greater the ratio of handling time to searching time. Eventually a threshold density is reached, where the survey comprises only handling time, and the relationship between abundance and the survey results is lost. The asymptotic nature of the relationship is such that as density increases, small changes in survey estimates can lead to large differences in abundance estimates.

This relationship is further complicated by the fact that the handling time per individual abalone also varies with density. For example, when densities are low, divers will often search by swimming some distance above the reef, to increase their field of view and hence their search efficiency. When an abalone is encountered under such circumstances, the diver may spend some seconds descending to measure the animal, and then ascending back to search depth, which is not the case when density is high (under which circumstances the diver is likely to remain close to the bottom). A further confounding effect is the practice of collecting or measuring only the first four abalone encountered in any patch (McShane et al. 1994, McShane 1995), in which case the handling time per abalone decreases with increasing patch size where patches contain four or more individuals.

Extrapolation of survey results from a time-based to an area-based estimate (e.g. (Shepherd 1985, McShane 1995, Shepherd and Baker 1998) is further fraught with problems (Nash et al. 1995, Hart et al. 1997b, Andrew et al. 2000a), and there is a tendency for such estimates to trend towards infinity when abundance is high.

Attempts have been made to reduce or eliminate handling time by estimating patch size according to various categories, rather than counting individuals within patches (Andrew et al. 2000a). However, such estimates are effectively educated guesses, which brings into question their accuracy. Furthermore, the practice when analysing such data has been to use the midpoint of the estimated patch size category to estimate abundance (e.g. for a "21 to 40 abalone" patch category, a value of around 30 or 31 might be used when estimating abundance). This practice can overestimate density, however, since the distribution of patch sizes in each category is likely to be skewed to the smaller end of the category.

Undetected inflation in the rate of Type I error in statistical analyses of timed swim data may also present a problem. It is a common practice in timed swim surveys, to analyse paired dives as though they were independent (McShane 1994, Shepherd and Partington 1995, Naylor et al. 2003), however, this may not be valid at the scale at which these surveys are conducted. Analyses based on such data are therefore likely to have an inflated error degrees of freedom, leading to a concomitant inflation of the type I error rate (Hurlbert 1984). In addition, where abalone are counted but not measured during the surveys, timed swims provide estimates of error only for the total population being targeted, and not for individual size groups (such as recruits and pre-recruits). In some cases however, it appears that the error estimate for the total population, has been applied to smaller size class abundance data extrapolated by combining data from total counts with that from length-frequency collections (Rodda et al. 1998b, Shepherd et al. 1999). Individual size classes are likely to exhibit more variability than the total population (particularly for smaller animals which have a large cryptic population component). Accordingly, such error estimates are likely to be biased downward. Again, this leads to a subsequent inflation in the rate of type I error when such data are analysed (Sokal and Rohlf 1995).

It has been repeatedly demonstrated that free swim collections lead to underestimation of the abundance of small and semi-cryptic individuals (McShane et al. 1988, McClanahan and Muthiga 1992, Findlay and Willerton 1996, Hart and Gorfine 1997). Conclusions based on abundance and/or length-frequency data collected using such methods, are thus likely to reflect these biases. The generally high number of ascents associated with multiple short timed swim dives also has implications for diver health and safety, as "bounce diving" may contribute to the risk of decompression sickness.

Although it has been shown that under some circumstances, timed swims can provide reasonable estimates of abundance (Hart et al. 1997b, Andrew et al. 2000a), key problems associated with the method would encourage researchers to use a more robust method for estimating abalone abundance where possible. As such, investigation of the utility of the timed swim method for estimating abalone abundance in Tasmania was not followed beyond the literature review stage.

4.3.5. Tag-recapture

A myriad of other methods have been used for benthic abundance surveys. Prince (1989f) used mark-recapture methods to assess the density of blacklip abalone. The accuracy of mark-recapture techniques is dependent on a number of assumptions being met, including no unquantified migration or mortality, equal catchability of tagged and untagged animals, 100% detection of tags and thorough mixing of tagged and untagged animals.Nash et al. 1995

4.3.6. Area-based sampling

The most widely applied family of methods to be used for assessing the abundance of haliotids worldwide has been that of area-based sampling, and the range of protocols employed is extensive. Both quadrats (square) and transects (rectangular) have been used to estimate abalone abundance for both long-term stock assessment purposes, and to meet the sampling requirements of more discrete studies.

Quadrats have primarily been used in abalone studies where the area of interest is relatively small. The most common quadrat size used is 1m^2 (Shepherd 1986, Prince et al. 1987, 1988b, Prince et al. 1988a, Peck and Culley 1990, Tegner 1992, Schiel et al. 1995, Lessard et al. 2002, Caballero-Alegria et al. 2004), although quadrat size has ranged from 0.25m^2 to 25m^2 (Wells and Keesing 1990, Guzman del Proo 1992, Findlay and Willerton 1996, Karlov 1998, Babcock and Keesing 1999, Hobday et al. 2001, Rodriguez-Valencia and Caballero-Alegria 2002, Hancock 2004).

Quadrats, particularly small ones, are commonly used in surveys of early life history stages (e.g. Prince et al. 1987, 1988b), and in ecological investigations into associations between abalone and other physical and biological habitat components (Schiel et al. 1995, Karlov 1998, Lessard et al. 2002, Caballero-Alegria et al. 2004). However, they have also been used for stock assessment purposes, most commonly for species of relatively small to moderate size such as *H. cracherodii* (Miller and Lawrenz-Miller 1993), *H. kamtschatkana* (Breen 1980, Farlinger and Campbell 1992, Campbell et al. 2000), *H. roei* (Hancock 2004) and *H. tuberculata* (Peck and Culley 1990).

The smaller area typically sampled with quadrats commonly leads to samples having particular characteristics. For example, searching individual quadrats tends to be relatively fast and simple, and search effectiveness may therefore be more thorough than for large transects. However, because abalone often have a contagious distribution, quadrat size tends to be small relative to patch size and inter-patch distance (Miller and Ambrose 2000). Consequently, abundance estimates tend to be relatively imprecise (Andrew and Mapstone

1987, McShane et al. 1988, McClanahan and Muthiga 1992, Krebs 1999), and require a greater level of replication. This is particularly so given that pilot studies are rarely, if ever, conducted to determine optimum sample unit size.

A key issue with area-based sampling techniques is achieving random allocation or distribution of sample units within an identified area (Andrew and Mapstone 1987, Eberhardt and Thomas 1991). To do this rigorously in marine studies is a slow and cumbersome process, and for this reason a large proportion of quadrat studies employ non-random placement strategies, such as systematic (Breen 1980, Campbell et al. 2000), haphazard (Prince et al. 1987, 1988b, Babcock and Keesing 1999), or selective positioning (Tegner 1992).

A number of strategies have been developed to increase the underwater efficiency and accuracy of random distribution of sample units. One such strategy is to position transects perpendicular to the shoreline, at random points along a defined section of coastline. This method requires repeated deployment and retrieval of sampling gear, and true randomisation is difficult to achieve on the small scale (~ 100m) relevant to the "meso-scale" patchiness observed in *H. rubra*. In the majority of cases, perpendicular transects will cross depth gradients in either biological of physical habitat, and zones of different abalone density. Comparisons among sites or regions are then problematic if the reef profile varies substantially among sites/regions. The multiple ascents associated with this method are also undesirable from the point of view of no-decompression limits and diver health, with such "saw-tooth" dive profiles believed to contribute to decompression sickness.

Several techniques have been used to assist underwater navigation, to allow replicate sample units to be randomly placed. Reference lines, such as chains are commonly used as a navigational aid against which to position transects. Serial autocorrelation between neighbouring transects is more likely to occur with this arrangement, than for example if the transect start and end positions were also randomised, or if transects were aligned along their long axes. Maintaining adequate spacing between neighbouring transects is important both for this reason, and to avoid spatial duplication of sampling effort due for example to navigational error or convergence of sample units (e.g. in bays where the shallow sections are wider than those at greater depth). Other techniques include using Cartesian reference axes / grids to determine underwater position, and navigating from a vessel on the surface where GPS and/or identifiable objects such as shore features or rocks simplify navigation.

Haphazard sample unit placement can be used but brings with it an inherent risk of bias (Hurlbert 1984, Andrew and Mapstone 1987), which is particularly problematic in the context of an ongoing monitoring program, where for example, such bias may be in different directions subsequent sampling occasions.

It is well established that area-based survey techniques (both quadrats and transects) give unbiased estimates of abundance, provided basic assumptions, such as the random spatial allocation of sampling units, are met. It is generally accepted however, that transects usually yield more precise estimates of abundance than do quadrats (Andrew and Mapstone 1987, McShane et al. 1988, McClanahan and Muthiga 1992, Krebs 1999, Miller and Ambrose 2000). Arguably the most fundamental of these assumptions is that sample units be representative, which is achieved in statistical terms through their random, independent positioning. The challenge in designing a fishery-independent abalone abundance survey program is identifying a method for spatial allocation of replicates within sites that minimises biases and is also practical and efficient. The radial method described by Hart et al. (1997b) appeared both practical and efficient, and was thus selected for more detailed investigation.

5. Radial Sampling Theory and Development of Algorithms for Representative Sampling

5.1. The Victorian Radial Transect Protocol

A novel and particularly efficient technique applied to abundance surveys for *H. rubra* in Victoria, Australia, involves the use of “radial transects”, hereafter referred to as the “Victorian” method (Gorfine et al. 1996, Hart and Gorfine 1997, Hart et al. 1997b, Gorfine et al. 1998). In this application, “fixed” abundance monitoring sites are periodically surveyed using strip transects which radiate from a central point, in a manner analogous to spokes radiating from the hub of a wheel.

Radial transects deployed using the Victorian method are relatively fast, efficient and practical to implement in the field (Callan et al. 1995, Gorfine et al. 1998). Once a survey location has been selected, site preparation involves merely deploying a “shot line” (i.e. a weighted and buoyed rope) from the surface at the appropriate position (as determined by GPS or shore features), and if necessary manoeuvring this to a secure position (which usually requires negligible effort). Each diver attaches a single floating transect line to the base of the shot line, which is then used to survey multiple replicate transects. Floating rope reduces entanglement with kelp and reef structures, speeds deployment and retrieval, and reduces the tendency of transect lines to “wash about” in the surge. The use of floating transect lines also prevents lines from settling at low points, thereby allowing sampling to be more representative of the range of microhabitats present, including the tops and sides of large boulders and bomboras.

To survey each transect, the diver follows a compass bearing, allowing the rope to slide along through the divers hand (or under his/her arm). Upon completion, divers can pull themselves back along their transect line to the starting position (which simplifies navigation and speeds swimming). This procedure enables strip transect surveys to be conducted more rapidly than conventional survey methods, such as those involving Cartesian reference axes and negatively buoyant and/or anchored transect lines. The procedure also provides an added element of safety, as transects remain attached to the shot line at all times, allowing the divers to be better monitored from the surface and more easily located underwater.

Fishery-independent surveys of *H. rubra* in Victoria, involve six replicate 30m x 1m “radial” strip transects at each site (Gorfine et al. 2002). Previously, the number of replicates has ranged between three and nine (Callan et al. 1995, Gorfine and Dixon 2002). Each transect is positioned with its proximal end 5m from the centre of the site (in order to avoid spatial overlap) and diverges from its neighbours at an angle of 40^o, or some integer multiple thereof.

It has been reported (Callan et al. 1995, Gorfine et al. 1998), that the radial transect method is comparable to timed swim surveys in terms of the range of field conditions under which it can be applied (due to the overall simplicity of navigation, the divergence of transect paths which alleviates the requirement that navigation be precise, and the use of floating reference lines). Historically, the major considerations in the preferential use of timed swim surveys have been their relative efficiency, and that they are less affected by sea conditions (although no studies have been published on the effect of conditions on results from either method).

While the Victorian radial method appears to be both a practical and efficient technique for underwater surveys of patchily distributed subjects such as abalone, the current sampling procedure has two key detractions. Firstly, the sites are not representatively sampled. Proportionally more effort is applied toward the centre (and conversely, less toward the outer edge) of the site, no sampling effort is applied within 5m of the centre of the site, and transects necessarily diverge in multiples of 40^o degrees leaving large interstitial segments unsampled (Figure 5). Secondly, there is a risk of serial correlation of adjacent transects, due to their relatively close proximity towards the centre of the site. These issues potentially violate the assumption of independence of replicates, and may not provide representative sampling within sites.

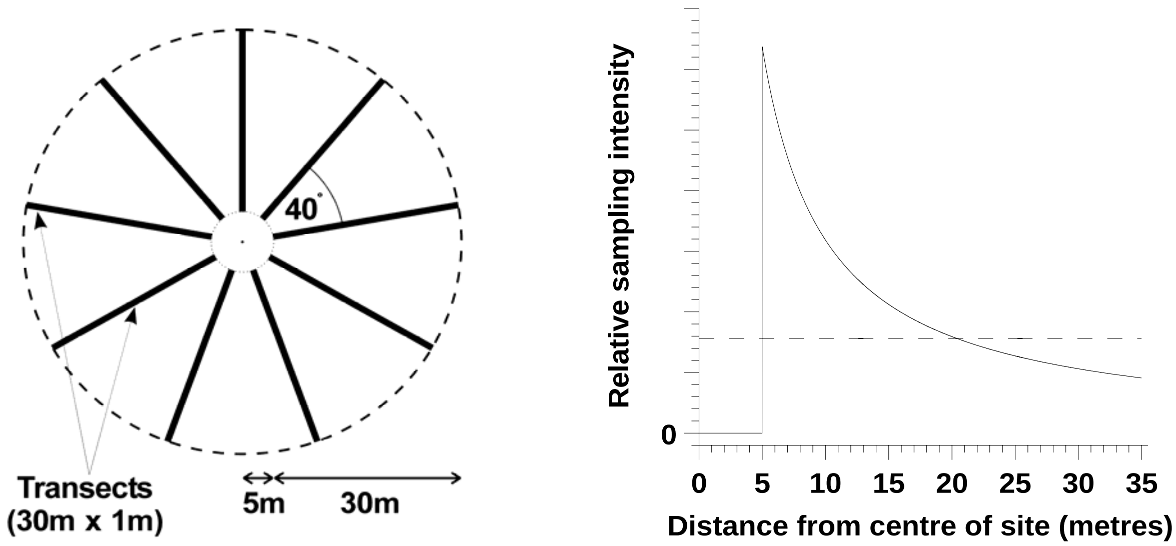

Figure 5. **(a)** *Graphical representation of the radial transect method as used in the Victorian blacklip abalone fishery. The 70m diameter circular sites are generally sampled using six 30m x 1m radial transects, the proximal ends of which commence 5m from the centre of the site.* **(b)** *Relative distribution of sampling effort with increasing distance from the centre of the site for the Victorian radial transect method (solid line), and the equivalent sampling effort if applied proportionately throughout the site (dashed line). The vertical axis has no values other than zero, as the actual magnitude of the sampling intensity depends upon the number of transects used; however the proportion (i.e. the shape of the graph and relative positions of the two lines) remains unchanged.*

5.2. Theory of radial techniques and complications with achieving representative sampling

5.2.1. Representative sampling

While spatial biases are inherent in conventional radial transect protocols, it is theoretically possible to use radial sampling techniques to distribute effort in a manner that is both spatially representative and effectively random. This can be achieved by using sample units which are substantially shorter than the radius of the circular site, and applying these in greater proportion as distance from the centre of the site increases.

It is an inherent principle of circular geometry that the areas of contiguous concentric annuli, with equal minor radii, are related to the area of the central circular section of equivalent radius in the ratio $2a$-1 (e.g. 1:3:5:7 etc; Figure 6a). Thus, by applying sampling effort to each annulus in these proportions (on average) (Figure 6b), the annuli can be sampled with equivalent intensity on the scale of their shared minor radii (for ease of communication, general references to annuli in this report can equally be taken to refer to the inner circular section as well as the surrounding annuli). Some minor caveats to this do exist however, the first and most important of which is that a gradient of differential sampling intensity occurs *across* each annulus, whereby relatively more effort is applied to those parts of the annuli closer to the centre of the site, than towards the outer side. Accordingly, it would be prudent to ensure that the annular minor radius selected is of a magnitude that it is unlikely to reflect any spatial pattern displayed by the survey subject. Given that it is unlikely under most circumstances, that biological or physical phenomena being sampled will follow a concentric annular pattern (particularly without this being recognised), this consideration is a minor one. The second caveat is that when using straight-edged sample units, there is some inter-annular overlap of the inner edge and/or outer corners, however this is negligible for both square quadrats or rectangular transects whose long axis is aligned with the radius along which it is positioned, and becomes less pronounced with distance from the centre of the site.

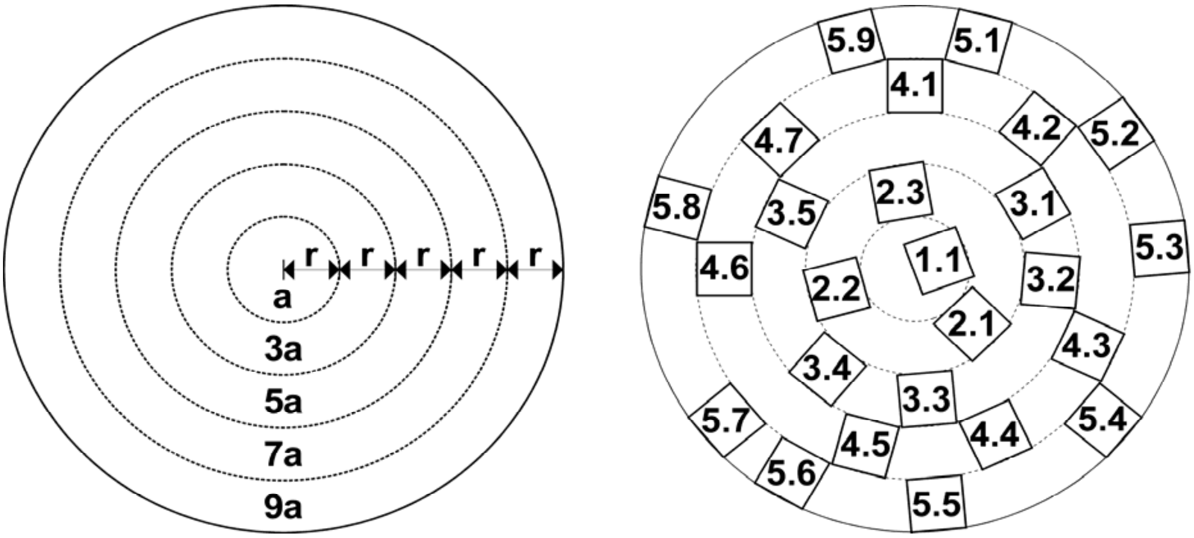

Figure 6. **(a)** *Relative areas of contiguous concentric annuli of minor radius r, and inner circular section of the same radius. If the area of the central circular section is a, then the area of the innermost annulus is 3a, the next annulus 5a, then 7a and so on.* **(b)** *Circular site sampled with consistent intensity in each annulus using radial quadrat sampling. Within each annulus, quadrats have been positioned at random along the site radii, with the imposed condition that they do not overlap. The numbers in the quadrats indicate annulus and quadrat number, and are shown merely to simplify interpretation.*

5.2.2. Spatial biases

When generating spatial coordinates for sample unit placement however, a problem arises with regard to maintaining a spatially representative distribution, particularly when sampling intensity is relatively high. When co-annular sample units that are contiguous at their inner ends are aligned along site radii, they diverge from their neighbours at an angle that depends both upon their width, and their position along the radius. The closer the annulus is to the centre of the site, the greater the angle of divergence of sample units, and hence the greater the proximal angle of the interstitial sector, and the proportion of the annulus that can not be sampled. Because of this phenomenon, the ratio of sample units that are contiguous at their inner ends which can be placed in each annulus (ignoring the central circular section) is approximately 3*n* (i.e. 3:6:9:… etc). A further complication is the fact that regardless of sample dimensions and overall sampling intensity, it is impossible to accommodate more than two sample units centred along site radii in the inner circular section of the site, without some degree of overlap. The two sample units that can be thus accommodated in the central circular region always lie along supplementary bearings, and are wholly contiguous at the centre of the site (Figure 7).

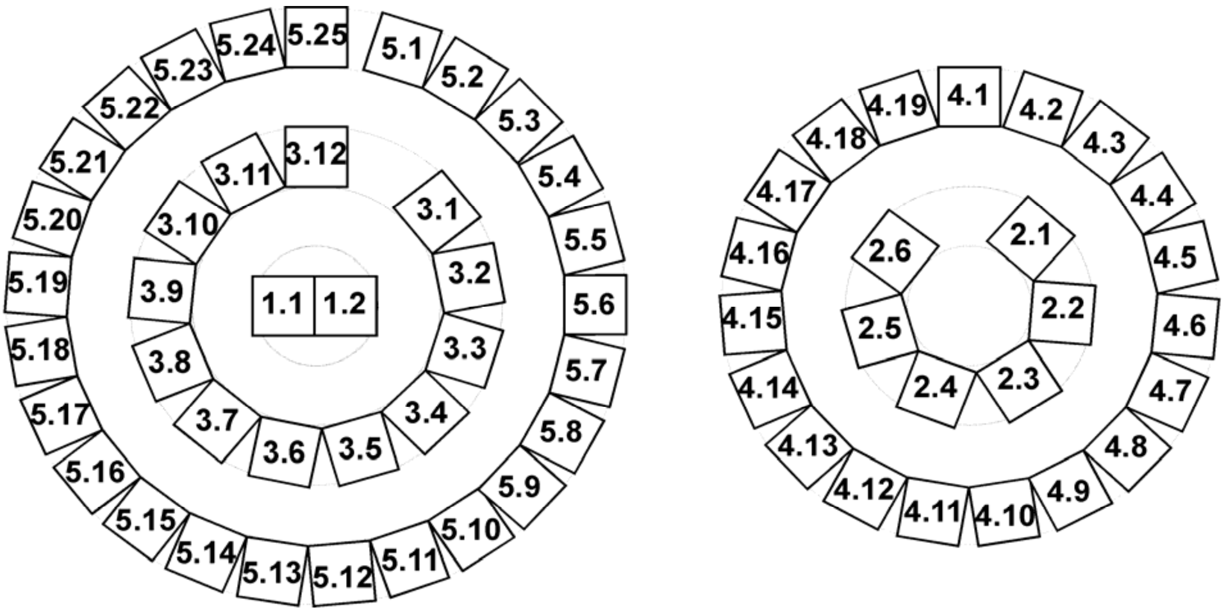

Figure 7. *Square quadrats positioned contiguously at their inner ends in each annulus of a radial site. Alternating annuli have been separated to aid visual interpretation. Sampling the central circular section and each annulus with equivalent intensity requires sample units to be placed in a ratio of 1:3:5:…:2a-1. Because contiguous sample units diverge at a greater angle in inner, relative to outer annuli, a greater proportion of the area of inner annuli cannot be sampled (without spatial overlap) on any one occasion, and hence the ratio of sample unit capacity of each annulus increases at a greater rate, which for narrow sample units is ultimately x:3:6:9:…:3(n-1). In addition, the inner circular section of the site can only ever accommodate a maximum of two sample units without spatial overlap. A less important problem is that of sample units overlapping neighbouring annuli at their inner edge or outer corners, which is more pronounced for inner relative to outer annuli and wider rather than narrower sample units.*

This difference between the relative number of sample units that an annulus can accommodate and the number required to achieve even sampling complicates the task of random positioning of sample units throughout the radial site. When sample units are allocated on the basis of the 1:3:5:…:2a-1 probability distribution required for representative sampling, a proportion of samples generated will be impossible to implement without spatial overlap, for all but the smallest sample sizes. This proportion increases with the intensity of sampling effort. Because inner annuli tend to fill first, a systematic spatial bias in the allocation of sampling effort is introduced, with these areas likely to be under sampled relative to more distal parts.

More serious complications to the generation of random samples can arise due to a number of factors associated with the practical implementation of the technique. For instance, the minimum resolution of compass bearing that a diver can reasonably attempt to navigate is arguably somewhere between 2.5° and 10°. Consequently within any annulus, there are only a limited number of bearings (between 36 and 144)[1] available to accommodate sample units. Because of the divergence of neighbouring radii, these positions will be physically closer to each other in inner, relative to outer annuli. As such, (the proximal ends of) sample units in inner annuli can generally be positioned closer together than those in outer annuli, with the magnitude of this effect depending on the relative dimensions of the sample units, and the number of annuli throughout which they are arranged.

There is likely to be a degree of navigational error experienced when implementing radial surveys, particularly when these are conducted by divers. In order to prevent (or at least minimise) spatial overlap of sample units, it is necessary to enforce an added degree of intra-annular separation of sample units. Because of the divergence of bearings, any given separation distance imposed will encompass a smaller range of bearings in outer, compared to inner annuli, as the distance between points on diverging radii increases with distance from their origin. Adding further complication is that limited resolution of bearings makes it impossible to maintain the same distance of separation between transects in all annuli, nor is this distance consistent along the length of sample units among different annuli.

Where inter-annular separation between sample units is imposed, added complexities arise since the annuli are disproportionately affected by the introduction of such regions of exclusion. In such a situation, the central annulus of any trio of concentric annuli has, on average, regions of exclusion imposed on it equivalent to the frequency at which sample units commence or end in the surrounding annuli. Furthermore, an exclusion zone of a given distance will cover a greater angle when imposed for sample units in the inner neighbouring annuli than those in the more outward one (because of the expansion of circumference with distance from the centre). Additionally (unless they are wider than the intra-annular exclusion zones), inter-annular zones of exclusion imposed on the central of the three annuli cannot overlap with other exclusion zones imposed due to sample units in the same annulus (either the inner or outer of the three). However, they can overlap with those imposed due to the presence of sample units in the annulus on the opposite side of that

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[1] i.e. $360^{\circ}/10^{\circ}$ to $360^{\circ}/2.5^{\circ}$

being affected. A further complication arises because the outermost annulus is only affected by inter-annular exclusion from the inner side and thus retains a greater capacity to accommodate sample units. Similarly, the central circular region is affected from only one side, but as this region can only ever accommodate two sample units (if these are centred along the radii) any such exclusions can disproportionately restrict sampling in this region.

Although all of the interacting sources of spatial bias identified above can make it difficult to generate sample arrangements that are truly random, where sample units lie wholly (or very nearly so) within annuli, it is possible to account for such bias in the analysis through the application of stratified sampling formulae. However, this complicates the analysis, and leads to a loss of within-site degrees of freedom (although this may be irrelevant where sites, rather than transects within sites are the error term of interest for a given analysis). Nevertheless, it remains a workable and valid solution.

Where transects are used, which overlap annuli in which other transects originate, however, a new level of complexity is introduced into the generation of samples. In such instances, the minimisation or elimination of spatial biases must be done during the generation of sample coordinates, as these cannot easily be accounted for in the analysis. Complicating this goal however, is that the capacity of each annulus to accommodate sample units is affected not only by sample units within that annulus, and to some extent those that immediately surround it, but by sample units that might start several annuli away yet traverse or abut the annulus in question.

Another source of systematic spatial bias arise which arises when multi-annular sample units are used, is that it is not possible to distribute sampling effort evenly throughout the annuli at the outer edge of the site (unless transects are considered to originate at their outermost point and converge inward, which in turn introduces a new and greater series of complications towards the centre of the site). Only one of the annuli that lie within one transect length of the outer edge of the site can be sampled with an intensity equivalent to that applied to the other annuli throughout the site. Accordingly, the longer transects are relative to the length of the site radius, the more pronounced is this effect (Figure 8).

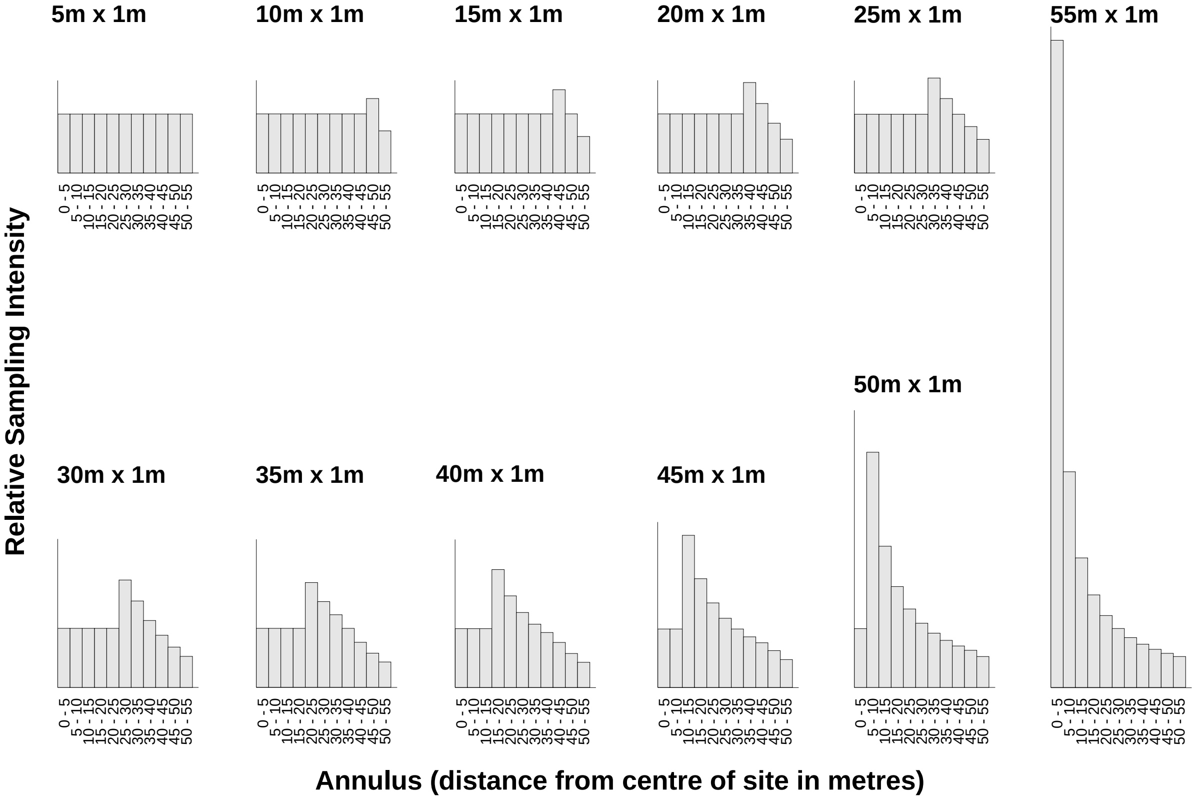

Figure 8. *Effect of transect length on the relative distribution of sampling effort (vertical axis) in each concentric 5m annulus of a circular radial transect site of 110m diameter (horizontal axis). Transects are arranged such that their central region is sampled with equivalent intensity to the average across the entire site. No units are shown on the vertical axis, since the actual values vary with the number of replicates used.*

A related problem with multi-annular sample units arises due to the divergence of the bearings along which they lay. Clearly, no transect can have its proximal end positioned in an annulus which closer to the edge of the site than the length of the transect itself. Therefore, where transects positioned at the site edge are either contiguous at their proximal ends, or have contiguous or overlapping intra-annular exclusion zones, no sampling effort can be applied in the interstitial space along their entire length. This is not necessarily the case for neighbouring transects that occur closer to the centre of the site, where sampling effort can be applied to the more distal regions of the interstices, as the sample units diverge. As a result, the distance between neighbouring sample units will be greater, on average, in outer annuli than in the others. This may in turn impede the capacity of the outer region of the site to accommodate sufficient transects, particularly where a degree of over-sampling is applied to the more proximal of these, in order to reduce under-sampling in the outermost annuli (e.g. as is the case for transects longer than 5m in Figure 8).

A third source of systematic spatial bias arises from multi-annular sample units whose ends are situated within less than one sample unit’s length from the centre or edge of the site (or more where additional inter-annular exclusion is imposed). In such instances, no sampling effort can be applied to those bearings between the transect (or any surrounding exclusion zone) and the centre or outer edge of the site. This is not the case however, for those sample units that are positioned further from the edge or centre, and as a result this bias only directly affects certain annuli.

In addition to the introduction of spatial bias in sample arrangements, the intensity with which a site can be sampled using radial techniques is also limited by the divergence of neighbouring sample units. This is because of the unavoidable presence of interstices between transects, which cannot be sampled during any one survey event, regardless of transect position. Again, the effect is amplified considerably when multi-annular sample units are used, and even more so than when additional intra-annular separation is imposed between transects.

5.3. Generating representative radial samples

5.3.1. Background

In order for radial sampling to be a valid and workable field technique, sample unit spatial distributions must be generated that are representative, and of sufficient intensity (replication, sample unit size) to achieve a desired level of precision. Accordingly, a desktop investigation was undertaken, whose primary objectives were to determine the effect of transect length on the spatial distribution of radial transects, and the maximum intensity with which a radial site can be sampled. The second major objective of this investigation was to investigate the performance of various models to minimise spatial bias in the generation of radial transect arrangements. The majority of the work focused on samples with realistic characteristics such as multi-annular transects, enforced spatial separation, and limited angular resolution.

5.3.2. Methods

Monte Carlo routines were developed to generate radial sample distributions for transects 1m wide and between 5m and 40m long, within radial sites of 110m diameter. An annular minor radius of 5m, and bearing resolution of 5° were imposed, as were minimum distances of separation where specified. These particular characteristics were selected because it is believed that they are likely to be both practical and relevant for abundance monitoring in the Tasmanian blacklip abalone fishery.

All of the models used in this study, generated transect coordinates such that each annulus should fill according to a $1:3:5:\ldots:2a-1$ probability function, in the absence of any secondary spatial biases[2], such as those described in the preceding section. For multi-annular transects (i.e. transects >5m length) however, it is not possible to impose this distribution across more than one of the annuli within a sample unit's length of the edge of the site. For these annuli, the probability function was modified such that the more inward of these annuli were over-sampled and those toward the outside under-sampled, with the central annulus, if one existed, theoretically being sampled with the 1:3:5: … : $2a$-1 distribution (as per the distributions in Figure 8).

Distances between transects were calculated under the simplifying assumption that transects were centred along bearings, and the distance was calculated as that between the central point of the ends of each transect minus 1 metre (to account for transect width). In general, this assumption slightly underestimated true separation distances. Except where transects are specified as being contiguous, an inter-annular separation of at least 3m was imposed to allow for navigational error, however no terminal separation was applied to transects which originated at the centre of the site. For these transects, it was assumed that the 1m transect strip lay to one side of the bearing (rather than the centre), which restricted transects in this region to bearings with at least 90^o separation (rather than a fixed 180^o if this assumption was not made). In each case, bearings for transects were randomly selected from those available within any given annulus.

Where minimum distances of lateral separation were imposed, this was done based on an assumption that navigational error on each diver's part would generally be no more than around $\pm 10^o$. Accordingly, transects at the outer edge of the site were separated by a minimum angle of 20^o. The distance between the transect segments thus separated was then applied as the minimum lateral separation distance between transects throughout the rest of the site. An exception to this rule was that where such a distance exceeded that corresponding to an angle of 90^o (which occurred only in the inner circular section and in some cases in the annulus immediately surrounding this), the minimum angle of separation was restricted to 90^o, which allowed several transects to start towards the centre of the site in any one sample. As the minimum separation distance decreases with increasing transect length, the effect of under-sampling of sites with long, relative to those with short transects is ameliorated to a large extent.

In terms of practical application, navigation is achieved by divers following compass bearings, and as such, it was necessary to translate minimum separation distances into minimum angles of separation. Because of the 5^o angular resolution used, it was generally not possible to apply a precise separation distance between all transects. In these instances,

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[2] Here, "secondary spatial bias" refers to systematic deviations in the distribution of sampling effort from the 1:3:5 etc. ratio required for even sampling, that arises due to differential availability of sufficient space in the various annuli (as opposed to the overtly recognised and unavoidable diminution of sampling effort with one transect's length of the edge of the site).

the angle of divergence applied was that which imposed a separation distance equivalent to *or greater than* that specified.

The spatial distribution of sampling effort was expressed in a number of ways. For all sample distributions generated, the relative frequency distribution of transect start positions was assessed in comparison to that specified in the algorithm. In most cases, spatial distribution was also expressed as the relative distribution of sampling effort between each of the individual annuli that comprise the site, both as observed minus “expected” proportions of sampling effort, and as an index weighted for the relative area of each annulus:

i.e.

$$O - E \times \left| \frac{(O - E)}{E} \right|$$

where: O and E are the observed and expected *proportions* of total sampling effort applied within a given annulus respectively.

In both cases, the “expected” distribution of sampling effort was that required to sample the site evenly (as per 5m transects in Figure 8), rather than that specified in the algorithm.

Both weighted and unweighted indices were used, as these provide different information. The unweighted index represents a quantitatively meaningful way of expressing the degree of over- or under-sampling within each annulus, however it does not account for the effect of this uneven sampling on the overall result. For example, if 10% of total sampling effort is applied in the innermost annulus of the site, in addition to that “expected”, then this has a much greater potential influence on abundance estimates than if this extra sampling effort was applied in the outermost annulus, given that there is a 21-fold difference in the relative areas of these two regions. The weighted measure on the other hand accounts well for this, however the output has limited numerical meaning, with values potentially ranging from a minimum value of –0.17 where the outermost annulus goes completely unsampled, to 119 where 100% of sampling effort is concentrated in the innermost annulus. In practice however, this maximum value cannot be achieved for transects longer than 5m (since each of these crosses multiple annuli). Nevertheless, the weighted index provides a useful relative measure of the distribution of sampling effort (e.g. a value of 0.02 in a given annulus indicates that this areas has twice as much undue influence on results as one with a value of 0.01).

5.3.2.1.Assessment of bias in radial transect coordinate generation

An algorithm was developed in which offset position selection for each transect was initially based on the 1:3:5:…:2*a*-1 probability distribution previously described. However, when a given annulus could no longer accommodate further sampling effort, the function was altered such that no transect coordinates subsequently selected would lie within that region. Sampling then continued on the basis of the new probability function, up to the specified sample size, or until no available start positions remained. When the required sample size could not be accommodated, the entire set of coordinates was rejected without being recorded, and a new set generated. Sampling continued with increasing intensity until a sample size was reached whereby some specified number (generally around 10000) of consecutive sets of coordinates were rejected, and the previous sample size was taken to be the upper sampling limit. For ease of communication, this algorithm will hereafter be referred to as the “original” algorithm.

The spatial distributions of samples generated with this algorithm were then examined to determine if they matched the desired patterns, and to assess the intensity with which radial sites could be sampled given the limitations imposed by the divergence of transects and any surrounding regions of exclusion. Assessments were made both for samples where the only restriction was to prevent transects from overlapping, and for those with additional imposed transect separation as previously described.

Overall sampling intensity was assessed by determining the maximum area that could be sampled, using a range of transect lengths. Again, this was done for samples both with and without additional enforced intra-annular exclusion regions. Representative allocation of transect coordinates was assessed by comparing observed patterns of sampling effort distribution generated through the algorithm, to that initially specified. To make this comparison, sets of sample coordinates were repeatedly generated until around 65500 individual transect start positions had been generated for each sample size.

Comparison of the frequency distribution of the final transect offset position generated in each sample provided a sensitive test of whether sample generation was truly random. Because only one transect position was recorded in each sample, fewer data points were obtained (the actual number depended on the sample size specified), and subsequently this data is more “noisy” than that used in the other tests described here.

5.3.2.2.Constraining secondary spatial bias

Following the completion of the simulation work above (Section 5.3.2.1), it was clear that a degree of secondary spatial bias was indeed present in the generated coordinates. Accordingly, a number of modifications were made to the sampling algorithm, and the new versions tested. Because of the scale and computing power required for this work, testing was restricted to 15m (x 1m) transects only (concurrent work on optimisation of radial transect parameters for *H. rubra* had shown this to be the optimum transect length; see section 6.4). Testing again involved circular sites of 110m diameter, with enforced exclusion as previously described (Section 5.3.2).

Initial modifications included increasing the width of the enforced exclusion zones and blocking out areas at random, in those annuli that were over-represented in terms of the spatial allocation of sampling effort. A range of other modified algorithms were investigated, in each of which the 1:3:5: … :2a-1 probability function was maintained, regardless of whether or not particular annuli could accommodate further sampling effort. These included versions in which:

(1) the entire set of coordinates was rejected once a transect offset position was selected which could not be accommodated without violating spatial exclusion rules (for ease of communication, this will be referred to as the "coordinates discarded" algorithm);

(2) the set of offset positions was selected initially, and sets of bearings repeatedly generated until the sample could be accommodated, or a given number of unsuccessful attempts was made, after which time an entirely new set of coordinates was generated (this will be referred to as the "offsets retained" algorithm);

(3) a similar model to (2) was used, but offset positions were selected on the basis of binomial probability with the chance of success (p) in each concentric annulus based on the 1:3:5: … distribution (this will be referred to as the "binomial" algorithm); and

(4) a set of the minimum number of radial offsets that would allow the distribution of sampling effort was generated, and these were subsequently sampled without replacement up to the desired level of replication. Where a sample could not be accommodated, the offsets were retained but new bearings repeatedly generated until the sample could be accommodated or a defined number of consecutive attempts had been unsuccessful, at which point the entire coordinate set would be rejected and the process commenced anew (this will be referred to as the algorithm involving "sampling without replacement").

In the binomial algorithm, the number of transects which started at a given annulus was selected by generating a random probability (0 to 1), and calculating the corresponding number of "successes" from the binomial distribution. Where indicated, an upper limit was placed on the probability value used to generate the transect offset positions, in order to reduce the concentration of sampling effort in a particular region of any given sample. Accordingly, the binomial algorithm was executed variously with no imposed upper probability limit (i.e. probability = 1), and with imposed upper probability limits of 0.95 and 0.8.

Again, sets of sample coordinates were repeatedly generated until around 65500 individual transect start positions had been generated for each sample size. The exception to this was made for the largest samples produced with algorithms other than the "original", where at least 30000 individual transect positions were generated (this reduction was due to the long computing times involved to generate the very largest samples).

5.3.3. Results

5.3.3.1.Assessment of bias in radial transect coordinate generation

Where the only prerequisite for sample unit separation was preventing overlap, random and representative allocation of transects could be maintained for relatively large sample sizes (Figure 9). The exception to this was for longer transects, where deviations from the specified distribution were observed at the centre of the site when sample sizes exceeded 560m^2 for 40m and 810m^2 for 30m transects (or 5.9% and 8.5% of total site area respectively).

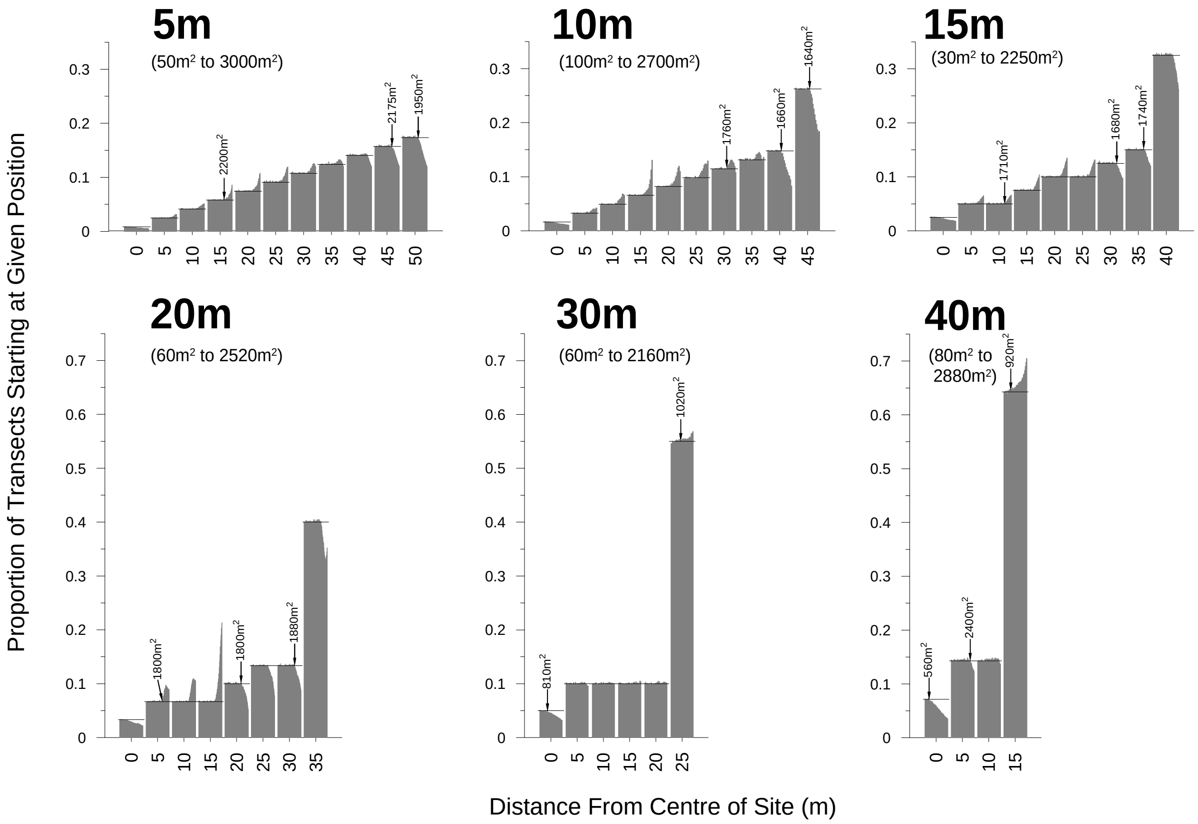

Figure 9. *Distribution of radial transect start positions for selected transect lengths (as indicated by graph titles) across a range of sample sizes (expressed as area sampled, and shown in parentheses under graph headings). In each case, the sites were circular with 55m radius. The upper sample size shown in each case is the largest that could be accommodated within the site. Horizontal black lines at each position indicate the distribution of start positions specified in the algorithm. Arrows and labels indicate the three smallest sample areas (or two in the case of 30m transects) at which the distribution of transect start positions begins to differ markedly from that specified, for each transect length.*

The largest sample size that could be generated without substantial deviation from the specified pattern was for 5m transects, where samples as large as 1950m^2 (20% of total site area) closely followed the specified transect distribution. There was a negative relationship between transect length and the minimum area that could be sampled without substantial deviation from the specified spatial distribution (Adjusted $R^2 = 0.82$, $F_{1,4} = 24.6$, $p = 0.008$).

In terms of the total area that could be sampled, this ranged from 2160m^2 (22.7% of total site area) for 30m transects, to 3000m^2 (31.6% of total site area) for 5m transects (Figure 9). There was no discernable relationship between transect length and the maximum total sample area that could be accommodated.

When strict conditions were placed on the separation of neighbouring transects (i.e. 3m minimum terminal spacing, 20^o minimum angle of separation between adjacent transects at the edge of the site, and an equivalent minimum distance of separation for transect segments closer to the centre of the site), the maximum total sample area that could be accommodated fell markedly to between 4.4% to 7.2% of the total site area (1st column, Figure 10). There was a general tendency for the maximum sample area to increase with transect length (Adjusted $R^2 = 0.79$, $F_{1,4} = 19.3$, $p = 0.012$).

Deviations from the specified distribution of transect start positions were apparent for sample sizes as small as 125m^2 (1.3% of total site area) when using 5m transects, up to 360m^2 (3.8% sample coverage) for 40m transects. Unlike the case for transects without additional imposed separation, there was no obvious relationship between transect length and the maximum area that could be sampled without substantial deviation from the specified distribution pattern (Adjusted $R^2 = 0.38$, $F_{1,4} = 4.13$, $p = 0.11$).

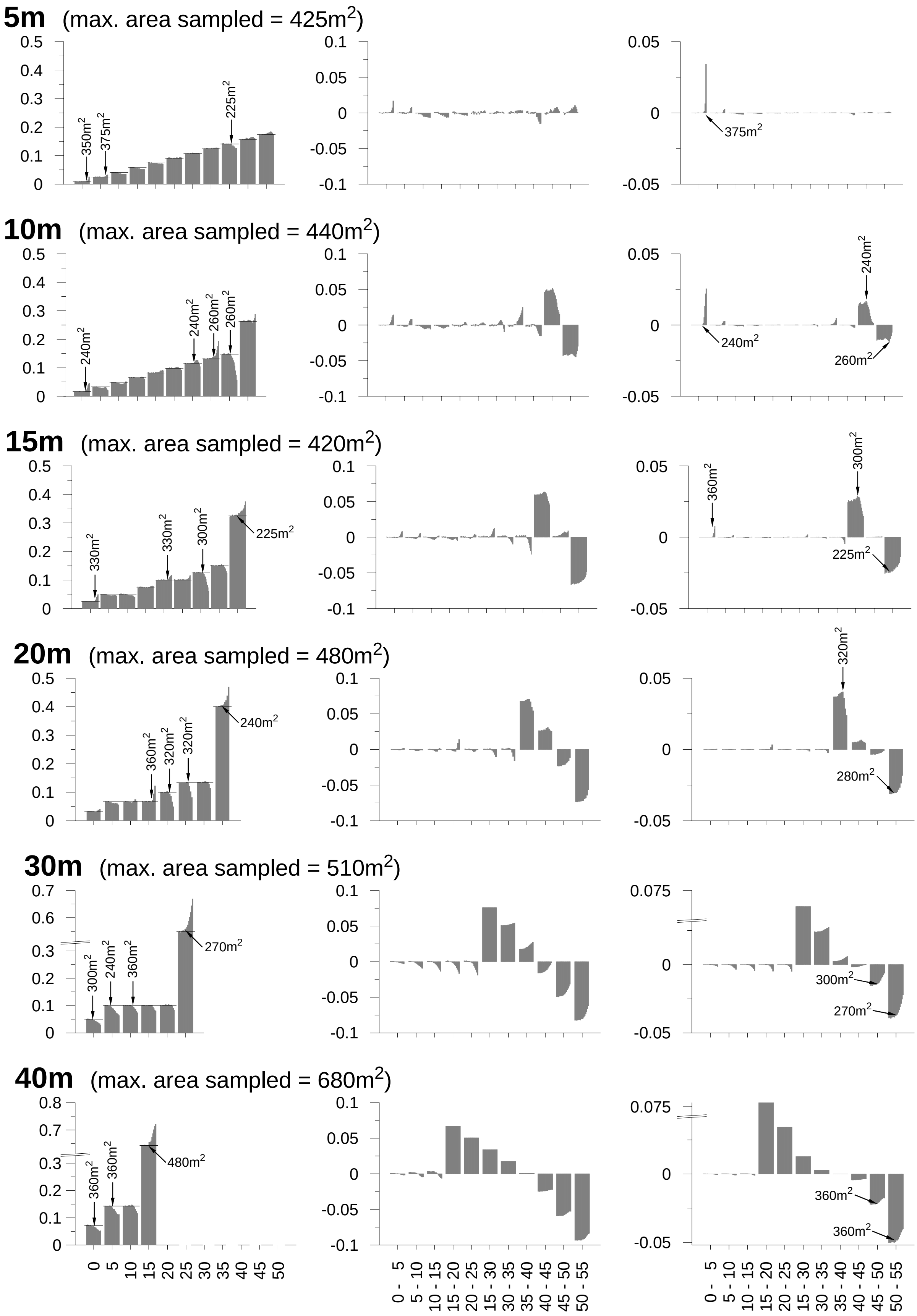
5m (max. area sampled = 425m^2)
350m^2
375m^2
225m^2
375m^2
10m (max. area sampled = 440m^2)
240m^2
240m^2
260m^2
260m^2
240m^2
240m^2
260m^2
15m (max. area sampled = 420m^2)
330m^2
330m^2
300m^2
225m^2
360m^2
300m^2
225m^2
20m (max. area sampled = 480m^2)
360m^2
320m^2
320m^2
240m^2
320m^2
280m^2
30m (max. area sampled = 510m^2)
300m^2
240m^2
360m^2
270m^2
300m^2
270m^2
40m (max. area sampled = 680m^2)
360m^2
360m^2
480m^2
360m^2
360m^2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
-0.1
-0.05
0
0.05
0.1
-0.05
0
0.05
0.075
0
5
10
15
20
25
30
35
40
45
50
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
15 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55

Figure 10. *Distribution of sampling effort for selected transect lengths (as indicated by graph titles) across a range of sample sizes. Transects generated have imposed minimum spacing (3m terminal separation, 20^o lateral for outermost transects, and equivalent distance for transects closer to the centre of site, capped at that equivalent to 90^o). In each case, the sites were circular with 55m radius. Sampling effort at each position is expressed as the proportion of total effort for samples of the specified size. Figures in the left column show the distribution of transect start positions generated. The vertical axes in this column show the proportion of transects in all generated samples of a given size. The horizontal axes indicate the offset distance (in metres) from the centre of the site. Horizontal black lines at each position indicate the distribution of start positions specified in the algorithm, and labels with arrows indicate sample sizes (expressed as area) at which the distribution of transect start positions begins to differ markedly from that specified. Figures in the central and right columns show the generated distribution of sampling effort in each annulus of the site. In both cases, the horizontal axes indicate the various annuli that comprise the site (in 5m increments). The central column shows the observed minus the "expected" proportions of sampling effort, whilst the right column gives this value weighted by the proportion of the total sample that constitutes the under- or over-sampling. Labels with arrows (in figures in the right column) indicate sample areas at which relative sampling intensity begins to rise or fall markedly.*

Examination of the spatial distribution patterns of the last transect generated in each sample provided a sensitive means to detect deviations from the patterns specified. In general (Figure 11), this revealed the presence of secondary spatial bias in samples slightly smaller than those for which such deviations were apparent when examining the spatial distribution of all transects (Figure 10). For relatively small samples, deviations from the specified pattern were negligible. Once a threshold level was reached however, these deviations tended to increase sharply, in many instances approaching either 0% or 100% representation.

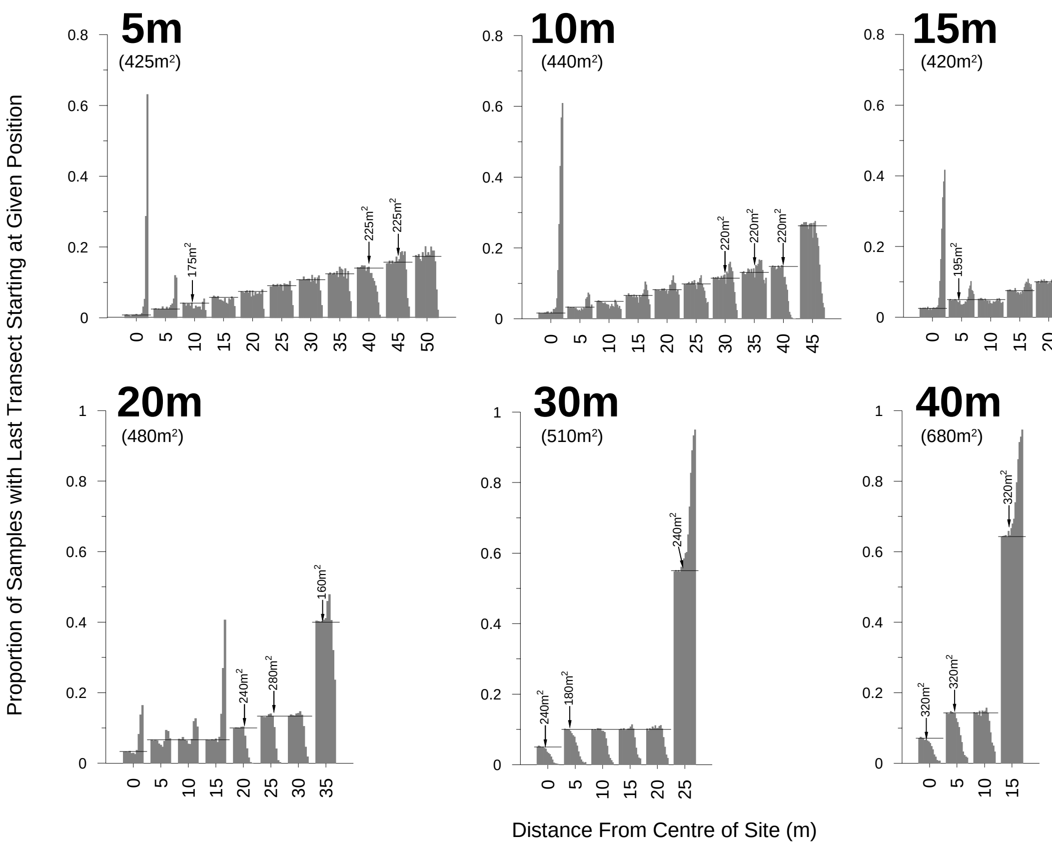

Figure 11. *Distribution of start positions of the last transect in each sample, for transects ranging in length from 5m to 40m, and sample areas ranging up to the maximum limit as specified in parenthesis under the title of each figure. Horizontal black lines at each position indicate the distribution of start positions specified in the algorithm, and labels with arrows indicate the sample areas at which the distribution of transect start positions begins to differ markedly from that specified.*

Despite the tendency of transect start positions to deviate from the specified patterns with increasing sample size, this does not necessarily manifest as a less representative distribution of sampling effort throughout the site (Figure 10). For 5m transects, deviations from the specified pattern have negligible effect on the spatial distribution of sampling effort, particularly for samples with an area smaller than about 375m^2 to 400m^2. For transects of 10m, 15m and 20m length, the over-representation of the most outward transect start positions coupled with under-representation of those annuli in close proximity, results in a more representative distribution of sampling effort for sample sizes beyond a given threshold (e.g. 225m^2 to 300m^2 for 15m transects). Accordingly, although the largest sample sizes that can be accommodated using 10m to 20m transects show the greatest deviation from the specified sampling patterns, these actually yield the most representative distributions of sampling effort for transects of that length. This is particularly the case when considered in terms of the weighted index of sampling effort distribution (right column, Figure 10), which takes into account not only the concentration of sampling effort, but the potential to affect survey results.

Once the transect length exceeds half that of the site radius (e.g. 30m and 40m transects), the representativeness of transect distribution diminishes sharply. This occurs because annuli in the intermediate region of the site are sampled in each transect, regardless of start position. As such, there is no secondary spatial bias observed in this region. In the outermost annuli however, some improvement in the distribution of sampling effort due to secondary spatial bias is observed for large samples.

Overall, representative distribution of sampling effort generally improves with total area sampled, but diminishes with increased transect length for transects with imposed spacing. “Contiguous” transects differed from this trend, in that for transects of 20m length or shorter, under-sampling of the outer annuli became more pronounced once a given threshold sample size has been reached (Figure 9).

5.3.3.2.Constraining secondary spatial bias

Attempts to reduce secondary spatial bias by increasing separation angles and/or excluding randomly selected bearings in over-sampled annuli, were unsuccessful. Although more representative sampling patterns were generally achieved, the total sample area that could be accommodated invariably diminished to such an extent that there was no net benefit to be gained by employing such processes.

Modifying the algorithms used to generate the radial transect coordinates produced distinct differences in the patterns of spatial sampling bias (Figure 12). Selection of transect offsets on the basis of binomial probability reduced the tendency towards over-allocation of transect start positions toward the outside of the site, but introduced some bias for smaller sample sizes (Figure 12b, c and d). When no upper probability limit was imposed upon the generation of sample coordinates, transect distribution more closely matched that specified (Figure 12b, left column), with small deviations observed for relatively small or large samples. This is reflected in the distribution of sampling effort among individual annuli (row b, centre column), with little deviation from the ideal distribution of sampling effort, except within one transect’s length of the edge of the site (where it is unavoidable). The slight over-allocation of transect start positions observed for large and small samples, does however add to the already inflated influence of the 40-45m annulus (row b, right column).

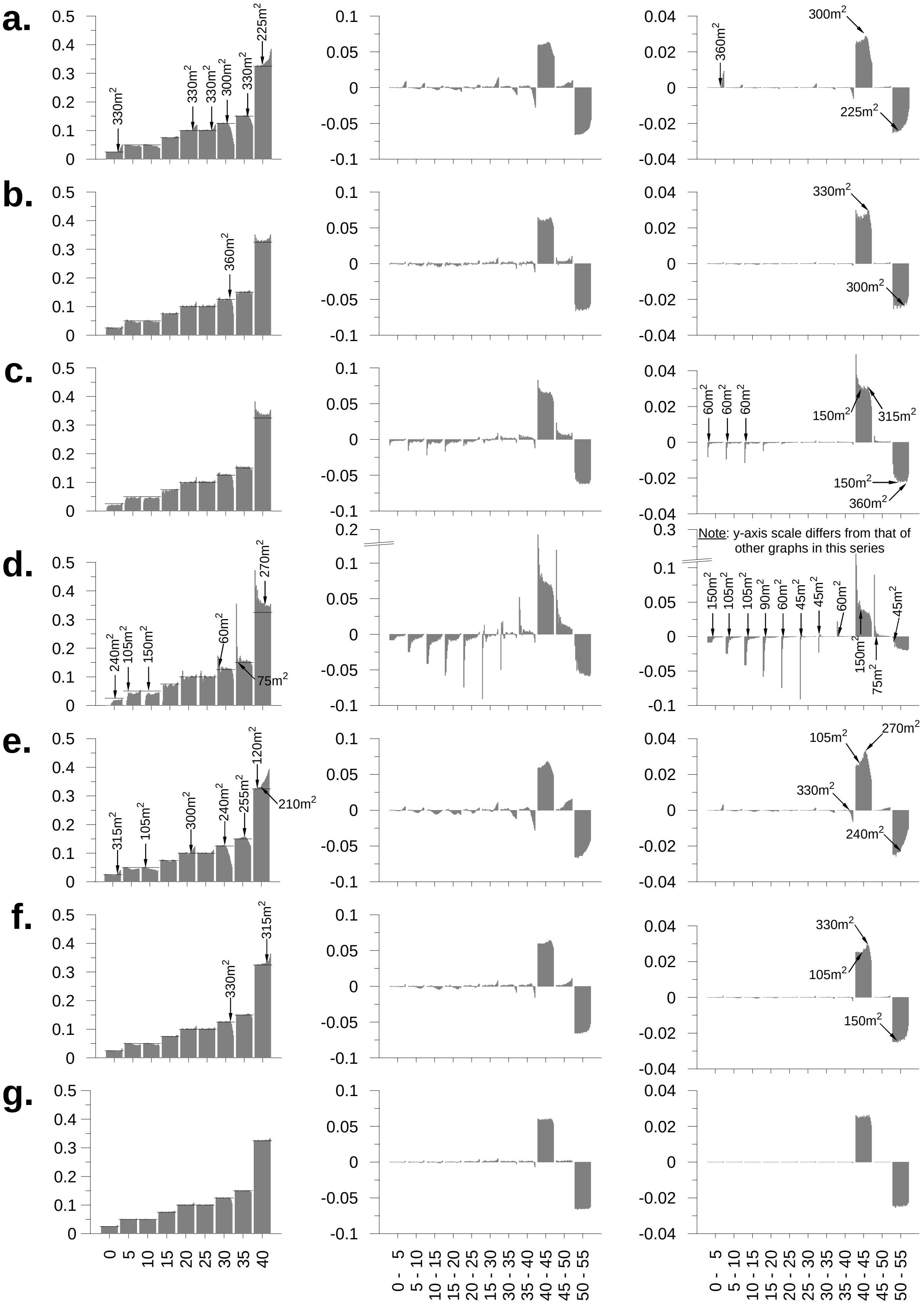
a.
330m^2
330m^2
330m^2
300m^2
330m^2
225m^2
360m^2
300m^2
225m^2
b.
360m^2
330m^2
300m^2
c.
60m^2
60m^2
60m^2
150m^2
315m^2
150m^2
360m^2
d.
240m^2
105m^2
150m^2
60m^2
270m^2
75m^2
Note: y-axis scale differs from that of other graphs in this series
150m^2
105m^2
105m^2
90m^2
60m^2
45m^2
45m^2
60m^2
45m^2
150m^2
75m^2
e.
315m^2
105m^2
300m^2
240m^2
255m^2
120m^2
210m^2
105m^2
270m^2
330m^2
240m^2
f.
330m^2
315m^2
330m^2
105m^2
150m^2
g.
0 5 10 15 20 25 30 35 40
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55

Figure 12. *Spatial distribution of effort among simulated radial transect samples, generated using different algorithms. All samples generated relate to 15m transects, with additional enforced spacing, as described elsewhere. Sample sizes range from two transects (30m^2) to a maximum of 27 transects (405m^2) in all plots other than those in row a, for which an additional transect could be accommodated (420m^2 total sample area). In each case, transect offset positions were generated based on a 1:3:5:…:2a-1 probability distribution, modified such that the central of the three annuli traversed by the outermost transects was sampled with the appropriate intensity (thereby leaving the inner of these three annuli over-sampled, and the outert annulus under-sampled). Algorithm details are as follows: (a) original algorithm; (b) binomial version with no upper probability limit; (c) binomial version with imposed upper probability limit of 0.95; (d) binomial version with probability limit of 0.8; (e) algorithm in which coordinates discarded; (f) version in which offsets were retained; (g) algorithm in which distribution sampled without replacement more complete descriptions of these algorithms are given in Sections 5.3.2.1 and 5.3.2.2.*

The plots are arranged in three columns. Figures in the left column show the distribution of transect start positions generated. The vertical axes in this column show the proportion of transects in all generated samples of a given size. The horizontal axes indicate the offset position (in metres) from the centre of the site. Horizontal black lines at each position indicate the distribution of start positions that had been specified in the algorithm, and labels with arrows indicate sample sizes (expressed as area) at which the distribution of transect start positions begins to differ markedly from that specified. Figures in the central and right columns show the generated distribution of sampling effort in each annulus of the site. In both cases, the horizontal axes indicate the various annuli that together comprise the site (in 5m increments). The central column shows the observed minus the "expected" proportions of sampling effort, whilst the right column gives this value weighted by the proportion of the total sample that constitutes the under- or over-sampling. Labels with arrows (in figures in the right column) indicate sample areas at which the distribution of transect start positions begins to rise or fall markedly.

Imposition of an upper probability limit on the generation of transect start positions using the binomial algorithm, resulted in a strong pattern of under-sampling of inner, and over-sampling of outer annuli, particularly for small samples (Figure 12c and d). As the size of the generated samples increased however (beyond around 150m^2), the pattern of spatial distribution more closely resembled that specified, although some under-sampling of the inner and over-sampling of outer annuli remained apparent. There was no strong tendency towards attenuation of the inherent over- and under-sampling near the edge of the site when large samples were generated.

When the algorithm was examined in which the entire set of sample coordinates was rejected if a selected offset position could not accommodate further transects (Figure 12e), the distribution of sampling effort for small samples, generally matched that specified. As sample size increased however, deviations from the specified pattern became increasingly marked, and for samples with total area between around 105m^2 and 270m^2, over-sampling of the 40m to 45m annulus became particularly apparent. Beyond this threshold however, the spatial distribution of sampling effort improved considerably, such that the inherent spatial sampling bias near the edge of the site was ameliorated to some degree.

A far less marked pattern of secondary spatial bias is apparent in samples generated with the algorithm in which offset positions were retained and new sets of bearings repeatedly allocated until the sample can be accommodated (Figure 12f). When the largest samples were generated, there is some reduction in "inherent" spatial bias at the edge of the site, however this is less pronounced than in other algorithms (e.g. Figure 12a and e).

Selection of transect offset positions without replacement, from a set generated using the 1:3:5:…:2*n*-1 distribution, produced a pattern of spatial distribution in which secondary spatial bias was almost completely eliminated (Figure 12g). Accordingly, there was neither attenuation nor amplification of the spatial biases inherent in the outer region of the site.

No formal study was conducted into the execution speed of the various algorithms used (since many individual computers with different processors and memory sizes were employed). However, anecdotal evidence indicates that the speed of the algorithms roughly matched the order in which they are presented in Figure 12. The original and binomial (p = 1.0) algorithms operated relatively quickly, whilst the "offsets retained" and the "sampling without replacement" algorithms were particularly slow.

5.3.4. Discussion

In the absence of the imposition of spatial exclusion zones around transects (beyond that required to prevent overlap), secondary spatial bias was apparent for long transects (30m and 40m) at considerably lower sampling intensity (8.5% and 5.9% respectively) than was the case for shorter transects (17% or more). However, this is around the 5% to 10% maximum threshold range of sampling intensity accepted for uncorrected sampling of finite populations (Cochran 1977) (although statistical correction can be made to allow more intensive sampling than this, most studies seem to be restricted to smaller sample proportions).

The secondary spatial bias apparent for large samples using 30m and 40m transects acts in the opposite direction to the inherent spatial bias apparent at the edge of the site. Accordingly, it has the beneficial effect of actually causing effort to be distributed more representatively in this region. That is, whist there is slight under-sampling at the central circular region of the site (which accounts for only 0.8% of the total site area), there is a concomitant increase in the intensity of sampling in the inherently under-sampled outermost region.

When radial sample coordinates are generated for smaller transects (20m and shorter), the secondary spatial bias operates in the opposite direction, causing the distribution of sampling effort to become less representative with increasing sampling intensity, beyond a given threshold. However, given that the distribution of sampling effort is inherently more representative than that associated with 30m or 40m transects, the secondary spatial bias observed for high-intensity samples using large samples is smaller in magnitude and affects fewer annuli than the inherent bias near the edge of the site when sampling with long transects. Furthermore, such bias does not become apparent until samples cover more than 17% of the total area of the site, and so is unlikely to be problematic for most applications. In those instances when resources are sufficiently abundant to allow the sampling intensity to exceed this level, then the potential efficiency improvements afforded by the radial transect technique may not be a critical consideration, allowing other techniques to be employed.

Under the restrictive separation conditions that were imposed on the generation of transect coordinates during this study, the amount of effort that could be applied during a single survey event fell substantially to between 4.4% and 7.2% of total site area. Indeed, when the "original" algorithm was applied, deviations from "random" and representative transect positioning were apparent in some instances when sample coverage was a small as 1.7% to 1.9% of the total area. At these small sample sizes however, such bias was generally negligible in terms of the overall distribution of sampling effort. Furthermore, for all (examined) transect lengths exceeding 5m, the effect of the secondary bias was to make spatial distribution of the transects more representative, particularly when considered in light of the likely potential influence of spatial such bises on the overall survey result (using the weighted index).

Although the original algorithm has an associated element of secondary spatial bias, it is the most suitable of those assessed, for the generation of 15m radial transect coordinates,[3] particularly when generating coordinates for relatively large samples. Compared to the other algorithms, the "original" algorithm required less computing power and allowed a greater area to be sampled. Additionally, secondary spatial bias associated with this algorithm led to a more generally representative spatial distribution of sample units once a threshold total sample area had been reached.

In instances where only small samples are required, the decision as to the most suitable algorithm is not quite as obvious. However, given that overall spatial bias can be most effectively constrained by generating large samples, it may be prudent to use the original algorithm to generate coordinates for such samples, and select the appropriate number from these at random (this secondary randomisation is necessary given that there is bias associated with the order in which offsets are selected). As additional advantage of generating more replicates than required is that this provides "redundant" coordinates, which can be used if selected coordinates place transects in habitat that is unsuitable for sampling. If such "spare" coordinates are not available, then it is difficult, and may indeed be impossible, to generate new coordinates for this purpose, particularly whilst in the field.

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[3] Concurrent studies (Section 6.6) demonstrated that 15m was the most appropriate transect length for surveys of blacklip abalone.

Regardless of the algorithm used, when coordinates are generated for 15m transects with the separation applied here, the largest sample that can be generated comprises 27 or 28 replicates (4.3% to 4.4% of total site area). Although this intensity should be sufficient for many applications, should larger samples be required to constrain variance, then it may be necessary to reduce the size of spatial exclusion zones between transects. This in turn, may require more care to be taken on the part of the researcher when navigating during surveys, with a subsequent loss of efficiency.

If only a small increase in sampling intensity is required, then the use of semicircular rather than circular sites may provide a solution. The benefits to be gained from such an arrangement are twofold. Firstly, where a “gap” in the site of 90^o or more is introduced, then exclusion zones that fall in this sector do not interfere with the placement of neighbouring transects (which is not the case for fully circular sites). Secondly, whereas a circular site with 5^o angular resolution has 72 possible bearings along which transects may be oriented, a semicircular site will have 37 (i.e. ½ x 72 + 1). However, although the use of semicircular sites can improve the intensity with which an area can be sampled, the actual number of replicates than can be accommodated is obviously smaller than if a fully circular site were used.

An alternative option would be to impose minimum separation distances that are *closest* to the desired exclusion distance permitted by the 5^o angular resolution (as opposed to the nearest distance equal to *or greater* than that desired, as was the case here). In addition, by assuming that the transect lies to one side of the radius (rather than straddling it), and calculating exact separation distances (i.e. eliminating the simplifying assumptions used in this study), a slightly greater maximum sample size could also be achieved.

Should the above solutions prove either unsuitable or inadequate, then 15m radial transects must be considered unsuitable for the task. In such cases, the only alternatives are use a different transect length, to employ an altogether different sampling technique.

Finally, although this work has been primarily focussed on the secondary spatial bias introduced when generating radial transect coordinates, a far greater source of spatial bias (particularly for longer transects), is that inherent near the edge of the site. Should this introduce substantial *statistical* bias into estimates of abundance and error, then either this must either be accounted for statistically (e.g. by recording the position along the radius of abalone encountered and applying the formula for stratified sampling), or the technique must be deemed unsuitable for the purpose. Given however, that any deviations from representative distribution of sampling effort generally occur over relatively narrow annuli, each of which covers an increasingly disparate area with distance from the centre of the site, statistical bias is less likely to present a problem than if similar deviations from representative sampling were concentrated in a relatively small block.

An Excel spreadsheet macro (See Appendix on enclosed CD-ROM: MACRO) has been developed to automate the generation of bearings and start distances to ensure replicates are fully randomised within each site.

6. Field Evaluation of the Modified Radial Transect Method

6.1. Comparison of surface-supply vs SCUBA for transect surveys

Prior to undertaking a detailed field study using the modified radial transect method, initial field trials were conducted to determine whether the type of air source used (SSBA or SCUBA) affected diver efficiency. Abalone research in Tasmania, like commercial abalone fishing, is generally conducted using surface-supplied air (SSBA or hookah). This requires that divers are attached to an air supply at the surface, via a floating hose, which also serves as a safety line. The hoses are relatively thick and have a tendency to create drag (particularly in current), and to foul in the kelps *Macrocystis pyrifera*, *Durvillaea potatorum* and to a lesser extent, *Phyllospora comosa*. During a field trial at a site with both thick kelp (predominantly *D. potatorum*) and moderate current, these effects were evident. A comparative study was then designed in which divers surveyed strip transects using both SCUBA and SSBA equipment. The design was orthogonal with two treatments (SSBA, SCUBA) and three divers. The study was conducted at two sites, however for logistical reasons, it was not possible to use the same divers at each site, and so separate analyses were performed.

No significant difference in the efficiency of operation could be determined between the two forms of air supply, or between divers. Consequently, field survey operations were primarily conducted using SSBA, although SCUBA was employed to a lesser extent when appropriate.

6.2. Field validation of the modified radial transect method

Overview of field experiments

A multifaceted experiment was conducted to assess the validity and practicality of monitoring abalone stocks using the modified radial transect technique, in comparison to the more conventional parallel transect arrangement. This research had the following six objectives:

1. To test the statistical performance of radial transects, in comparison to conventional parallel transects, in terms of density estimation and precision;

2. To test the sensitivity of the radial method to uneven spatial coverage of sampling effort by determining the effect of radial transect length on statistical performance;

3. To determine the optimal sampling parameters (particularly transect length and sample size) for blacklip abalone surveys;

4. To determine the likely minimum detectable differences of surveys;

5. To determine the relative efficiency of radial and parallel transects through cost-benefit analysis;

6. To quantify and compare serial autocorrelation between replicate transects for both radial and parallel samples

6.2.1. Methods

6.2.1.1.Description of sites used for detailed field validation

Abalone abundance data was collected using both radial and parallel transect methods from three sites in south-eastern Tasmania: Betsey Island (43.044°S, 147.4841°E), George III Rock (43.5095°S, 146.9822°E) and Black Reef (43.5376°S, 146.9699°E)[4] (Figure 13), between March and June, 2002. These sites were selected to encompass the range of abalone densities likely to be encountered throughout the Tasmanian blacklip abalone fishery. The benthic topography at all sites was of low to moderate profile (generally <2m), however at a smaller scale, was also relatively complex, with many cracks and crevices.

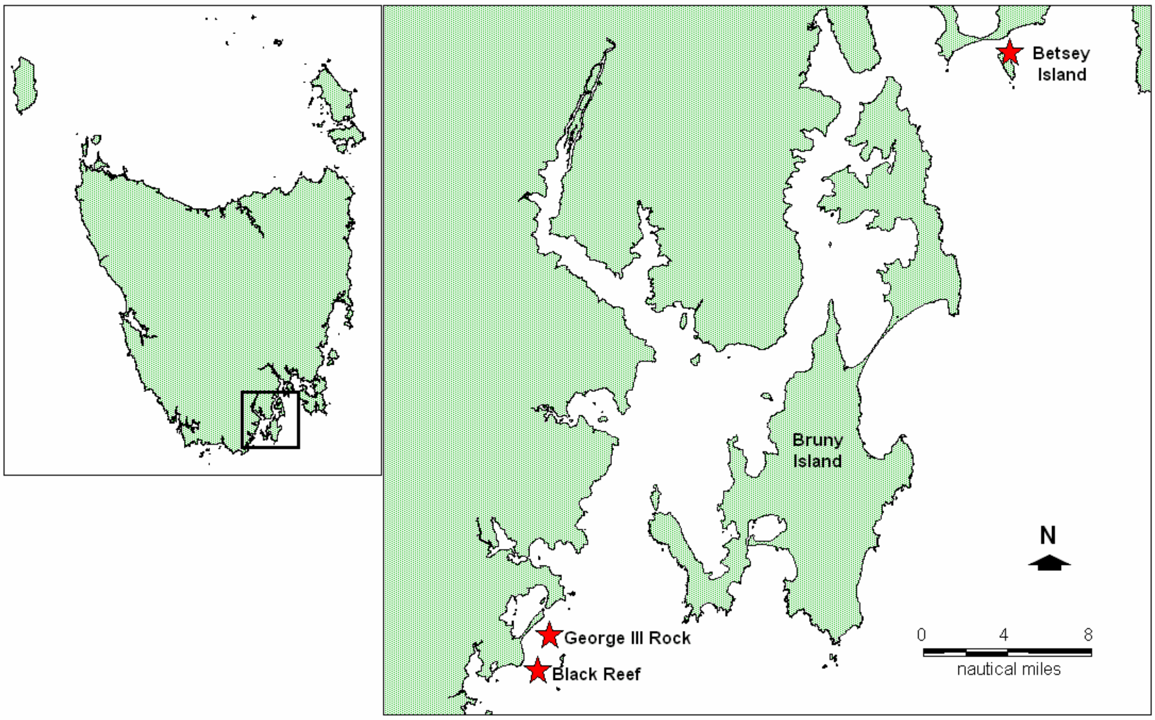

Figure 13. *Map of the three locations used for the initial intensive comparative sampling experiments. George III Rock is in an area that the Tasmanian Abalone Industry has agreed not to fish. Black Reef is part of the Actaeon reef complex, an extremely productive area in the abalone fishery, and Betsy Island is a convenient lower density South-East Coast location for blacklip abalone.*

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[4] Map datum AGD66

In southern Tasmania, swell comes predominantly from a south-westerly direction, although southerly and westerly swells are also relatively common. The site at Betsey Island is situated off the north-eastern corner of the island, at the northern end of Storm Bay, and as such is protected from swells to some degree. However large swells can wrap around Betsey Island to such an extent that surf occasionally breaks adjacent to the site. Depth at the site ranges from around five to 12 metres (Figure 14). Algal density here is moderate to high, and mostly comprises a diverse mixture of low phaeophytes and rhodophytes. The density of abalone in this area is relatively low compared to other commercially fished sites, although sufficient to attract occasional commercial fishing effort.

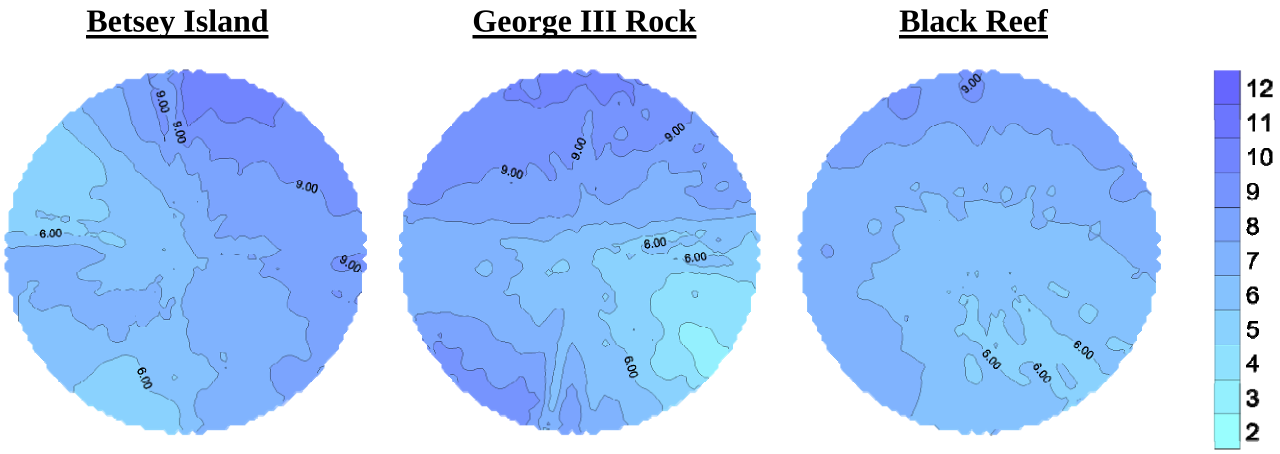

Figure 14. *Depth profiles of the three study sites used to compare the performance of radial and parallel transects. Contours were produced by Kriging, smoothed over a linear distance of around five metres in each direction. As such, small-scale variation and localised depth extremes are not shown. Depth is expressed in metres.*

The George III Rock site is exposed to the south, but far less so to the west (although large south-westerly swells may wrap around the adjacent coastline and arrive here from a southerly direction) (Figure 13). The site ranges in depth from around three to eleven metres (Figure 14). Shallower than six metres, there is almost complete coverage of *D. potatorum*, and from six to nine metres of *P. comosa*. Below the kelp canopy, non-geniculate coralline algal species dominate. At the deepest, northern edges of the site, the algal cover becomes a little lighter, with a light to moderate canopy of *M. pinnatifida*. This site was closed to abalone fishing in April 1984, and apart from a fish down experiment conducted there in 1987 (Prince 1989e), no legal abalone fishing has occurred at the site since that time.

The site at Black Reef is situated on the north side of the reef (which breaks the surface at low tide), and as such receives some, albeit minor protection from southerly swells. It is also somewhat protected to the west (again, south-westerly swells tend to wrap around the coast here such that they actually approach approximately from the south). Despite the limited protection provided by the reef, the power of the swells frequently encountered in this region is such that the site may be considered very exposed. Depth at the site ranges from around six to nine metres (Figure 14). *D. potatorum*, is sparsely distributed above around eight metres, with *P. comosa* and *M. pyrifera* distributed (also sparsely) below this depth, although the zonation between the algal types is not nearly as strong here as at the George III Rock site. There is a moderate to high coverage of non-geniculate coralline algae throughout the site.

The reef complexes around and including Black Reef are the most heavily fished in the state (Tarbath et al. 2004), and quite possibly the world. An indication of the fishing intensity around this area is that commercial abalone divers were encountered on and around the site every day that sampling was undertaken; occasionally, divers were even encountered underwater as their fishing path crossed directly in front of that of the survey divers. For this reason, it was originally expected that *H. rubra* density would be lower at Black Reef than at George III Rock, and it was on this basis that the site was selected. It was later determined however, that the abalone were more dense at this site than at the nearby unfished site (although the overwhelming majority of abalone here were below the legal minimum size limit).

6.2.1.2.Field data collection

At each of the three sites, radial transect data was collected from circular areas of 55m radius. Transects were 50m x 1m in size, and were oriented radially from the centre of the site in 5^o increments, giving 72 (pseudo-)replicates at each site. Data were recorded as the number of emergent *H. rubra* encountered in contiguous 5m sections along each transect, and no abalone were removed from the substratum or measured. This intensive field sampling provided the baseline dataset for subsequent simulations.

Each transect started 5m from the centre of the site, and as such the central area of all sites was not sampled. This was done to speed the surveys, since overlap of transect paths within this $78.5m^2$ area would have meant it was sampled with $360m^2$ of sampling effort, which was considered a waste of resources. As this unsurveyed section represents less than 1% of the total area of the site, its omission was not considered likely to adversely affect results.

Before commencing the survey, divers used 1m long poles to measure from their left armpit to some point on their outstretched right hand. The point at which the end of the rule touched the right hand was noted, and subsequently used to estimate the width of each transect. Only very occasionally did divers choose to carry a 1m measuring device while they conducted the surveys. The decision rule employed during surveys was that if any part of an abalone was found directly under the transect line, then it was included in the count; and if there was reasonable doubt as to whether an abalone was inside or outside the 1m wide swathe at the other side of the transect strip (as determined from the outstretched hand), then it was excluded. All divers worked to the same side (the right) of the transect lines. At the beginning and end of each transect and at each 5m mark along the transects, divers were instructed to pull their transect lines tight to ensure that each section extended for the full five metres.

For logistical reasons not all divers conducted surveys at all sites. Of the pool of five divers used, all five were involved in the radial survey at Betsey Island, four at George III Rock, and only two at Black Reef. Only one diver participated in radial surveys at all three sites.

Each site was sampled over consecutive days: three days at Betsey Island and four days at both George III Rock and Black Reef. Each diver was allocated a sector of the site, and undertook all of the sampling therein. This strategy was followed in favour of one of random interspersion of diver effort, since differences in diver effectiveness (if these existed) may have otherwise masked serial autocorrelation had such a strategy been pursued.

Conventional parallel strip transect surveys were also conducted at the same sites, as soon as practicable (within a week Betsey Island and George III Rock) either following, or in the case of Black Reef, prior to, the radial surveys. However large swells at the Black Reef site meant that the surveys here were separated by about three weeks. The duration of each parallel survey was kept to a minimum, with no individual sample taking more than seven days from commencement to completion. The same pair of divers was used at all sites for collection of this sample. Both of these divers had participated in the radial transect surveys at the Betsey Island and George III Rock sites, but neither was involved in the radial sampling at Black Reef. At the three sites, each diver was to sample ten replicate 20m long transects and five replicate transects of 30m and 40m length (thus a total of 40 parallel transects were to be sampled at each site). The original intention had been to sample five replicate 10m and 20m transects, however the 10m transects were extended to 20m to increase the size of the dataset available for Monte Carlo sub-sampling. Each transect was 1m wide, and abundance data was recorded per 5m section along the transect.

To facilitate navigation around the site, two reference axes were laid parallel to each other, 40m apart, and 20m from an imaginary line bisecting the circular radial transect site. Parallel transects were oriented perpendicular to these (for ease of communication, the direction parallel to these axes will be referred to here as the *y* direction, and that parallel to the transects as the *x* direction). The reference lines were marked every 2.5m, which was the *y* axis resolution. The same floating transect lines which had been used for the radial surveys were also used for the parallel surveys, and transect widths were similarly estimated. The transect lines were marked every 5m, and this defined the *x* axis resolution. Thus, parallel transects could be positioned at 2.5m intervals in the *y* direction and 5m intervals in the *x* direction. Negative and positive directions were arbitrarily assigned in both directions. All transects were sampled on the same side of the rope (the positive direction).

At the Betsey Island site, a minimum separation of 1.5m was maintained between parallel transects (i.e. 2.5m minus the 1m occupied by the transect), however the experience at this site was that the risk existed for spatial overlap of transect paths due to navigational error on behalf of the divers. As a result, a separation distance of 4m was imposed at the other two sites. A minimum distance of 5m separated collinear transects at all sites.

Because of the unusual shape of the sites, and problems associated with evenly distributing sampling effort within one transect length of the site edges (Underwood 1997b), *pp*.43-

44), a compromise was made between under-sampling near the edges, and sampling beyond the bounds of the radial site. This was that the centre of each parallel transect was confined within the radial site, but up to half of each transect could protrude beyond this boundary. Accordingly, a small proportion of the parallel transect effort at each site was applied beyond the boundaries of the circular site defined by the radial transects (Figure 15). There was no obvious distinction between habitat type or abalone distribution inside and outside the radial site boundaries at any of the sites.

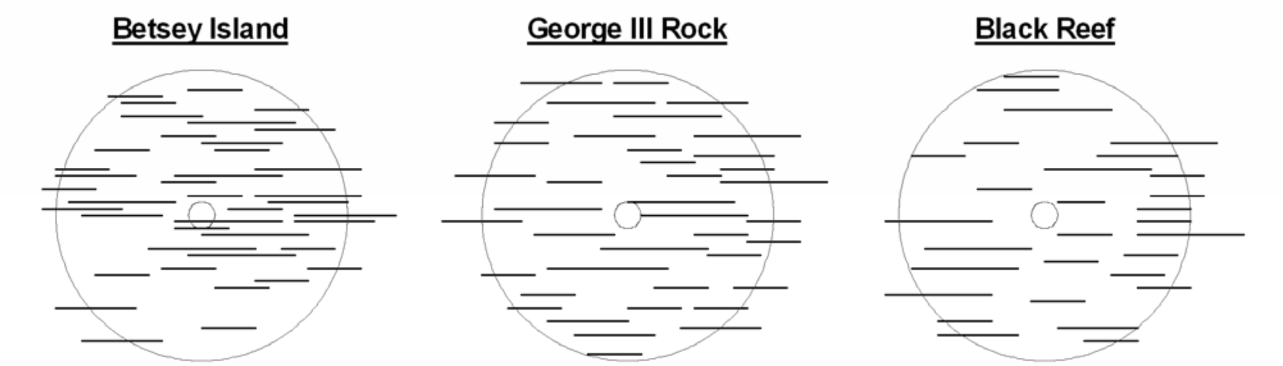

Figure 15. *Schematic diagram showing the spatial distribution of parallel transects, relative to the area sampled using the radial technique. The parallel survey at the Black Reef site could not be completed, due to an extended period of heavy swell. At the George III Rock site, an error in transcribing coordinates on the diver's data sheet meant that two 40m transects theoretically followed the same path for 35m of their length.*

The coordinates of each position with 5m resolution in the *x* direction, and 2.5m resolution in the *y* direction, were calculated, and these were selected at random for positioning the central points of transects. Where coordinates were selected such that the separation of transects was not achieved, then these were rejected and the process repeated until a suitable pair were selected.

At Black Reef, where the parallel survey preceded the radial sampling, logistical difficulties prevented completion of this sample prior to the radial sampling being undertaken. However, after completion of the radial sample, a sustained period of heavy swell was experienced, which prevented transect operations at the site for several months. Eventually, because of the time that had elapsed, completion of the parallel sample was abandoned. As such, only 29 parallel transects were sampled at this site (Figure 15).

At the George III Rock site, an error in coordinate transcription led to two of the 40m transects overlapping for 35m of their length (assuming that navigation was accurate). The data for the overlapping sections of the two transects, although not identical, was very similar. As such, only data from one of the overlapping sections was used for estimating precision, density or power. Analysis of this dataset was undertaken using both a Monte Carlo sub-sampling routine, and in the case of 40m transects, a direct comparison.

6.3. Precision and concordance of density estimates from radial and parallel transects: field validation

A Monte Carlo routine was used to sub-sample the datasets generated by both radial and parallel surveys, in order to test the accuracy and precision of these methods for 1m wide transects of 10m, 20m, 30m and 40m length. One of the primary purposes of this study was to test the validity of radial transect sampling, and the practical performance of the algorithm used to facilitate this. Accordingly, the decision was made to sub-sample the radial dataset without replacement, thereby maintaining the patterns of secondary spatial bias associated with the allocation of sample units inherent in this technique (Section 5.3.2.2). For consistency, a similar strategy of sampling without replacement was also applied to sub-samples taken from the parallel transect data. To avoid confusion, transects to which the data relate (i.e. those surveyed in the field), will generally be referred to here as “data elements” rather than transects.

The parallel sampling routine was restricted such that only one section from any data element could be sub-sampled during a single sampling iteration. For example if the subject of interest was the performance of 10m transects, only a single 10m section from any one data element could contribute to a particular Monte Carlo-generated sample, even where the data elements which were being sampled related to transects of 30 to 40 metres length. All data elements had equal probability of selection during any iteration, regardless of length. Because physical spacing between data elements was imposed during the actual surveys, no further spatial exclusion was imposed during Monte Carlo sub-sampling of this dataset.

For samples that are drawn without replacement, there is an inherent downward bias on standard error for sample sizes in excess of $n/2$ (where n represents the entire population from which samples are being drawn) (Bros and Cowell 1987, Manly 1992). Beyond this limit, each pair of samples must contain common elements, leading to a downward bias in sample variance. Although this was not strictly the case in this application, as individual elements of the dataset were further sub-sampled along their length (*i.e.* where the sample unit length being investigated was shorter than that of the data element), a conservative approach was nevertheless taken, and an upper limit of $n/2$ was placed on the size of samples drawn from the dataset.

Unlike the case of the parallel transect dataset, no spatial exclusion had been imposed during the collection of the radial transect data, beyond the 5^o resolution of transect divergence. In order, therefore, to realistically simulate the patterns of spatial distribution of radial sample units and any biases inherent therein, zones of exclusion around each sample unit were incorporated in the Monte Carlo sampling routine. These exclusion regions were the same as those described in Section 5.3 of this report, and were of sufficient distance and angle as would be imposed during field sampling in order to prevent spatial overlap of neighbouring transects due to navigational imprecision on behalf of the survey divers (e.g. 20^o minimum separation between transects in outer annuli, and a comparable distance between those in annuli closer to the centre).

The maximum sampling intensity that could be applied to the radial transect dataset was about 3 to 5% of the total area of the site, due to the enforced (virtual) spatial separation between sample units specified in the sampling algorithm. Because actual radial transect data collection was applied with a sampling intensity of around 37%, it was unnecessary to limit the maximum sample size to being half the size of the statistical population. However, in order ensure equity in the comparison of density estimates generated by sub-sampling the two data sets (particularly in terms of precision), the radial sample sizes selected for the comparison were the same as those that constrained the parallel samples.

Ten thousand estimates of abalone density were generated for each combination of transect length, survey type and site. Precision was measured as the standard error of these 10000 estimates (calculated directly from their standard deviation). Accuracy was assessed both by concordance between the means of the estimates generated by the two sampling methods, and by comparison to a precise and unbiased density estimate calculated by applying the formula for stratified sampling (Krebs 1999) (Box 1), where the strata were the concentric annuli defined by the 5m long radial transect sections.

Box 1. Stratified sampling formula applied to determine an unbiased estimate the density of *H. rubra* within radial transect sites, from the data collected during the radial transect surveys.

The estimated density across the entire site, $\bar{x}_{ST}$, was given by:

$$\bar{x}_{ST} = \frac{{}^{L}\Sigma_{h=1} \, [N_h \; \bar{x}_h]}{N}$$

Where: N_h = size of stratum h,

h = stratum number

L = total number of strata

$\bar{x}_h$ = mean density in stratum h

N = total number of sample units used across all strata

Estimation of the mean density through stratification was based solely on the data collected during the radial transect survey. Because the curvature of the concentric annuli that constitute the strata becomes more pronounced with increasing proximity to the centre of the site, it was difficult to reliably apportion the parallel transect data to specific annular strata. Imprecise navigation on the part of the survey divers, which is likely to be far more pronounced lateral to, than along the transect (given that the transects were pulled tight every five metres), further confounds the appropriate allocation of parallel sampling effort, but does not present a problem for the radial data.

The unbiased density estimate derived from the radial transect survey data was used to provide a benchmark estimate of abundance against which to compare the parallel and Monte Carlo generated radial transect estimates. This was deemed appropriate for several reasons. Firstly, it is widely held that area-based samples generally give unbiased estimates of abundance. As such, a precise estimate generated using data obtained from an area-based sample, such as those collected during the radial survey, should provide an accurate reflection of abundance against which to compare the performance of the different sampling protocols. This is supported by the results of Hart et al. (1997b) and Prince (1989c), who both reported general concordance between area-based survey estimates of *H. rubra* abundance, and other estimators also considered to be accurate. Given this, and the intensity and relatively even dispersion of sampling effort achieved with this method, the radial dataset is assumed to be representative of the abundance of abalone within each strata (and thus across the site when the strata-wise means are appropriately weighted). Furthermore, the intensity with which the radial transect data were collected ensures that the estimate thus generated is also precise. Finally, if inherent biases do exist in estimates based on transect surveys (apart from those introduced through the spatial biases associated with radial sampling), then these should be equivalent for all estimates generated here, given that the techniques differed only in the spatial arrangement of sample units, and that spatial bias was removed from the reference estimate through stratification. If statistical biases impinge upon estimates generated by radial sampling, they do so due to the spatial bias inherent in the positional allocation of sample units generated by the radial sampling algorithm (i.e. the phenomena being tested), and not due to some inherent property of the underlying dataset upon which the samples were based.

Assessment of transect performance was repeated for sub-samples taken both from the complete parallel dataset, and from the subset of parallel data elements relating to those positions which lay within the boundaries of the radial transect sites. This was done to insure against the (albeit unlikely) possibility that the distribution and density of abalone immediately beyond the edge of (two sides of) the radial site differed substantially.

In the parallel transect datasets, the number of data elements relating to the longest (i.e. 40m) transects was relatively small (only ten at most). This was particularly true of the “constrained” parallel data sets, from which it was not possible to generate valid sub-samples with more than three members. In order to maximise the information that could be gleaned from the 40m parallel transect data therefore, a single mean and standard error estimate (i.e. $sn^{-\frac{1}{2}}$) was calculated from the complete 40m transect dataset at each site. For the sake of consistency in the radial-parallel transect comparison, this standard error estimate was compared to the average of the 10000 separate sample-wise standard deviation estimates (again, $sn^{-\frac{1}{2}}$), generated from Monte Carlo sampling of the radial dataset, and not the actual standard deviation of estimated means as was used for the other comparisons.

6.3.1. Results and discussion

Density estimates calculated using both radial and parallel methods are generally in agreement with the estimate of "true" density, with the exception of longer parallel transects at George III Rock (Figure 16). This discrepancy most likely arises from the smaller sample size collected during the original parallel transect survey yielding a less precise estimate of density. Estimates generated by subsequently sub-sampling this dataset therefore, would be biased toward this imprecise value.

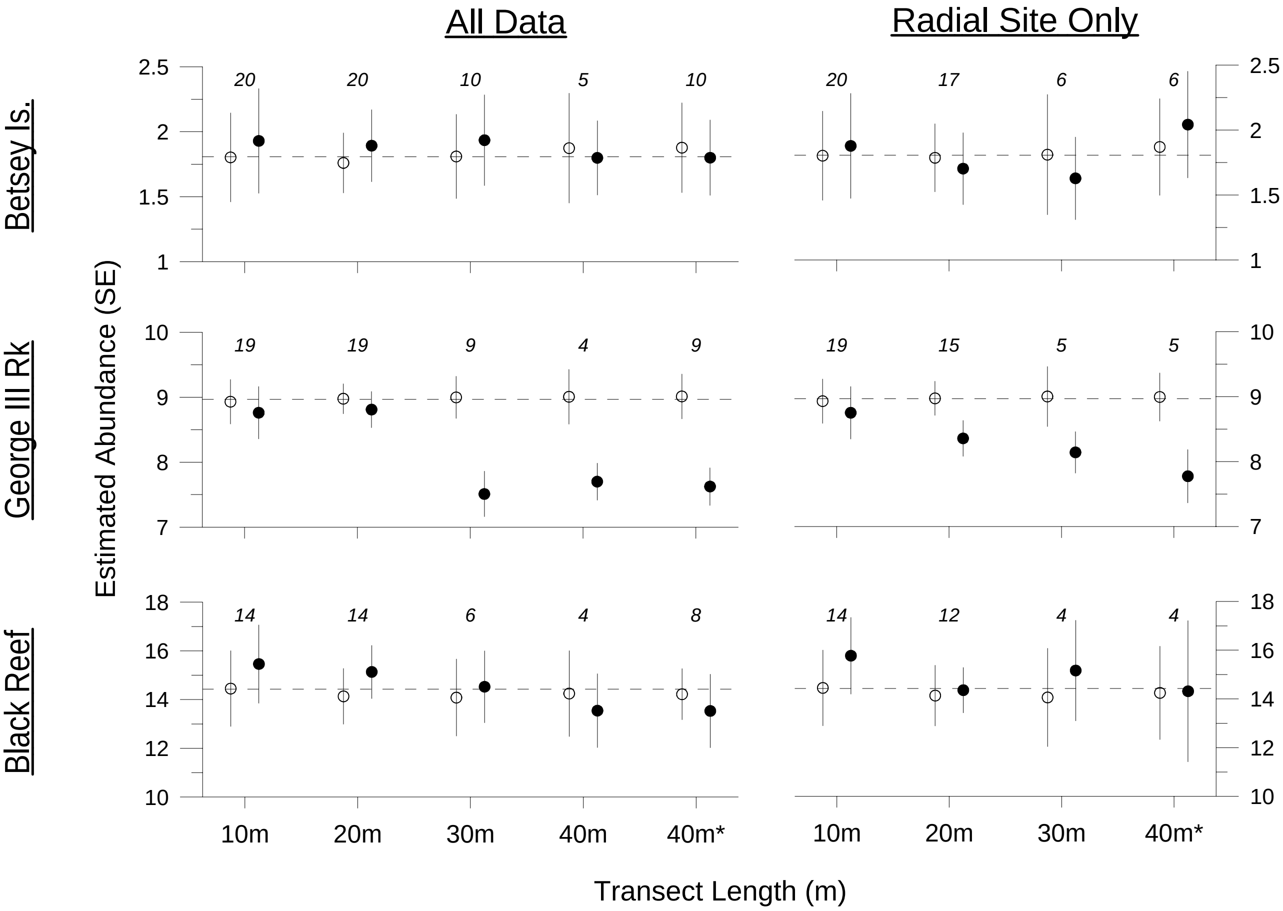

Figure 16. *Mean density estimates (number of abalone per 10m²) generated from 10000 Monte Carlo iterations of both radial (o) and parallel (•) transects. The dashed line (- - - -) on each plot is the estimated "true" density of abalone at that site, calculated by taking the stratified mean of the radial transect data. Error bars are the standard error of the 10000 mean density estimates, except for data points marked "40m*", which for radial transects represent the mean of the 10000 individual sample wise standard error estimate* ($sn^{-½}$*), and for parallel transects the standard error estimate for the single 40m sample comprising all transects of that length. The numbers in italics above the data points are the sample sizes (i.e. number of replicates) to which these data relate.*

There appears to be a downward trend in estimates of abalone abundance with increasing parallel transect length, particularly for the George III Rock site (for data points constrained to the area bounded by the radial transect site), and to a lesser extent for the Black Reef site (for the entire dataset). This pattern is most likely the result of the 40m transects falling by chance, in areas with lower abalone density during the initial survey (particularly at the George III Rock site), and having increasing influence on the results as the shorter, more representative data elements are eliminated from the analysis.

Alternative interpretations of the apparent inaccuracy of the parallel transects at the George III Rock site can however, be hypothesised. These include that transects, either radial or parallel, do not provide an accurate reflection of the density of abalone at this site; that conditions may have varied between the radial and parallel surveys to a such an extent that results were affected; or that the divers who conducted the parallel surveys may have differed in their effectiveness from those that were involved in the radial transect survey.

A range of conditions were experienced at both the George III Rock and Black Reef sites throughout the course of both the radial and parallel transect surveys, and at both of these sites (but particularly at Black Reef), swell often made survey conditions difficult. However, no substantial difference was noted in the conditions under which the two types of survey were conducted at either of these sites. At Black Reef, several weeks elapsed between the radial and parallel surveys being conducted, however this was not the case at George III Rock, where the estimates made by the two types of survey results are most disparate. Differences in conditions or in the distribution of abalone in response to conditions, are therefore unlikely to explain the difference in the estimates at George III Rock.

Because it was deemed more important for the purposes of this study to detect serial correlation than diver differences, transect bearings were not allocated to divers in either a random or representative manner. As such, no formal analysis can be conducted on the radial dataset to test for a diver effect. However, there are several factors which suggest that the disparity at George III Rock is unlikely to be due to an operator effect. Two small (unpublished) investigations involving one of the two divers that collected the parallel transect data, and the others that were involved in the radial transect surveys, revealed no significant difference between divers, and no observer effect was detected following analysis of the parallel transect data. Statistically significant diver differences have been reported however, for transect surveys of *H. rubra* in Victoria (Hart et al. 1997b, Gorfine et al. 1998). In the case of (Gorfine et al. 1998), a statistically significant diver effect was detected in the collection of annual survey data, but not during formal diver comparison trials. The difference related both to divers that apparently lacked diving aptitude, and to a very experienced former abalone diver. No difference was detected between the effectiveness of nine other divers involved in the Gorfine study, and in the case of the experienced diver, the result was confounded by spatial factors.

All participants in this study were experienced and capable divers, although one diver was generally more experienced and adept at finding abalone. This individual participated in radial transect surveys at all sites, including surveying around 60% of the radial transects at Black Reef. As no substantial difference between survey methods was apparent at either the Black Reef or Betsey Island sites, the apparent discrepancy in the George III Rock data is unlikely to be due to this diver's experience. Similarly, the two divers that were used to conduct the parallel transect surveys at all sites were also major contributors to the collection of the radial survey data at both Betsey Island and George III Rock. As such, a substantial difference in diver performance is unlikely.

Arguably the most notable feature of the results is the strong concordance between estimates generated using the Monte Carlo radial sampling algorithm, and the estimates of "true" density derived using stratification (Figure 16). This indicates that no additional statistical bias is introduced into the density estimated by the biases inherent in the radial transect samples, even for transects of 40m length, where the spatial biases are most marked (Figure 16). For shorter transects, where sampling effort is distributed relatively evenly throughout the site, this result is unsurprising given that it is unlikely that the narrow annular patterns that characterise the spatial bias inherent in the radial sampling technique would be reflected in patterns of abalone distribution (Figure 17). For long transects of 30 to 40 metres, however, where the bands of spatial bias are far broader, the result is particularly encouraging, and demonstrates the robustness of such estimates to the non-random distribution of sampling effort. Prudence dictates however, that the absence of statistical bias in the result for long transects here is not taken as universally true, and further testing is recommended in situations were it is conceivable that patterns of density may coincide with those of spatial bias in the method. An example of such a situation may be where the centre of the site is placed at the pinnacle of a domed reef where the distribution of benthic organisms may follow approximately annular depth contours.

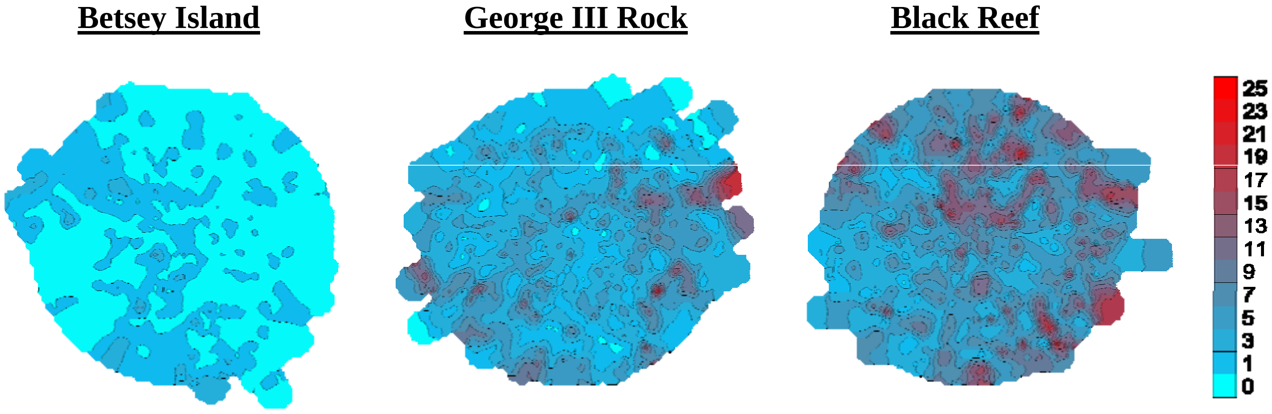

Figure 17. *Density profiles of* H. rubra *at the three study sites, determined from both radial and parallel transect counts. Contours were produced by Kriging, and are smoothed over a linear distance of around five metres in each direction. As such, small-scale variation and localised extremes of abalone density are not shown, except at the extremities of projecting points (which represent positions where transects were positioned beyond the boundaries of the radial sites), where there are few neighbouring data points to average across. Density is expressed in abalone per 10m^2.*

6.4. Effect of radial transect length on statistical performance

The severity of the spatial bias inherent in radial transect sampling varies with the length of the transect, and its ratio to the radius of the site (Section 5.2). A degree of spatial bias in the intensity of sampling effort is ubiquitous across all annuli, however in the modified method developed in this project, this bias is relatively small, and oscillates with diminishing amplitude across each concentric annulus throughout much of the site. At the outer region of the site however, in cases where transect traverse multiple annuli, this oscillation ceases, and is replaced instead by a stepwise diminution of sampling intensity. As a result, all but one of those annuli whose width is defined by the radial resolution (i.e. the resolution with which sample units are positioned along the radius), must be sampled at either greater or lower intensity than those occupying the rest of the site (Figure 8). For short transects, this band is narrow, and distributed in a disparate annular shape that is unlikely to reflect meso-scale (metres to hundreds of metres) biological or physical distributions, and as such is unlikely to be result in statistical bias. Where transects are relatively long however, this band is wide, and as such may conceivably capture some natural pattern. Furthermore, when the ratio of transect length to the site radius is relatively large, this band is concentrated over a smaller area and distance, further exacerbating the potential for statistical bias.

A secondary source of spatial bias exists that rises with increasing sampling intensity. This occurs because the capacity of annuli to accommodate further sampling differs between annuli, even where the allocation of sample units has been made on the basis of a theoretically sound probability function (Section 5.2). The variation in the capacity of annuli to accommodate sample unit arises in large part from the fact that prevention of spatial overlap of sample units is dependent on the length of the polygon formed by the proximal ends of contiguous sample units, which is a first order function, whereas even distribution of sampling effort is achieved on the basis of area, which is a second order function. This secondary bias varies with the length of transects (and radial resolution and length), and is exacerbated by the enforcement of artificial zones of separation between sample units to allow for imprecise navigation on the part of the surveyor.

6.4.1. Methods

When the performance of radial and parallel transects ranging in length from 10m to 40m was compared (Section 6.3), it appeared that radial transect sampling produced unbiased estimates abalone density. However, the intensity of sampling with the radial transects investigated was generally constrained by small size of the parallel transect dataset against which they were compared. As such the effect of increased sampling intensity on radial transects of various length remained to be quantified, as did the effect of increasing sample size on the precision of such estimates.

The sensitivity of radial transect sampling to sampling intensity and sample unit length was again tested by Monte Carlo sub-sampling of the intensive radial dataset used in previous investigations. This dataset was sub-sampled with increasing intensity, for sample units ranging in length from 5m to 40m. The mean density estimate from these samples was again compared to that of the unbiased estimate of "true" density obtained through annular stratification. Percentile confidence intervals about the mean estimates provide an indication of relative precision.

6.4.2. Results and Discussion

No substantial bias was apparent in any of the density estimates, irrespective of radial transect length or sampling intensity at any site (Figure 18). For transects greater than 10m at the Black Reef site however, the Monte Carlo sampling routine does appear to slightly underestimate the density of *H. rubra*. Although this bias is consistent across all sample sizes for all but 10m transects, its magnitude was, on average, less than 2% of the unbiased estimate. Considered in the context of the width of the 95 percentile confidence limits, such bias is negligible. The density estimates from the 40m radial transects at Betsey Island also appear to have a very slight but consistent inaccuracy associated, although the bias here is in the opposite direction. Again, the magnitude of the bias is negligible, being less than 4% of that of the unbiased estimate.

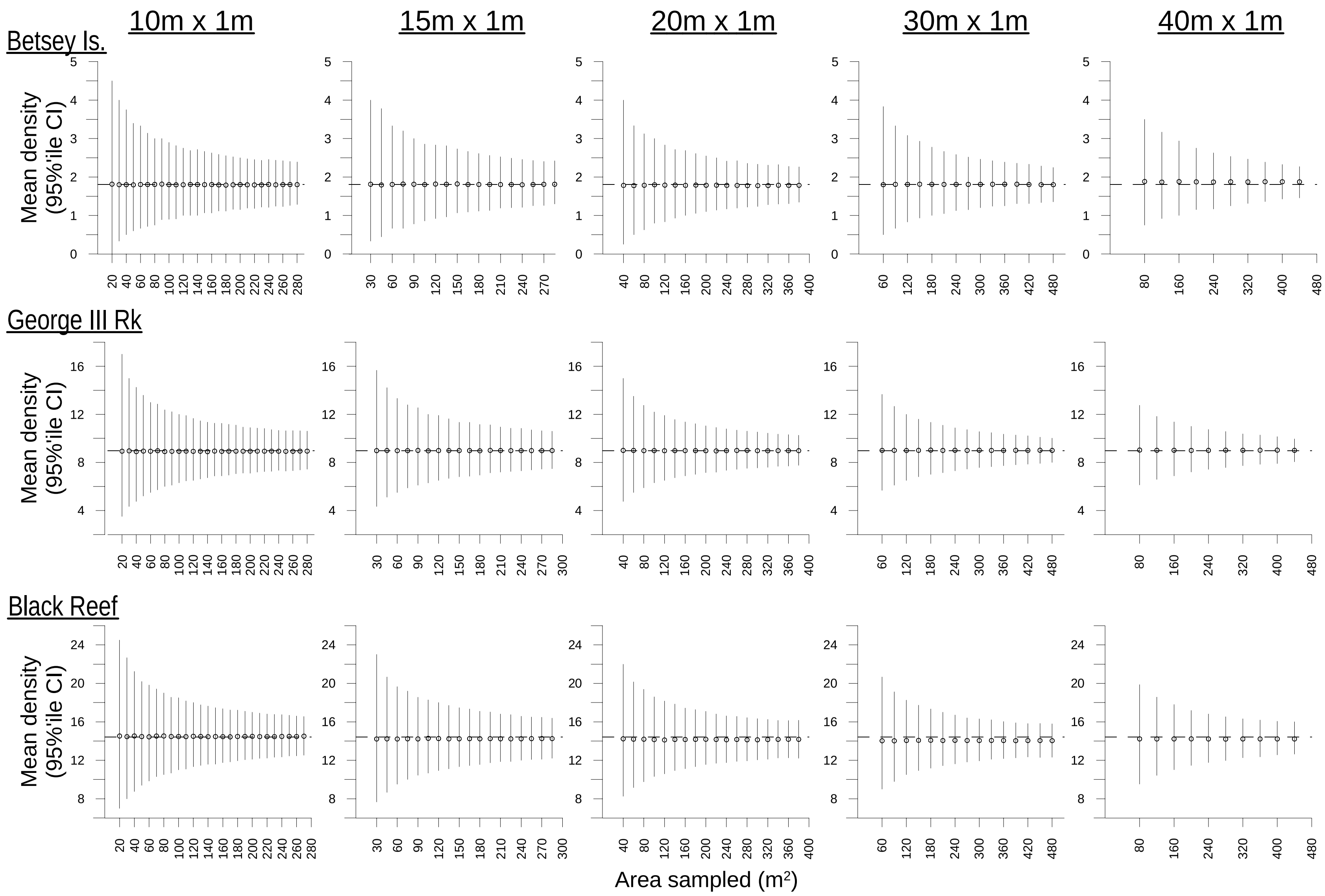

Figure 18. *Mean density estimates (abalone / 10m2), and 95 percentile confidence intervals, generated from 10000 Monte Carlo iterations, for 1m wide transects, ranging in length from 10m to 40m. The dashed line indicates the unbiased estimate of mean density at each site calculated through stratification.*

It should be noted that the radial transect sampling algorithm applied here has an additional element of associated spatial bias. Because the central sections of the each site used in this study were not sampled, sampling intensity could not be spread evenly throughout the rest of the site, but rather the annulus whose inner edge was one transect length from the centre of the site, was necessarily and systematically oversampled. This is unlikely to account for the bias detected at the Black Reef site, as this was consistent across a range of transect lengths, however it may (or may not) go some way to providing an explanation the bias detected when using 40m transects at Betsey Island.

That some statistical bias, however small, is apparent in density estimates generated with radial transects, is notable. Again, such biases, where present at all, are always likely to be small for shorter transects or where the ratio between transect length and site radius is small, given that in these cases the spatial bias is spread over a relatively dispersed and narrow annular pattern. Where the opposite is the case however (long transects and/or short site radii), it may be wise to consider the use of such radial protocols in relation to the likely detectable effect size that the survey is designed to detect. Where the detection of small effect size is expected (or hoped for), then further study of the performance of the protocol may be wise.

The Victorian radial transect application (Callan et al. 1995, Gorfine et al. 1998), uses transects which are long (30m) relative to the radius of the site (35m). As such, this technique may to be subject to somewhat larger biases than those detected here. Unfortunately however, the nature of the dataset collected in this study, and the inherent properties of the Victorian radial transect protocol, are such that valid assessment of this protocol cannot be achieved by the methods applied here, since sample-size is relatively inflexible (bound by 40^{o} increments), and comparison of sample unit length is spatially confounded (given that all transects start at points equidistant from the centre of the site). Such a comparison would be a useful exercise however, and could be achieved through computer simulation studies if simulated populations can be generated with realistic spatial distribution patterns.

Despite the very minor bias detected for some combinations of site and transect length, the estimates generated through the application of the radial sampling algorithm were fundamentally sound. As such, the modified radial transect method represents a viable and valid technique for assessing blacklip abalone abundance.

6.5. Assessing serial autocorrelation in radial and parallel transects

6.5.1. Methods

A fundamental requirement for valid estimation of statistical error, is that replicate sample units are independent. Where the value of one sample unit is dependent on the value of preceding or subsequent sample units, error is underestimated (and degrees of freedom overestimated), and the sample units are psuedoreplicates (the extent of the pseudoreplication being dependent on the degree of correlation between the data). For the modified radial transect arrangement to be accepted as providing valid estimates therefore, it is important that independence among replicate transects is assessed.

The presence and magnitude of serial spatial autocorrelation was assessed for both radial and parallel transects, again using a Monte Carlo algorithm to sample the datasets collected at the Betsey Island, George III Rock and Black Reef sites. At each site, and for both transect arrangements, the datasets were sub-sampled across a range of sample sizes (in the case of parallel transects, up to half the size of the dataset for the reasons described in Section 6.2.1.2).

For radial transects, spatial ordering for the test was done principally on the basis of the bearing along which the transect ran, however this was not possible for parallel transects, which were all aligned along common bearings. In the case of the latter, the data were treated as though the circular site had been bisected in the y direction (see Section 6.2.1.2), thereby separating it into two halves. Ordering was then made on the basis of position along the y-axis, in a clockwise manner around the site (i.e. down one half of the site, and then up the other). Although this may have resulted in a reduction in the sensitivity of the MSSD test for parallel transects (e.g. where transects on opposite halves of the site were closer than those on the same side), it was done both to make the tests for the two methods as analogous as possible, and because in the case of the parallel transects, any decision on ordering was necessarily somewhat arbitrary. For both methods, secondary ordering was done on the basis of distance from the centre of the site (the central point in the case of radial transects, and the centre line in the case of parallel transects).

The mean square successive difference (MSSD) test (von Neumann et al. 1941) was used to assess independence among replicates. Under the MSSD, the sum of the square of differences between successive measurements (δ^2) is compared to that of the residuals (s^2). If the replicates are independent, then the ratio of δ^2 to s^2 (denoted as η) should differ by a factor of two (Zar 1999). If successive replicates are correlated, then $\delta^2 < s^2$, and thus $\eta < 2$ (alternatively, $\eta > 2$ if successive replicates follow an alternating pattern).

A fundamental assumption of the MSSD is that of normality in the distribution of the variates (the successive differences), particularly where samples contain less than 20 (Young 1941) to 50 (Sokal and Rohlf 1995) elements. Because the upper limit on parallel sample sizes was constrained by the size of the dataset to fewer replicates than this, the assumption of normality could not be met. Accordingly, a distribution of the test statistic, η was calculated for each sample through a randomisation process (5000 iterations for each sample), and the percentile limits of this distribution used to determine significance. The significance levels reported are the proportion of significant left-tail results ($\alpha = 0.05$) from 1000 Monte Carlo iterations for each combination of transect type, length and site. The left-tailed test was used because it was deemed unlikely that abalone distribution would follow an ordered sequence (in which case, the right tail must be included).

The range of sample sizes that could be assessed for serial autocorrelation was somewhat restricted. Samples with fewer than six elements were deemed unsuitable for testing, as they contained insufficient replicates to produce the distributions against which the test statistic were compared[5]. Because a maximum of only ten 40m parallel transects were sampled at any site, the largest unbiased sample that could be repeatedly drawn was limited to ($n/2 =$) five or fewer replicates (Bros and Cowell 1987, Manly 1992). As such, 40m parallel transects could not be assessed. No more than 20 replicate 30m transects were surveyed at any site, which restricted the maximum sample size that could be assessed to ten or less. At the Black Reef site, where only 12 parallel transects longer than 30m were surveyed, only samples containing ($n/2 =$) six replicates could be assessed for transects with this arrangement. Separate assessments of autocorrelation levels among parallel transects were made both for those transects (or sections thereof) which lay wholly within the boundaries of the radial site, and for all transects.

6.5.2. Results and Discussion

A degree of serial spatial autocorrelation was detected at all sites, and exhibited a generally positive relationship with both sample size, and transect length (Figure 19). However, the rate at which the autocorrelation could be detected (which is a function of its magnitude relative to background variance), differed between the various sites and sampling schema.

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[5] For samples that contain five replicate transects, the maximum number of permutations that comprise the universe of the test statistic is ($5! =$) 120, whilst for a sample size of six it is ($6! =$) 720 and for seven is ($7! =$) 5040. However, if two or more replicates share the same value (i.e. the same number of abalone), fewer unique values of the test statistic η can be generated.

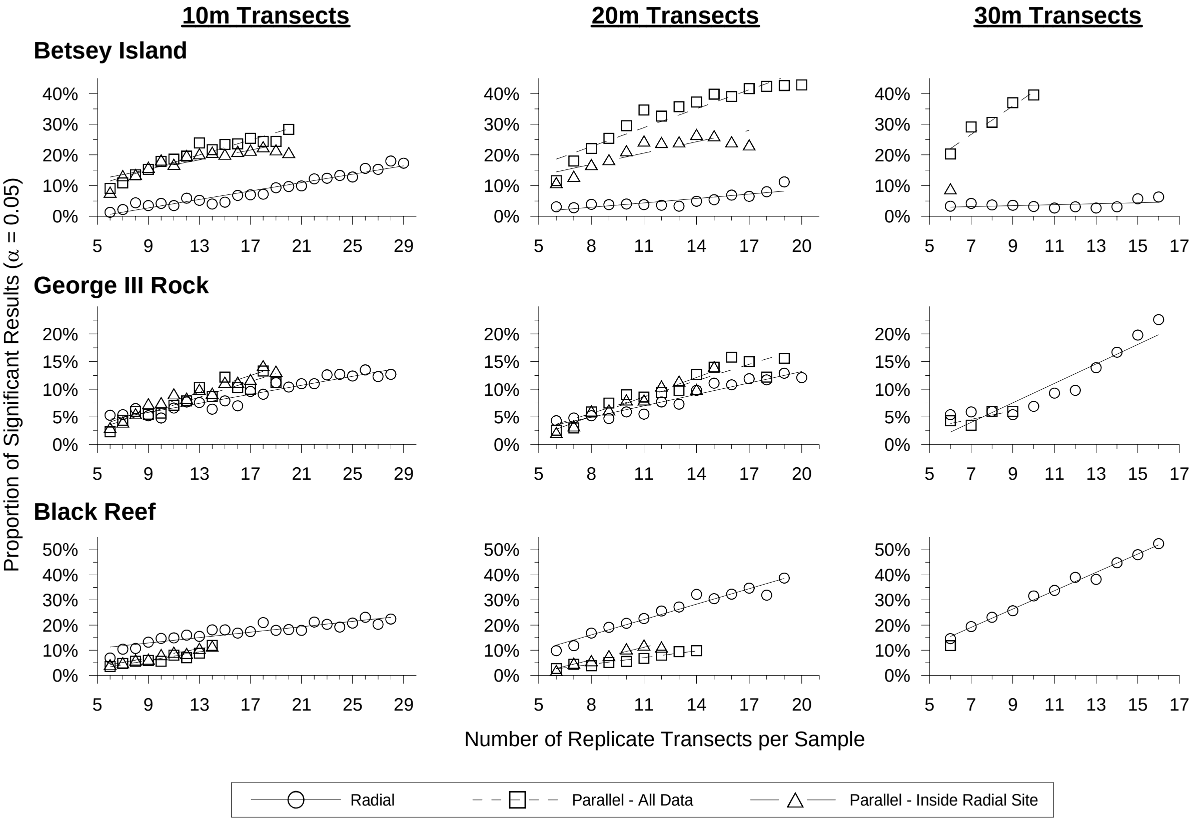

Figure 19 *Proportion of significant results ($\alpha = 0.05$) from left-tailed Mean Square Successive Difference tests for serial autocorrelation. Assessments of independence were made for radial and parallel transects of varying length, at each of the three survey sites. Although regression lines fitted to the data generally give inadequate descriptions of the trajectories (of the rates of significance with increasing sample size), they are included to provide a coarse indication of the general trends in the results.*

The limited size of the datasets relating to 30m parallel transects restricted the range of comparisons that could be made between the two methods. Nevertheless, it was apparent that the relative performance of these transects varied between sites. The effect of the extra length of these transects was less clear.

At the (low density) Betsey Island site, the rate at which significant correlation was detected for radial transect samples, only exceeded that expected by random chance when relatively large sample sizes (greater than around 15 or 16 replicates) were generated. By contrast, serial correlation amongst parallel transects at this site was detectable for all transect lengths examined, even in the smallest samples.

At the Black Reef site the rate at which significant correlations were detected was higher for radial transects (particularly those of 20m length), and exceeded 5% even for relatively small samples. Neither method clearly outperformed the other at the George III Rock site, where rates of significant results exceeded those that might be expected by chance, for larger samples obtained using both radial and parallel transect arrangements.

The greater extent of serial autocorrelation observed among parallel transects at Betsey Island might be explained, at least in part, by the smaller minimum distance imposed between these transects during data collection, relative to that at the other sites (i.e. assuming that navigation was precise, at least 1.5m separated transects at Betsey Island , as opposed to 4m at the other two sites) (Figure 15). Because abalone are non-randomly distributed, where transects are positioned in close proximity to each other, they are more likely to sample common densities than those spaced further apart. Furthermore, if navigation was not precise (as was suspected), some apparently "neighbouring" transects may have actually sampled the same physical space over a portion of their area.

The fundamental differences that exist in the way that the data were collected and analysed, complicate direct comparison of the relative extent of serial autocorrelation between radial and parallel methods. The intensity of parallel transect sampling was much lower than that of radial sampling at all sites, particularly at Black Reef where parallel sampling was incomplete. As a result, the average distance between the replicate data elements from which the sub-samples were drawn, is greater for parallel transects (despite the closer proximity of some individual replicate transects at the Betsey Island site). In the context of abalone surveys, serial autocorrelation reflects spatial patchiness. As the distance between transects decreases, correlation due to patchiness at small scales is reflected in the sampling, and is a function of sampling effort and not just sample unit arrangement.

These issues, considered in conjunction with the differing criteria for defining "neighbouring" transects described in Section 6.5.1, prevent more formal analyses of serial correlation among the two methods from being validly made. Accordingly, definitive conclusions of their relative sensitivities to serial autocorrelation are difficult to draw. Nevertheless, it can be concluded that data collected from transects distributed in a conventional parallel pattern were not, as a general rule, more "independent" than those distributed using the modified radial method. Moreover, there is no logical reason to believe that this should be the case as unlike those arranged in parallel, radial transects follow divergent paths. Pielou (1969) discussed patterns of aggregation in terms of intensity (strength of aggregation) and grain (the relative size of aggregations and distances between these). Where grain size is large, parallel transects are more likely to co-sample the mosaic pattern of these grains, whereas divergent radial transects are more likely sample independently. This was also the experience of Nash et al. (1995), who detected correlation between parallel transects, but not between collinear transects.

Regardless of the transect arrangement used, the power to detect serial autocorrelation in samples taken by either method is low, such that statistically significant correlations were found on less than 45% of occasions in all but one of the sampling schema investigated. This indicates that the extent of such correlation is also generally low for either method, relative to the natural variation between all transects.

6.6. Minimal detectable population change

6.6.1. Methods

The sensitivity of radial transect surveys for detecting population change was investigated in relation to transect length, area sampled, and statistical power and confidence. This work was again based on the data collected from the intensively sampled sites at Betsey Island, George III Rock and Black Reef. Average minimum detectable effect sizes were calculated for each site and transect length from 5000 paired *t*-tests on sub-samples generated using the "original" Monte Carlo sampling algorithm (Section 5.3.2).

The rates of Type I and II error were fixed under four scenarios $\alpha = \beta = 0.05$, $\alpha = \beta = 0.1$, $\alpha = 0.2$, $\beta = 0.1$ and $\alpha = \beta = 0.2$. It is widely held (Peterman 1990, Antcliffe 1992, Underwood 1993, Green 1994, Mapstone 1995, Buhl-Mortensen 1996, Keough and Mapstone 1997, Ortiz 2002, Underwood and Chapman 2003) that in the context of environmental or fisheries monitoring programmes, the importance of protecting against Type II error (the failure to detect a change where one exists) is as great, or greater, than that of protecting against Type I error (falsely concluding that there has been a change, when in fact, there has been none) (Toft and Shea 1983, Andrew and Mapstone 1987, Peterman 1990, Mapstone 1995, Buhl-Mortensen 1996, Underwood 1997a). It was on this basis that the convention of setting the rate of Type I error (α) to 5% was relaxed, and the rate of Type II error (β) was constrained.

Minimum detectable population change was expressed relative to the unbiased population estimate for each radial transect site. This was calculated using the formula for stratified sampling (Box 1). Transect lengths investigated ranged from 10m to 40m.

6.6.2. Results and Discussion

The relationship between minimum detectable population change and sample area (unsurprisingly) took the form of a negative power curve, initially falling rapidly but showing diminishing towards an asymptote of zero percent, as sample area increased (Figure 20 and Figure 21). There was a clear relationship between transect length and the minimum effect size that could be detected for a given total sample area at all sites and all levels of α and β considered. The relative strength of this relationship varied from site to site, but was strongest at the Black Reef and Betsey Island sites, and for smaller values of α and β.

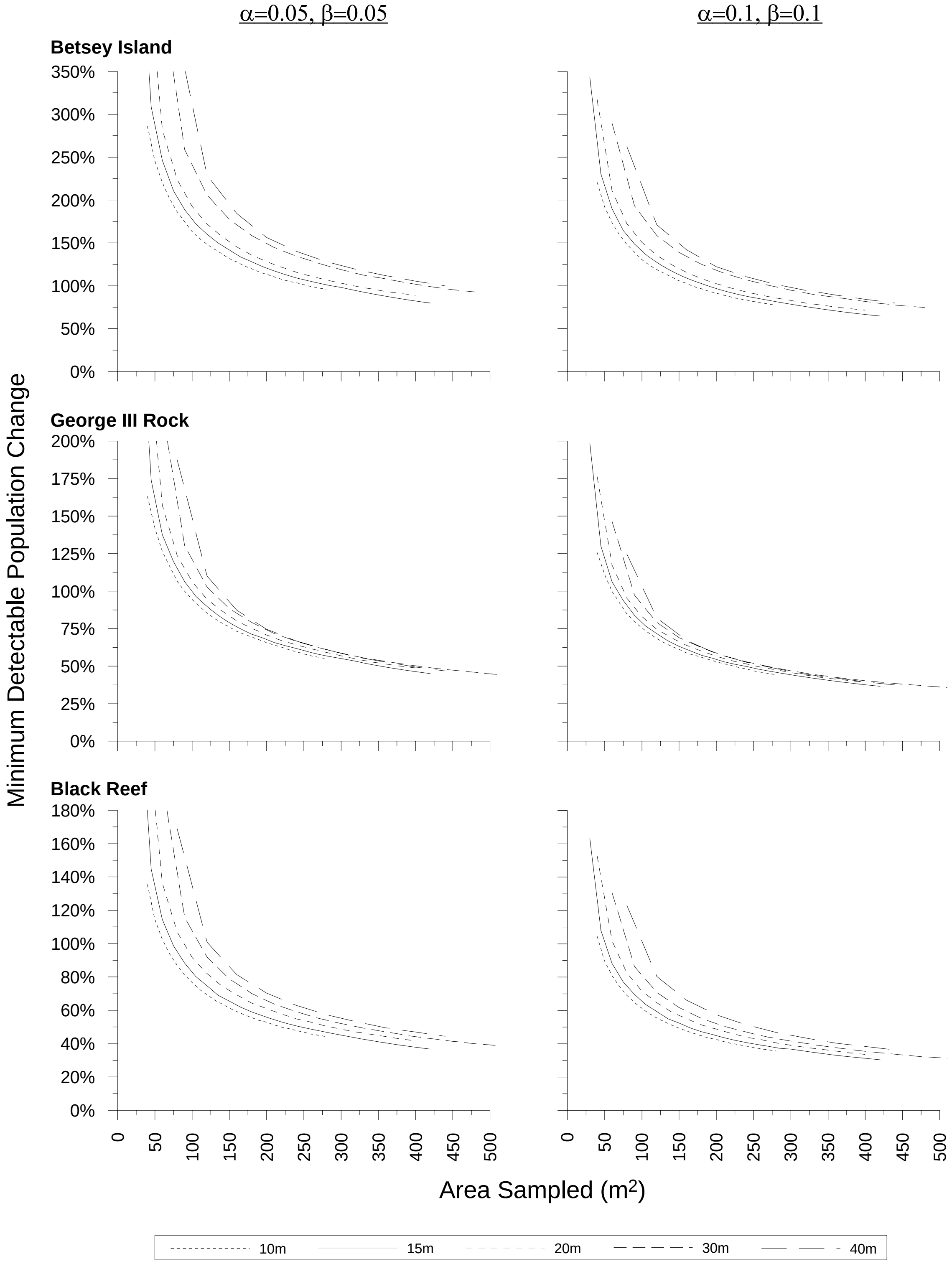

Figure 20. *Average minimum detectable effect size from 5000 paired t-tests on randomly drawn sub-samples from blacklip abalone surveys at Betsey Island, George III Rock and Black Reef. Transect lengths ranged from (1m x) 10m to 40m (as per legend). Effect size is expressed relative to the density estimate for each site calculated using the formula for stratified sampling, and plotted against total sample area (m^2).*

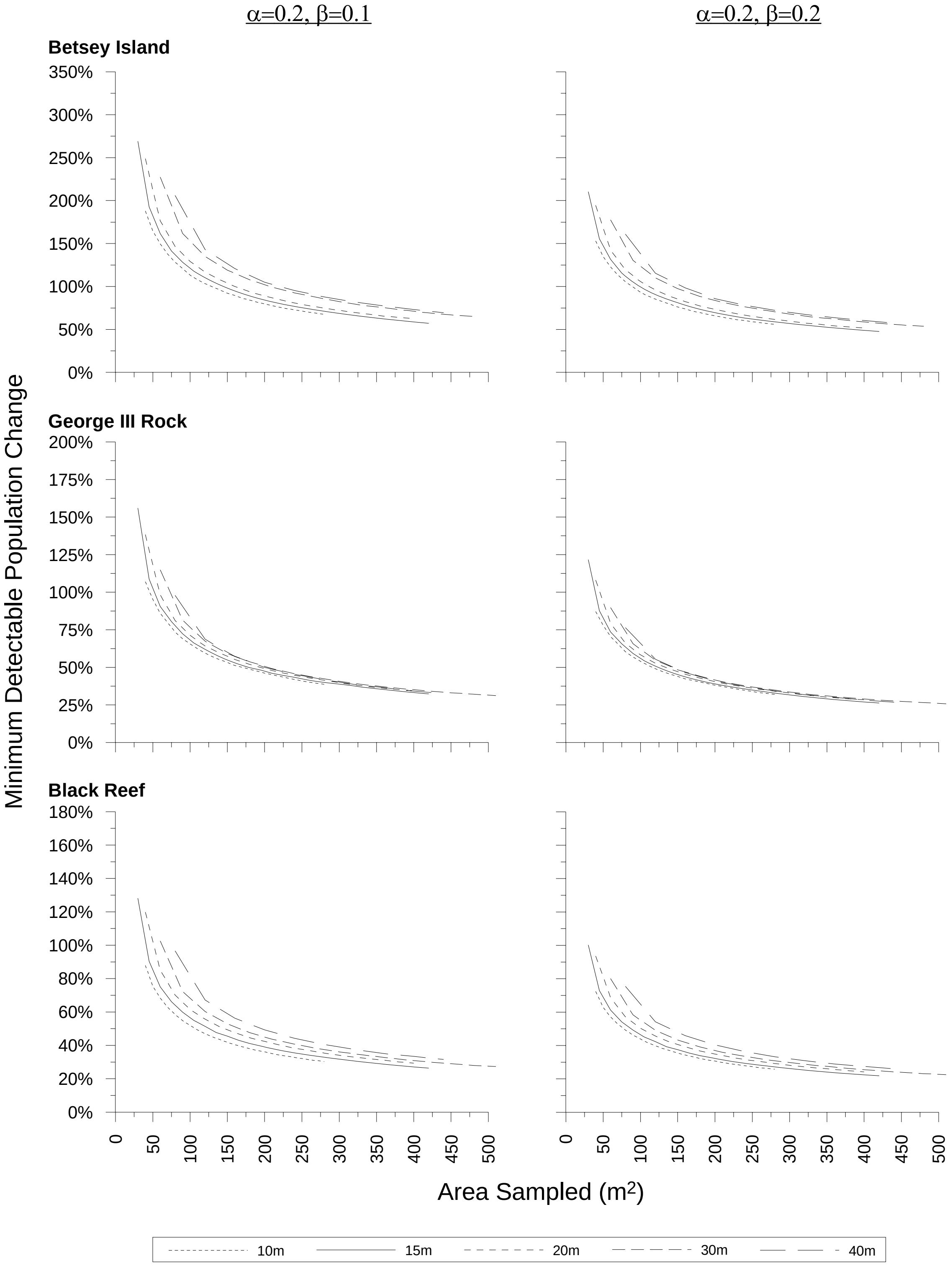

Figure 21. *Average minimum detectable effect size from 5000 paired t-tests on randomly drawn sub-samples from blacklip abalone surveys at Betsey Island, George III Rock and Black Reef. Transect lengths ranged from (1m x) 10m to 40m (as per legend). Effect size is expressed relative to the density estimate for each site calculated using the formula for stratified sampling, and is plotted against total sample area (m^2).*

The influence of transect length on power was most notable in the more vertical region of the graphs where the total area sampled was relatively small. As the sampled area increased, the differences in sensitivity between transects of different length became less marked. This was particularly apparent at the George III Rock site, where transect length made little difference to power for larger samples.

Although surveys undertaken with shorter transects were more sensitive than those conducted using longer units when considered in relation to total sample area, this does not necessarily mean that shorter transects are preferable. This is because the efficiency with which an area is surveyed is influenced by a number of factors in addition to total sample area (such as time spent navigating between transect positions, and deploying and retrieving transect lines). Thus for example, four 30m long transects may not require as much effort to survey as twelve 10m long transects. The issue of optimum sample characteristics is addressed elsewhere (Section 6.7).

6.6.2.1.Survey sensitivity

Ideally, surveys should be sufficiently sensitive to detect relatively small changes in density. In practice however, such sensitivity is usually difficult to achieve in fisheries or environmental monitoring situations (Peterman and Bradford 1987, Peterman 1990, Antcliffe 1992, Mapstone 1995), as survey subjects commonly display patchy, aggregated distributions, leading to inflated sample variance and low power. The minimum level of detectable change that might be considered acceptable from a survey program depends upon the purpose of the program, however as a general rule, the less sensitive a survey program, the less useful it will be as an indicator of population status.

In general, the radial transect surveys investigated here were not highly sensitive to changes in density (which is typical for abalone studies), particularly when statistical power and confidence were constrained to the 90 - 95% levels. In percentage terms, survey sensitivity increased with abalone density (the estimated densities were 0.18, 0.90 and 1.4 abalone m^{-2} at the Betsey Island, George III Rock and Black Reef sites respectively). In terms of actual abalone numbers however, the opposite was the case. For example, from the $\alpha = \beta = 0.1$ scenario (Figure 20), a sample of twenty replicate 10m transects could only reveal a density change of around 92% at Betsey Island, but was sufficiently sensitive to detect a 42% change at Black Reef -- in terms of actual numbers however, this represents a sensitivity of 0.17 abalone m^{-2} at Betsey Island, but only 0.61 abalone m^{-2} at Black Reef.

At the Betsey Island site, population changes as large as 50% could not be reliably detected, even with the largest sample sizes considered, except when both α and β were relaxed to 0.2. Even then, this was only achievable when the sampled area exceeded around 350m^2 (Figure 21). At the George III Rock and Black Reef sites, 50% population change was detectable in all scenarios considered, for samples ranging in area between around 420m^2 and 110m^2 at the former, and around 350m^2 to 75m^2 at the latter site (depending on the transect length, and power/confidence scenarios considered). A smaller population change of around 25% could be detected (within the range of sample sizes considered) at both the George III Rock and Black Reef Sites, but only when α and β were relaxed to 0.2 at George III Rock, or $\alpha = 0.2$ and $\beta = 0.1$ or 0.2 at Black Reef (a 30% change could be detected at Black Reef when both α and β were fixed at 0.1).

Although improvements in power diminished as sample area increased, the downward trajectory of the minimum effect size remained noticeable over the range of survey areas considered here (particularly at Betsey Island). This suggests that tangible improvements in power may be gained by sampling more than $500m^2$; to do so in the context of radial sampling however, would require relaxation of the exclusion zones around individual transects, in order to accommodate the extra replicates.

Regression lines fitted to the 10m x 1m transect data yielded the tightest relationship between effect size and sample area of any transect length considered (although all were tight). The R^2 values of these lines exceeded 0.999 for all sites and confidence/power levels investigated, except $\alpha = \beta = 0.05$ where R^2 exceeded 0.998 at all sites. This allowed projected estimates to be made with some degree of (albeit undefined) confidence (Table 2). For samples of up to $950m^2$ (around 10% of the total site area: the upper limit that can be applied without correction for finite sampling, (Cochran 1977)), the projected effect size that can be detected under the scenario $\alpha = \beta = 0.05$ ranges from 22% at Black Reef to 48% at Betsey Island, whilst under the $\alpha = \beta = 0.2$ scenario, it ranges from 30% to 14%. Given the relatively small improvements in effect size to be gained from such intensive sampling, it is unlikely that this would ever be applied in a broad-scale monitoring program. This might, however, be useful in the context of a more discrete study (e.g. a manipulative experiment).

Table 2. Relationship between minimum detectable effect size and total area sampled using 1m x 10m transects, extrapolated from a sampling intensity of just under 5% (450m) to around 10% (950m).

	Relationship	Area sampled (m^2)					
		450	550	650	750	850	950
$\alpha = \beta = 0.05$							
Betsey Island	Min Effect Size = 20.999 x Area$^{-0.5509}$	73%	65%	59%	55%	51%	48%
George III Rock	Min Effect Size = 11.949 x Area$^{-0.5483}$	42%	38%	34%	32%	30%	28%
Black Reef	Min Effect Size = 10.144 x Area$^{-0.5585}$	33%	30%	27%	25%	23%	22%
$\alpha = \beta = 0.1$							
Betsey Island	Min Effect Size = 15.349 x Area$^{-0.5317}$	60%	54%	49%	45%	43%	40%
George III Rock	Min Effect Size = 8.7385 x Area$^{-0.5292}$	34%	31%	28%	26%	25%	23%
Black Reef	Min Effect Size = 7.3615 x Area$^{-0.5393}$	27%	24%	22%	21%	19%	18%
$\alpha = 0.2; \beta = 0.1$							
Betsey Island	Min Effect Size = 12.665 x Area$^{-0.5212}$	50%	45%	42%	39%	37%	36%
George III Rock	Min Effect Size = 7.2108 x Area$^{-0.5187}$	29%	26%	24%	22%	21%	21%
Black Reef	Min Effect Size = 6.0745 x Area$^{-0.5288}$	23%	21%	19%	18%	17%	16%
$\alpha = \beta = 0.2$							
Betsey Island	Min Effect Size = 10.089 x Area$^{-0.515}$	43%	39%	36%	33%	31%	30%
George III Rock	Min Effect Size = 5.7406 x Area$^{-0.5124}$	25%	23%	21%	19%	18%	17%
Black Reef	Min Effect Size = 4.8737 x Area$^{-0.5226}$	20%	18%	17%	15%	14%	14%

6.6.2.2.Increasing sensitivity

Although the surveys were not particularly sensitive to small changes in density, particularly at the Betsey Island site, a number of factors can be manipulated to improve this. These include site size, replication, using longer time series, analysing for population change in only one direction, and adjusting expectations of statistical confidence and power.

6.6.2.3.Site size

Reducing the physical area of sites may improve power in two ways. Firstly, the distribution of abalone is likely to be more homogenous over a smaller area than a large one. Constraining the size of sites may thus reduce the inherent variability of the population being surveyed, thereby improving power. Secondly, applying a given sampling effort in a small site will result in a greater proportion of the total area being sampled than would be the case if an equivalent area were sampled within a larger site. Again, the result is reduced sample variance and increased power. However decreasing the area to which survey results relate, may have the undesired effect of reducing the representativeness of results in terms of trends throughout the broader fishery.

6.6.2.4.Replication

Arguably the most fundamental way to improve sensitivity is to increase replication. In the context of a repeated measures (i.e. fixed site) monitoring program, replication is important at the level of both transect and site, as well as through time. Maximising replication with regard to one or all of these levels may be achieved in a number of ways including allocation of resources, optimising survey efficiency, “trading off” within-site, among-site and temporal replication, focussing the survey program in target areas, and altering the frequency with which sites are surveyed (temporal replication).

Increasing replication is not easily achieved, as the limits on research expenditure are self-evident. In many ways however, this represents the most satisfactory solution for maximising both spatial and temporal replication. Some opportunity may exist to increase replication by improving survey efficiency (for example with regard to measuring abalone and recording data), although given that radial transects represent arguably the most efficient technique available (Section 6.7) any such gains are unlikely to be great.

Maintaining low levels of within-site replication across a large number of sites has been deemed appropriate in some applications (Van der Meer 1997), however for dive surveys, the preparation time required for sampling at each site favours the maintenance of a reasonable degree within-site replication[6]. In addition, adequate replication of transects within sites minimises the confounding effect of spatial variability on temporal trends, and increases the robustness of statistical analyses on the data (Harris 1985). This latter consideration may not be as important however where Generalised Linear Models are applied, as these are not constrained by assumptions of normality.

Maximising replication at the site level adds degrees of freedom, and thus power, to analyses of trends across broad areas where site is used as an error term. Sampling at a large number of sites also helps to ensure that survey results are representative of trends in the broader fishery. This is particularly important where fixed sites are used, as is the case in radial transect surveys.

Manipulating the frequency of temporal sampling can either free or reduce resources for spatial replication. In general, increasing temporal replication enhances power in repeated measures designs (Gerrodette 1987), as well as allowing trends to be detected sooner simply

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[6] Bernstein and Zalinski (1983) suggested a relatively simple (albeit imperfect) method for determining the optimum ratio of within- to among-site replication, based on the relative costs and variances of replication at each level. However such optimisations require an estimate of time by location variance, which could not be determined from this data.

because of the shorter temporal sampling period. However, seasonal effects may preclude sub-annual survey frequencies. Ultimately, once the optimal balance of spatial and temporal replication is achieved, further increases in replication require an allocation of resources from elsewhere.

An alternative approach to increasing replication is to focus survey effort on a few, important regions of the fishery. This allows sampling to be maximised in these areas (albeit at the expense of other “less important” regions), thereby improving the power of surveys in the target zones. This approach may be appropriate in situations where relatively small areas (in geographic terms) contribute a large proportion of the total catch (historically, currently or potentially). Such cases exist in the Tasmanian abalone fishery, most notably in the “Actaeons” region between the southern end of Bruny Island, Partridge Island and South East Cape.

6.6.2.5.Time series

Although the power to detect relevant population change between consecutive survey events may be relatively low, in a repeated measures model this increases with time. This is due both to the increase in temporal degrees of freedom (Gerrodette 1987), and the cumulative effect of density changes over multiple time periods. Nevertheless, trends in relative abundance (particularly in the negative direction) must be detected in a sufficiently timely fashion, in order to allow management actions to be sufficiently responsive to avoid unacceptable depletion.

6.6.2.6.Unidirectional vs bidirectional Analyses

The power of an abundance monitoring program can be improved considerably if one-tailed, rather than two-tailed analyses are used (Gerrodette 1987, Sheppard 1999). The suitability of this approach depends on the aims of the survey programme, and as such is fundamentally a decision for fisheries managers. In the context of fisheries monitoring, where detecting depletion in sufficient time to take appropriate management action might be considered far more important than failing to recognise population growth (Peterman 1990, Fairweather 1991, Antcliffe 1992, Mapstone 1995 #16, Buhl-Mortensen 1996, Keough and Mapstone 1997, Underwood 1997a, Underwood and Chapman 2003), this may be an appropriate tactic to adopt.

Although unidirectional hypothesis testing can improve statistical power and confidence, such an approach has a number of disadvantages. Most obviously, it provides no information about trends in the opposite direction to that being tested. This problem may be mitigated however, by taking the novel approach of analysing the two tails at different levels of confidence and power, depending on the perceived importance of detecting growth or depletion. A second disadvantage of unidirectional hypotheses testing is that there exists an elevated possibility of committing a Type III error (incorrectly interpreting the direction of a significant effect (Hsu 1996)). This is most problematic when α is large and the effect size relatively small (Leventhal and Huynh 1996), as is likely to be the case in a fishery monitoring situation, but can be alleviated through careful examination of the data series.

6.6.2.7.Adjusting the levels of α and β

The application of statistical techniques has traditionally been heavily influenced by manipulative experimentation, with its emphasis on statistical confidence, somewhat at the expense of power. However in terms of an environmental or fisheries monitoring application, failing to detect a trend (i.e. committing a Type II error) may be far more deleterious than falsely identifying one that doesn't exist (a Type I error), particularly in respect to negative population change. Accordingly, it is has been widely suggested that in such situations, β should be set at or below the value of α. (Peterman 1990, Fairweather 1991, Antcliffe 1992, Underwood 1993, Green 1994, Mapstone 1995, Buhl-Mortensen 1996, Keough and Mapstone 1997, Underwood 1997a, Ortiz 2002, Underwood and Chapman 2003)

Traditionally, α has been set at a level of 0.05, and it has been suggested that where this is retained, then it might be appropriate to also set β at this level (Peterman 1990, Underwood 1993, Sheppard 1999). This has the result however, of strongly limiting the minimum effect size that can be detected from a given survey effort (Green 1994) Figure 20).

The willingness to sacrifice confidence for power in monitoring studies (by relaxing the $\alpha = 0.05$ convention), appears to be increasing. For monitoring studies, an upper limit on β of 0.2 has been widely suggested (Peterman 1990, Antcliffe 1992, Buhl-Mortensen 1996, Keough and Mapstone 1997, Ortiz 2002), and is arguably a sensible upper boundary for α as well. A novel approach for determining the appropriate values of α and β was suggested by Mapstone (1995) whereby the minimum effect size is selected, and α and β allowed to vary, albeit at a fixed ratio which reflects their relative importance (e.g. 1:1 or 2:1). Relaxing α whilst constraining β can afford considerable improvement in the sensitivity of surveys (Figure 20 and Figure 21), and as such may be a valuable approach (again, this ultimately depends on the management goals of the fishery, and must be considered when making management decisions).

6.6.3. Other applications of survey results

Data from fishery-independent surveys are increasingly being incorporated into stock assessment models (Worthington et al. 1997, Mayfield et al. 2004a, Gorfine et al. 2005), both as input, and to validate model output. As such, the use of such data for stand-alone analysis may not be as relevant today as in the past, with survey results representing just one aspect of a broader synthesis of the state of stocks, and the likely outcomes of management strategies.

Model inputs may either take the form of raw survey data, which is analysed in the model, or of output from analyses such as Generalised Linear Models which have been applied to such data. In either case, the value of such information is considerably diminished if the data provide a poor reflection of abundance. Similarly, the value of the data for model validation is intimately related to the precision (and hence power). It is important therefore that confidence limits around such data are sufficiently small to constrain the range of model outputs to an acceptably precise level.

Another potential application for fishery-independent surveys is to provide “snapshots” of abundance at locations throughout the fishery, for the purpose of medium- to long-term reference. This approach may be particularly useful, for example, where the sheer physical area of the fishery precludes regular research activities on a fishery-wide scale (let alone the development of a sensitive fishery-wide monitoring program). Indeed, the experience in the Tasmanian abalone fishery is that some broad areas of abalone-bearing state waters may be excluded from any type of research activity over a period of a decade or more. As a result, little is known about the state of stocks in such areas (e.g. abundance and size composition). This has been the case in the north of the state, where the abalone are considered “stunted”: changes in zoning and size limits in recent years have directed increased fishing activity to this region, and the chance for collecting valuable baseline data has been missed. Given that it is unlikely that the resources required to conduct regular surveys in such areas will become available in the foreseeable future, “snapshots” of population characteristics can provide a useful reference.

The value of “reference” surveys is not limited to rarely visited locations however. For example, even regularly visited areas, such surveys would provide a formal and quantitative measure of abundance and size structure, which can be invoked when less quantitative indicators point toward abundance changes. Data from such surveys also provide important protection against shifting expectations of baseline abundances amongst researchers and fishers (Tegner and Dayton 1998, Rogers-Bennett et al. 2002), and provide a reference in the event of future environmental impacts.

In terms of providing medium- to long-term reference data, the sensitivity of surveys is less important than is generally the case for a “conventional” monitoring program. Because of the greater temporal scale of such surveys, an ability to detect small effects is of little importance, as over time any consistent trends will lead to more substantial cumulative changes. Alternatively, where only minor changes have occurred over long periods (e.g. several years to decades), then this is unlikely to provide cause for concern. This does not however, mean than poor power or precision is acceptable outcome from such surveys: far from it. Rather, it means that power need not be so great as to ensure that very small effects can be detected over a relatively short period. An additional benefit is that the data can be accumulated across a broad area over a number of years, unlike the case of a monitoring program where annual surveys at all (or at least most) sites might be deemed more appropriate.

6.7. Optimal sampling parameters and cost-benefit analysis

An investigation was conducted into the relationship between the costs of conducting radial and parallel transect surveys, and transect length, number of replicates, and variability. Once again, the data collected from the surveys at the Betsey Island, George III Rock and Black Reef sites (Section 6.2.1.2), formed the basis of this work.

6.7.1. Analysis of variance: transect length

Prior to the investigations to optimise transect length, a comparison of the estimates generated from parallel transects of 10m, 20m, 30m and 40m length was made. The purpose of this analysis was to determine if transect length had a significant effect upon the density estimate (that is, were the estimates free from, or at least equally affected by any biases). This was done using a three-way factorial ANOVA model, with the terms transect length (fixed), diver and site (both random).

6.7.2. Optimising survey parameters

During the collection of both the radial and parallel transect data, divers used the timestamp feature of their dive computers to indicate whenever they commenced or completed each 5m x 1m transect segment. From this information it was possible to calculate both the time taken to survey a 1m wide swathe along a given distance, and that spent between transects (e.g. navigating between positions, and removing and setting up the transects), for both radial and parallel samples.

In terms of an ongoing abalone survey program, it is important that abalone encountered along the transect are measured, rather than merely counted as was the case in this pilot survey (where the intensity of sampling precluded measurement). This allows estimates of error to be generated for each size category of interest (e.g. recruits and pre-recruits), and avoids the well documented biases associated with “free swimming” collection of abalone (McShane et al. 1988, McClanahan and Muthiga 1992, Findlay and Willerton 1996, Hart and Gorfine 1997) to determine population size-structure as has been employed elsewhere (Gorfine and Dixon 2002, Mayfield et al. 2004b).

Measuring all abalone encountered along each transect slows the survey process somewhat, regardless of whether abalone are measured underwater, or collected and then returned following measurement at the surface. Accordingly, in order to assess performance of the techniques under the scenario of abalone being measured, the average time per 5m x 1m transect section recorded during this study was scaled by a factor of two to account for the extra time. Later surveys showed this to be a reasonable estimate, except where abalone were particularly dense, in which case survey time was underestimated.

The time required to conduct a survey of any given transect length and sample size was calculated for each method at each site by:

$$\text{Sample time} = T_{setup} + \frac{[(T_{seg} \times n_{seg}) \times N] + [T_{nav} \times (N\text{-}1)]}{S}$$

where: T_{setup} = time taken preparing and dismantling survey site for specified survey method

T_{seg} = average time taken to survey each 5m x 1m transect section

n_{seg} = number of segments / transect

T_{nav} = average time spent between replicates using specified method

N = total number of replicate transects / site

S = number of individuals undertaking the survey

This formula fails to fully account for cases where the number of replicate transects is not evenly divisible by the number of divers. In such situations, some individual divers are required to survey more transects than others, thus adding to total survey time. Neither does it take into account that even when each diver surveys the same number of transects, total survey time is determined by the time it takes for the “slowest” diver to complete their transects, rather than the average time.

Setup and retrieval time at each site was treated as being independent of the number of divers participating in the survey. Site setup for radial transect surveys of abalone is generally done almost entirely from the surface, and only requires a single diver to secure and/or free the anchor point on some occasions. Occasionally a diver may “swim” the shot line anchor back to the boat, but in such cases is generally assisted in this task from individuals at the surface (i.e. the diver lifts the anchor weight from the bottom, and both diver and anchor are then pulled to the boat). Parallel transect sites require that a reference line be laid out and anchored underwater at both ends; a task that can be achieved by a single diver, with little, if anything to be gained by using additional divers (and having them accumulate bottom time which is in limited supply). Equipment retrieval in both cases is generally done by the diver who was last to complete their allocated transects.

6.7.3. Cost-variance products

Initial investigations into optimum transect length and arrangement (radial or parallel) were based on the technique described by Wiegert (1962). Wiegert considered the optimal sample unit size as that which provides the smallest product of cost and variance (following Wiegert

(1962), time is used here as a proxy for cost). The sample time (i.e. cost) required to survey a single transect of given length was expressed relative to that for the fastest (i.e. shortest) radial transect (5m x 1m). Variance estimates (which were standardised per 10m^2 area), were similarly expressed relative to that of the sample unit with the smallest variance (which in each case was the 40m transects). Following Krebs (1999), the sample size from which variance was estimated for each transect length, was that relating to a standard total sample area: in this case, 120m^2.

Because of the limited size of the datasets relating to parallel transects, particularly those longer than 20m, the variance values used were the averages from 10000 Monte Carlo sub-samples of the radial datasets. A second, albeit minor, reason for doing this was that a section of some parallel transects extended beyond the boundary of the radial transect sites (although this is unlikely to have substantially affected sample variance).

Applying variances calculated from radial transects, to the assessment of parallel transects, was deemed appropriate given that both methods generally performed similarly in terms of abundance and precision estimates, except in those instances where the accuracy of longer (30m and 40m) parallel transects appeared to fall away slightly (Section 6.3). Where such differences occurred, it was most likely due to the limited size and precision of the parallel transect dataset, thus these data were considered less than ideal.

6.7.4. Precision-effort Plots

Investigations into cost-benefit outcomes and optimal transect size and type (radial or parallel) were conducted using a procedure developed from that described by Bros and Cowell (1987). This method was proposed for optimising sample size in situations where an *a priori* decision on minimum effect size either has not or cannot be made. The technique is based around the tendency of variability to diminish with increasing sample size, and involves Monte Carlo sampling to repeatedly draw samples of two to $N/2$ elements (where N is the total number of elements in the dataset). Standard error estimates are calculated for each sample, and the mean and most extreme error estimates are plotted against sample size.

Based on "the law of diminishing returns", Bros and Cowell infer that the minimum sample size to apply to surveys should be such that further increases in sampling effort lead only to relatively minor diminution of the average standard error estimate, or of the range of standard error estimates (whichever is greater). Maximum sample size is determined by feasibility, and the trade-off between the cost and the benefits of increasing sample size.

The method employed here, although based on Bros and Cowell's, is modified to allow transect dimensions to be considered concurrently with effort. The modified method involves plotting indices of precision (although not necessarily standard error as per Bros and Cowell's method) against the time required to obtain such samples.

Approximate effort thresholds were calculated, and superimposed on the plots to provide an indication of the precision that could be expected, according to the number of sites sampled in a given day. For parallel transect surveys, the relationship was determined using both the parallel transect data, and by incorporating the power-sample size relationship from the radial transect surveys, with the estimated costs of parallel surveys (both sets of results are presented). Again, this was done primarily because of the limited size of the parallel transect data set, particularly in relation to longer transects, and the apparent accuracy (and hence representativeness) of the data relating to the radial transects (Section 6.3).

The effort thresholds are based on a number of assumptions, including a maximum available sampling time of six hours per day (this excludes travel time to the first site, and that from the last site) and a 50 minute period "lost" between surveys at different sites (which incorporates factors such as travelling time, and diver and vessel preparation), which are common to both survey types. Survey duration at any one site is specific to transect arrangement (i.e. radial vs parallel), and incorporates both a fixed component (the time spent on site preparation and post-survey equipment retrieval) and a variable component (sampling time), which changes with sample unit size and level of replication. It has been assumed here that two divers operate concurrently during all survey dives.

A number of separate precision indices were used to assess optimal sample parameters. In order to allow the results of pilot studies from several sources (in this case, several sites) to be graphically examined on the same scale, standard error estimates were scaled by the mean abundances, to give estimates of relative error (sometimes also referred to as precision, e.g. Andrew and Mapstone 1987, Gorfine and Dixon 2002)). Following Bros and Cowell, both the mean error estimate and the range of extreme error values were considered. The second index of precision applied was the spread of the Monte Carlo-generated mean abundance estimates. This index is important as it reflects the degree to which spatial imprecision is likely to confound estimates of temporal variability throughout a time series (temporal variability reduces the power of repeated measures analyses to detect temporal trends). The final group of precision indices used was minimum effect size from 5000 paired *t*-tests of randomly drawn sub-samples from the relevant dataset. Effect sizes were calculated at a range of statistical confidence and power levels (as described in Section 6.6). Each index provided a different perspective on the performance of the surveys, and on the effects of transect length and sampling effort.

According to Bros and Cowell (1987), the maximum number of Monte Carlo iterations applied should be restricted to 10% of the total sample pool. This restriction is based on the comment by (Tukey 1962) that between 0.1% and 10% of data are likely to be outliers. However, this restriction leads to somewhat imprecise (and hence variable) estimates of the average and extreme error values. As a result, visual interpretation of minimum sample size from such graphs is dependent on the outcome of the particular set of Monte Carlo runs.

The approach used here differed somewhat, in that a large number (10000) of Monte Carlo draws were used for each sample size, and the "extreme" values were determined as the (two-tailed) 90 percentile limits of the generated spread of estimates. This provides a much smoother and more consistent output than that from Bros and Cowell's method, and subsequently aids interpretation of the results. In addition, it allows curvilinear regression lines to be tightly fitted to the results, which may assist with extrapolating results beyond the limits of the analysis (albeit with an inherent degree of uncertainty).

In order to avoid plotting the five and 95 percentile estimates on the same figure as the mean estimates, the width of this range was calculated (for both relative error and density estimate spread) and plotted separately. This again provided a smooth and repeatable output against which Bros and Cowell's implied criteria in this respect could be assessed. It also substantially reduced the number of lines in each plot, which in itself greatly aided visual interpretation given that multiple transect lengths were considered concurrently in each plot.

Bros and Cowell (1987) suggested that the minimum sample size (analogous to minimum sampling effort here) should be greater than "the location of the region of greatest change in slope (of the tangent to this curve)". This definition is clearly flawed, given that the second derivative of an exponential decay function (which describes the rate of change of the gradient of this tangent), is itself a function of exponential decay, and as such has its greatest value at the smallest possible sample size. A more logical minimum boundary for sample size or effort might be when the gradient of the tangent to the decay curve (i.e. the first derivative of the regression equation) is –1, however this definition is sensitive to the units used to calculate the regression equation. Visual assessment of the appropriate point is similarly inadequate, as the slope of the tangent to the line is dependent on the relative scales at which the two axes of the graph are drawn. A more sensible definition of minimum sample size is the point or region of the graph beyond which variability (e.g. relative error) is unacceptably high, or rises at an unacceptable rate given a small change in effort. This definition is the one that has been applied here.

The process of selecting an appropriate sample size is simplified by overlaying effort thresholds, such as the site/day thresholds applied here. The optimum sample size should be in the close vicinity of these thresholds, as there is little if anything to be gained by selecting a sample size that falls midway between two such points (provided that the assumptions upon which these are based are sound).

6.7.5. Results and Discussion

Analysis of variance on the parallel transect data revealed a significant effect of site, but none of transect length, diver or any higher order term (Table 3). Because sampling at the Black Reef site was not completed, the analysis was not orthogonal, however since "transect length" was fixed, the results were insensitive to the ordering of the terms. The transect length x diver interaction term approached significance at the 5% level ($p = 0.076$), which may reflect that divers differed in the number and length of transects that they completed at the Black Reef site.

The clear absence of a length effect provided no indication that transect dimensions had any effect on abalone abundance estimates. The probability value was sufficiently high ($p = 0.78$), that length related biases were not considered any further when selecting the optimum transect length.

Table 3. Results of three-way factorial ANOVA on parallel transect data.

Source	DF	Sums of Squares	Mean Square	F Value	Pr > F
Diver	1	0.03882641	0.03882641	0.75	0.4771
Site	2	25.58729089	12.79364545	248.05	0.0040
Length	3	0.15733718	0.05244573	0.37	0.7783
Diver*Site	2	0.10315285	0.05157642	0.36	0.6994
Length*Diver	3	0.76077657	0.25359219	3.82	0.0764
Length*Site	6	0.68066411	0.11344402	1.71	0.2657
Length*Diver*Site	6	0.39836186	0.06639364	0.46	0.8344
Error	84	12.06548552	0.14363673		

6.8. Optimisng survey parameters

For the purposes of comparing the performance of radial and parallel transects, the efficiency differences between the two methods were considered to lie in only the time spent in site preparation and retrieval, and in navigating between transect start positions. The actual process of searching and navigating along the transect lines was considered equivalent for both techniques, despite the experience during this work that parallel transects took a little longer to survey than radial transects of equivalent length (regardless of whether considered in relation to the times of all divers, or only those who surveyed both kinds of transect). The difference experienced in this study may have been due to the need to exercise greater navigational care when surveying the parallel transects (whose paths, unlike those of the radial transects, did not diverge); however, it may have also merely been a chance effect; this cannot be determined with certainty, given that allocation of radial transects was not random (Section 6.2.1.2). Accordingly, transect search times for both parallel and radial transect surveys were pooled, and the average time taken to survey each 5m x 1m section thus determined and applied, regardless of survey type. Any bias that thus arose from this decision was in favour of the well established parallel transect arrangement.

Radial transect sites were deployed and retrieved quickly and easily, taking one diver a total of around only five minutes (combined time) to compete both tasks. Setting up the reference lines for the parallel transects on the other hand, took two divers over an hour at all sites, and nearly two hours at Black Reef, whilst retrieval of these lines and anchors added another ten minutes or more. The need to carefully align the reference axes to ensure that the parallel transect site was correctly positioned over the radial transect site, and the large dimensions of the site (110m in one direction and up to 150m in the other) undoubtedly slowed the task, however laying and anchoring the negatively buoyant reference lines in swell was difficult and inefficient. In addition, at the Black Reef site, the rocks that cover the bottom are relatively small and would move under the strain of the swell-swept reference lines, making the process of anchoring the lines a difficult one. In the context of an ongoing survey program, where a degree of imprecision may be acceptable when positioning the reference lines, parallel transect sites could undoubtedly be established far more rapidly than was the case here. Nevertheless, the simplicity of the radial transect system proved far more conducive to efficient operation. For the purposes of comparing the two methods, analyses have been based on the very conservative assumption that parallel sites take around 15 minutes for one diver to set up and dismantle. This adds a high degree of conservatism to any conclusion drawn about the relative efficiency of radial transects.

The time taken between transect searches varied with both method and site (Table 4), but in each case proved to be lower for radial transects. Despite being constructed from floating material, snagging of transect lines, particularly in *D. potatorum* at the George III Rock site, was an occasional inconvenience, and clearing fouled lines added to the time spent between transects. Estimates of the time taken to survey a transect of given length and type were calculated using the information gained during the surveys (Table 4).

Table 4. Average time taken to complete specified tasks at each site (minutes:seconds), using radial and parallel transects. These times were used for determining the "optimum" transect length, and to examine the relationship between survey power and time per sample.

	per 5m x 1m section (unscaled)	Between transects:	
		Radial	Parallel
Betsey Island	2:03	4:05	8:11
George III Rock	2:38	6:30	9:45
Black Reef	2:11	2:30	8:06
Average	2:17	4:22	8:40

6.8.1. Cost-variance products

Comparison of the relative cost-variance products for each site and method (Figure 22), revealed the transect length considered "optimal" according to the definition of Wiegert (1962) differed across both sites and survey methods. At the (unfished) George III Rock site, the cost-variance product fell across the entire range of transect lengths considered. At the two fished sites, shorter transects (10 to 20m) better met the criteria. For radial transect samples at the fished sites, the cost-variance product generally rose when transect lengths exceeded around 10m to 20m, although the rise was not as marked for parallel transects. This difference reflects the greater ratio of search time to time spent between transects, for longer parallel sample units, compared to radial transects of equivalent length.

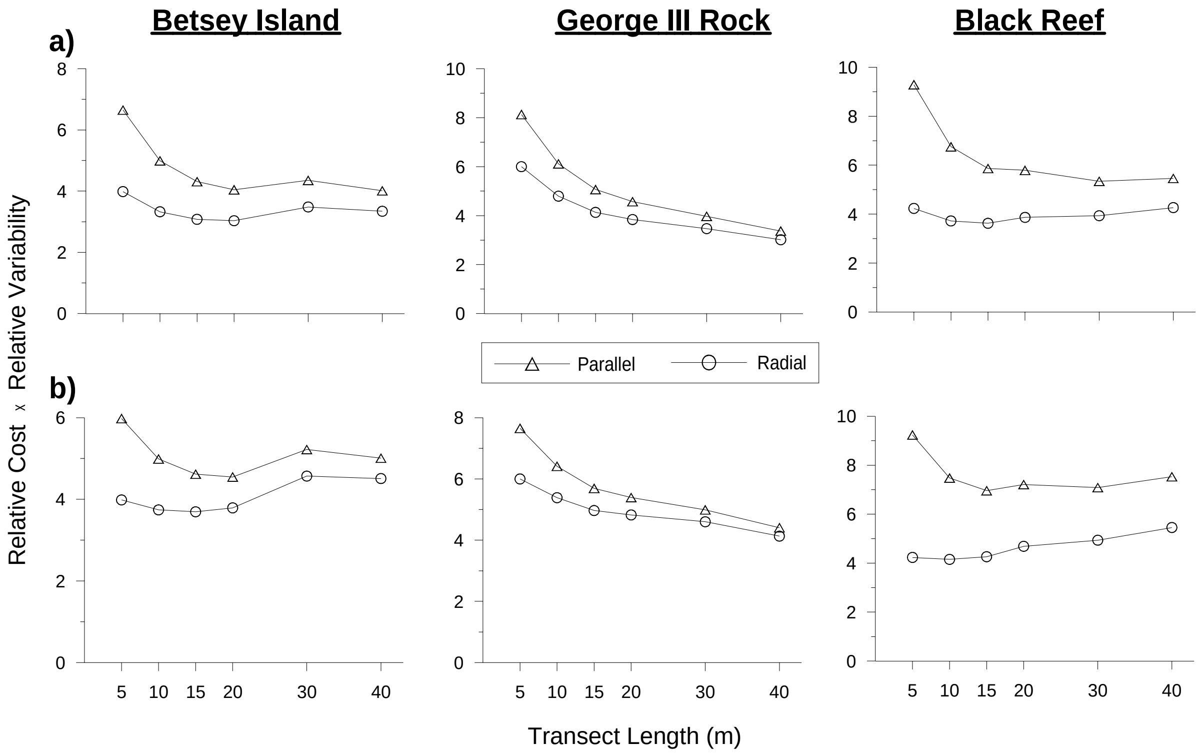

Figure 22. *Plots of (Relative Cost x Relative Variability) versus transect length for radial and parallel transects at each of three sites: (a) abalone counted but not measured; (b) abalone "measured" (i.e. survey time scaled by a factor of two). Relative cost was standardised on a site by site basis (and among scaled and unscaled survey times) against that for a 5m radial transect, and as such values are comparable within, but not among plots.*

In all cases, the surveys employing a radial transect arrangement outperformed those in which transects were arranged in parallel. Given that parallel transects were less efficient both in terms of site setup and time spent navigating between transects, this result was inevitable, as a common variance estimate was used in the analysis for both techniques. Similar analyses were also performed using the variance estimates obtained from the parallel transects (not shown here), however the results were erratic: nevertheless, radial transects generally outperformed those with a parallel arrangement.

For cost-variance products calculated using the unscaled survey time data (i.e. that relating to counts, but not measurements of abalone), the "optimum" transect length estimate from radial surveys was 15m to 20m at the Betsey Island site and 10m to 15m at the Black Reef site (Figure 22a). When scaled times were used (Figure 22b), short transects were again the better performers at these two sites. For parallel transects at these sites, the product of cost and variance tended to plateau beyond transect lengths of around 15m to 20m.

The relationship at the George III Rock site differed quite markedly from those at the other sites, and was qualitatively similar for both scaled and unscaled estimates. Here, the cost-variance product decreased with increasing sample unit size across all transect lengths, and both arrangements considered (although for radial transects, the rate of improvement slowed beyond a length of around 15m – 20m).

A tendency towards convergence in the performance of radial and parallel transects with increasing transect length was apparent in all cases, reflecting the diminishing proportion of total survey time spent between transects as length increased. This was most notable in longer (30m and 40m) transects at the George III Rock site, where little separated the performance of surveys conducted using transects with either arrangement.

6.8.2. Precision-effort plots

Plots of relative error versus effort for surveys in which abalone were measured (left column, Figure 23) revealed inconsistent performance among different sites, transect lengths, and transect arrangements. When three or fewer sites were sampled per day, shorter (10 - 15m) radial transects outperformed longer ones on the basis of the Betsey Island and Black Reef data (although the difference between transect lengths was not great). On the basis of the George III Rock data however or when more than three sites were sampled on the basis of the Betsey Island data, longer transects appeared preferable.

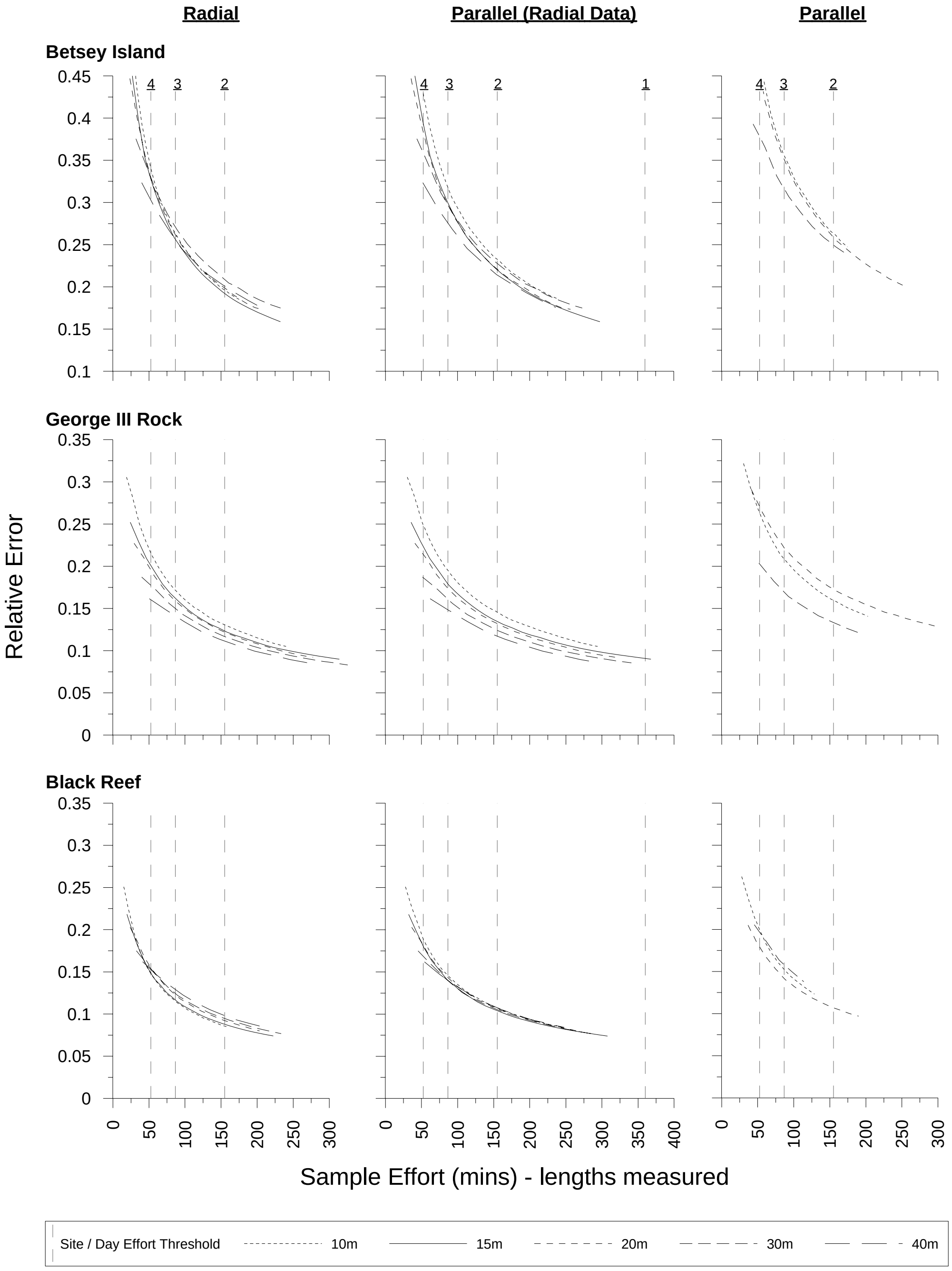

Figure 23. *Average relative error (S.E. ÷ $\bar{x}$) estimates from 10000 randomly drawn Monte Carlo samples of blacklip abalone survey data from Betsey Island, George III Rock and Black Reef. Transect lengths range from 10m to 40m, and results are expressed relative to scaled survey time (i.e. estimated time for measuring rather than merely counting abalone). Dashed vertical lines represent coarse effort thresholds, beyond which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the relative error estimates calculated from radial transect data, and the right hand column uses data only from the limited parallel transect dataset.*

Assessment of parallel transect performance using the error estimates from the radial transects (middle column, Figure 23), revealed that relative error was invariably (and inevitably, given the relative inefficiency of surveys with this transect arrangement) higher than when equivalent effort was applied to radial transects. The George III Rock results indicate that precision is inversely related to transect length. On the basis of the Betsey Island data however, 40m parallel transects are preferable when more than two sites are sampled per day, but there is little difference between the performance of 15m, 20m and 40m transects when two or fewer sites are sampled. At Black Reef, parallel transect length appears to have little effect.

When parallel transect performance was based on the variance data collected using these transects (right column, Figure 23), 30m transects (the longest ones considered) generally performed best, or in the case of the Black Reef site, only a little worse, than the other lengths considered. In all cases however, the relative inefficiency of parallel transect was even more apparent in these plots than when parallel times were combined with radial data.

Victorian surveys for blacklip abalone are designed around a relative error target of 0.25 (Gorfine and Dixon 2000). This moderate precision target allows within-site replication to be constrained to a degree, thereby freeing resources which can be directed towards increasing the number of sites surveyed. Adoption of a 25% precision target in Tasmania might allow up to three sites to be sampled daily, on the basis of the Betsey Island radial transect data, or four or more on the basis of the results from the other two sites (Figure 23). It is salient to note however, that the relative error considered here is the average value, and hence in practice, this value will be exceeded on around 50% of occasions.

If radial transect survey effort was applied at the two sites/day level (~155 min/site), the average relative error falls to just below 0.2 for most transect lengths on the basis of the Betsey Island data. Given that the 90 percentile range of relative error values at this survey intensity is around 0.1 for 10m – 20m transects (Figure 24), then at this level of effort, relative error should fall either below or around the 0.25 target on 95% of occasions[7].

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[7] Since only one tail contributes to inflation of the relative error estimate, and $0.2 + (0.1 \div 2) = 0.25$.

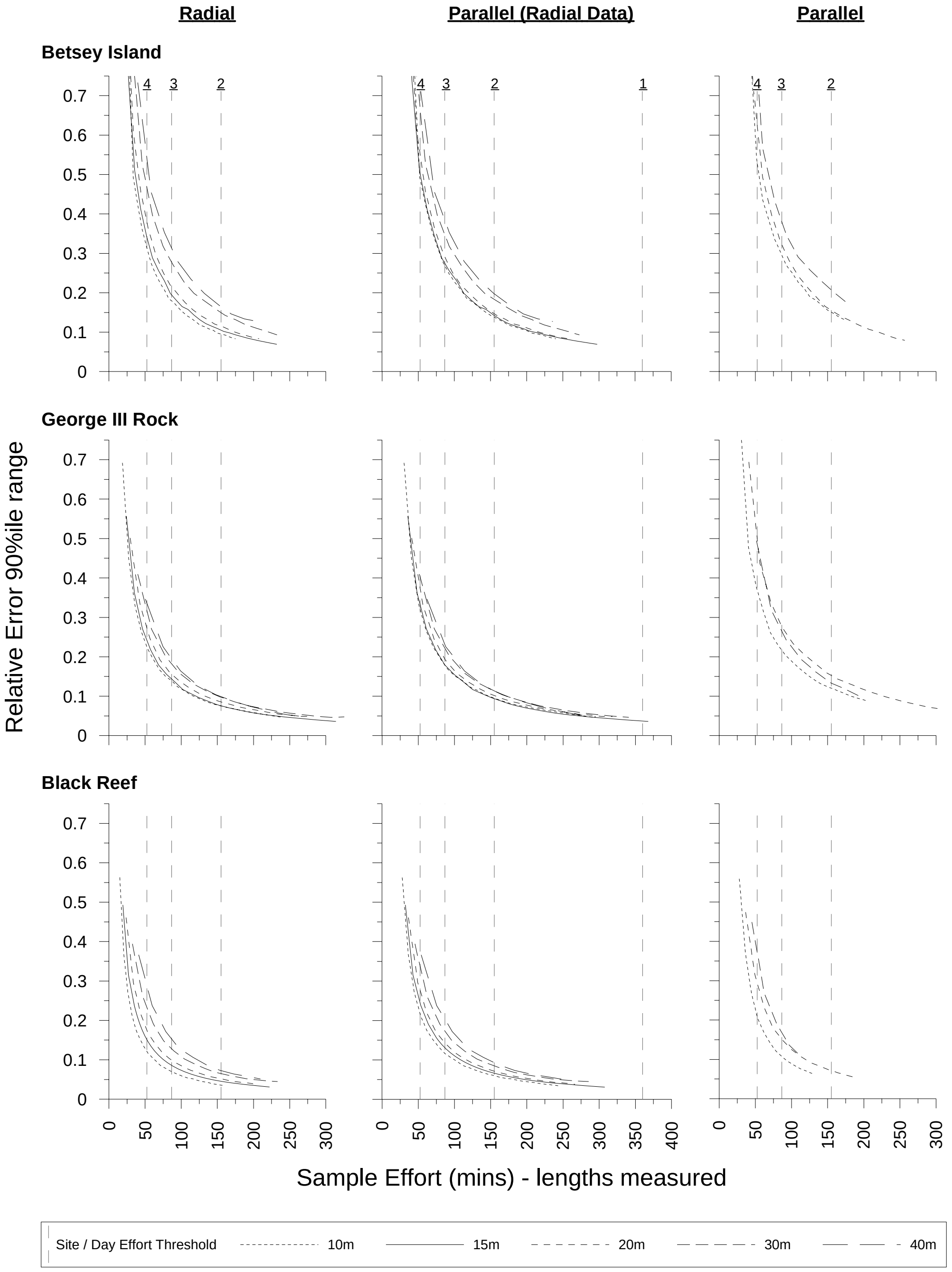

Figure 24. *Ninety percentile relative error (S.E. ÷ $\bar{x}$) range (two-tailed) from 10000 randomly drawn Monte Carlo sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from 10m to 40m, and results are relative to scaled survey time (i.e. estimated time for measuring rather than merely counting abalone). Dashed vertical lines represent coarse effort thresholds, beyond which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the relative error estimates calculated from radial transect data, and the right hand column uses data only from the limited parallel transect dataset.*

At George III Rock, sampling at the four sites/day intensity (~50 mins/site) using radial transects yields relative error values of 0.16 to 0.22, depending on transect length. However the corresponding 90 percentile error range at this intensity is 0.23 to 0.35. Again, taking a conservative approach by reducing survey intensity to three sites/day ensures that relative error falls within the desired target range 95% of the time.

On the basis of the Black Reef data, a radial survey intensity of four sites/day yields estimates that fall within the target range on 95% of occasions, except when 40m transects are used (as these have the widest spread of estimates).

A still more conservative approach to optimising survey intensity considers the rate at which the error falls between at a given level of effort, as implied by Bros and Cowell (1987). At Betsey Island, although relative error is around 20% at the two sites/day threshold, this continued to fall at a relatively steep rate beyond this point (Figure 23). This might be interpreted to suggest that two sites per day is around the maximum that should be attempted. Tangible improvements in results are likely to be gained by spending an entire day surveying such a site, however it is very unlikely that such an intensive allocation of resources would be feasible in the context of a broad-scale survey program.

At the George III Rock and Black Reef sites, reasonable improvements in precision could be achieved by increasing sampling effort to the two sites/day level, however further improvements in error began to taper somewhat beyond this limit. Again, this suggests that two to three sites/day may be an appropriate effort level at which to sample.

The width of the 90 percentile range of relative errors (Figure 24) initially falls more rapidly, and then tapers off more markedly (i.e. the index of the line that describes the power curve is more negative) than the corresponding mean relative error values. As such, this plot gives no reason to suspect that the minimum effort limits derived from the mean relative error plots are inadequate. Interestingly, in all cases the width of the 90 percentile relative error range was positively related to transect length (that is, shorter transects always yielded more consistent estimates of error than longer ones).

Interpretation of the range of Monte Carlo generated density estimates is qualitatively similar to that from the plot of mean relative error (Figure 25). However, given that the decay curves for the mean density estimate range are not as smooth as those relating to relative error, interpretation of the most appropriate transect length cannot be made with the same confidence. Nevertheless, the results suggest that 10m to 15m radial transects were generally the best performers at Betsey Island, whilst longer transects (whether radial or parallel) are indicated by the George III Rock results. The Black Reef results on the other hand, indicate that transect length made little difference.

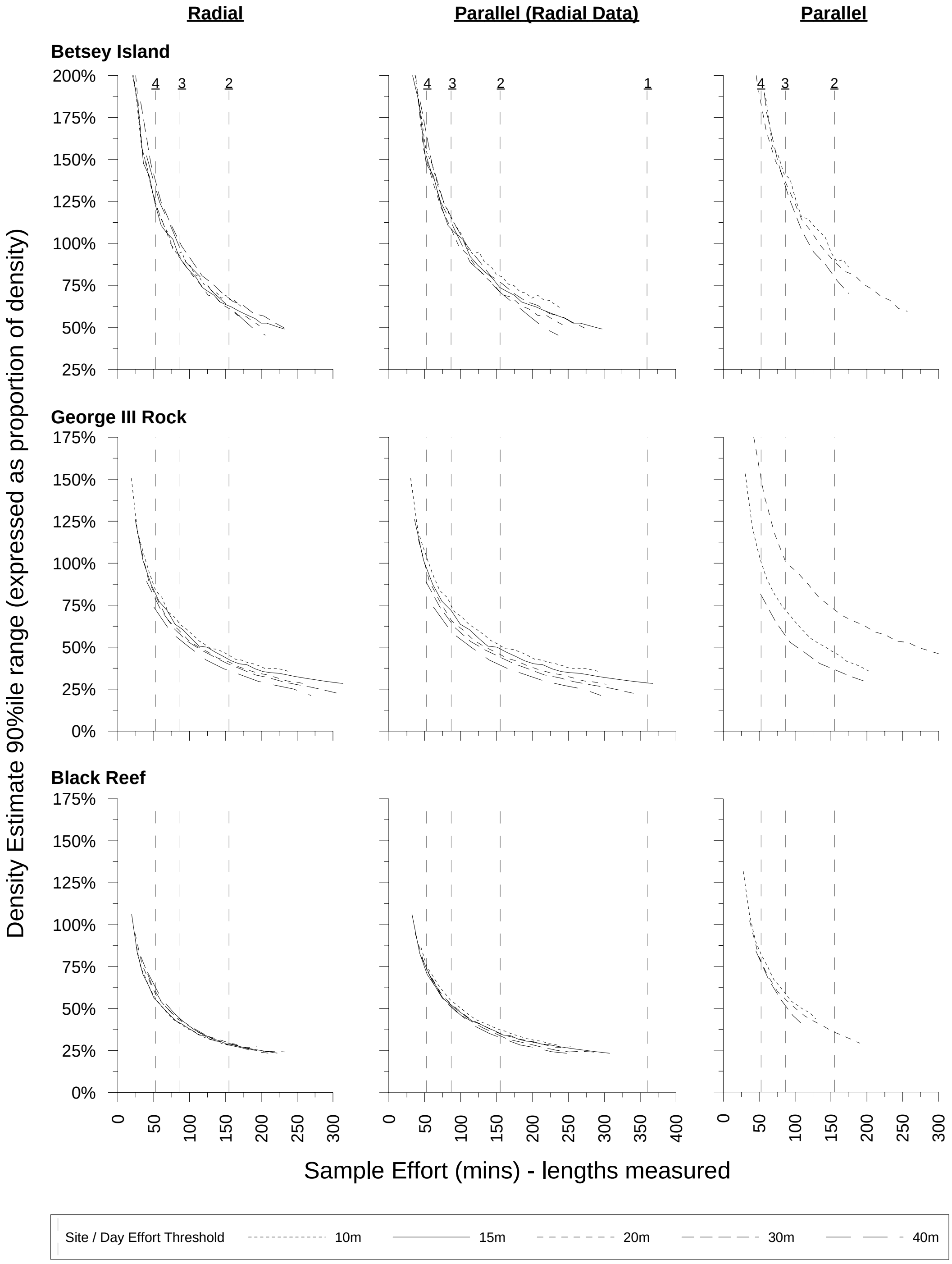

Figure 25. *Ninety percentile range (two-tailed) of density estimates from 10000 randomly drawn Monte Carlo sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from 10m to 40m, and results are relative to scaled survey time (i.e. estimated time for measuring rather than merely counting abalone). Dashed vertical lines represent coarse effort thresholds, beyond which the number of sites sampled per day decreases by one. Results for radial transects are shown in the left column. The centre column combines the times for sampling parallel transects with the range of density estimates calculated from radial transect data, and the right hand column uses data only from the limited parallel transect dataset.*

The range of Monte Carlo generated density estimates remained fairly wide, even when sampling was relatively intense. This was most notable at the Betsey Island site, where radial sampling with equivalent intensity to two sites/day still yielded density estimates with a 90 percentile range that was 60% to 70% that of the mean estimate. Such variability is likely to considerably reduce the power of surveys to detect changes over time, with spatial variance likely to swamp temporal effects. Again, the Betsey Island radial data suggest a maximum sampling intensity of two sites/day, although reasonable precision gains are likely if sampled at the (albeit unfeasibly expensive) one site/day level. There is limited benefit to sampling with more than two sites/day intensity on the basis of the George III Rock radial transect data, and only minor gains from sampling fewer than three sites/day on the basis of the Black Reef results (the width of the 90 percentile range of density estimates falls from around 40% to around 30% of the mean when sampling intensity increases from the three sites/day to the two sites/day level based on the Black Reef results).

Radial transects again outperformed parallel transects on the basis of the width of the density estimate range for a given sampling effort. This difference was more apparent when the performance of parallel transects was assessed using the data collected with these transects (as was the case for relative error).

When minimum detectable density changes were examined in relation to survey effort (Figure 26 to Figure 29), it was immediately apparent that short transects (10m - 20m) outperformed longer ones according to these criteria, regardless of whether a radial or parallel arrangement was used. Parallel transect results from the George III Rock site were the one exception to this rule. In terms of sampling intensity, one to two sites/day were again generally indicated on the basis of Betsey Island data. Two to three sites/day were indicated from the George III Rock data, and three to four sites/day on the basis of the Black Reef data. As statistical power and confidence are relaxed, improvements in minimum detectable effect size realised by sampling extra sites diminish.

When parallel transects are assessed using effect size values calculated from the parallel transect data, the efficiency of these transects again appears lower than when radial transect data were applied to the parallel survey times.

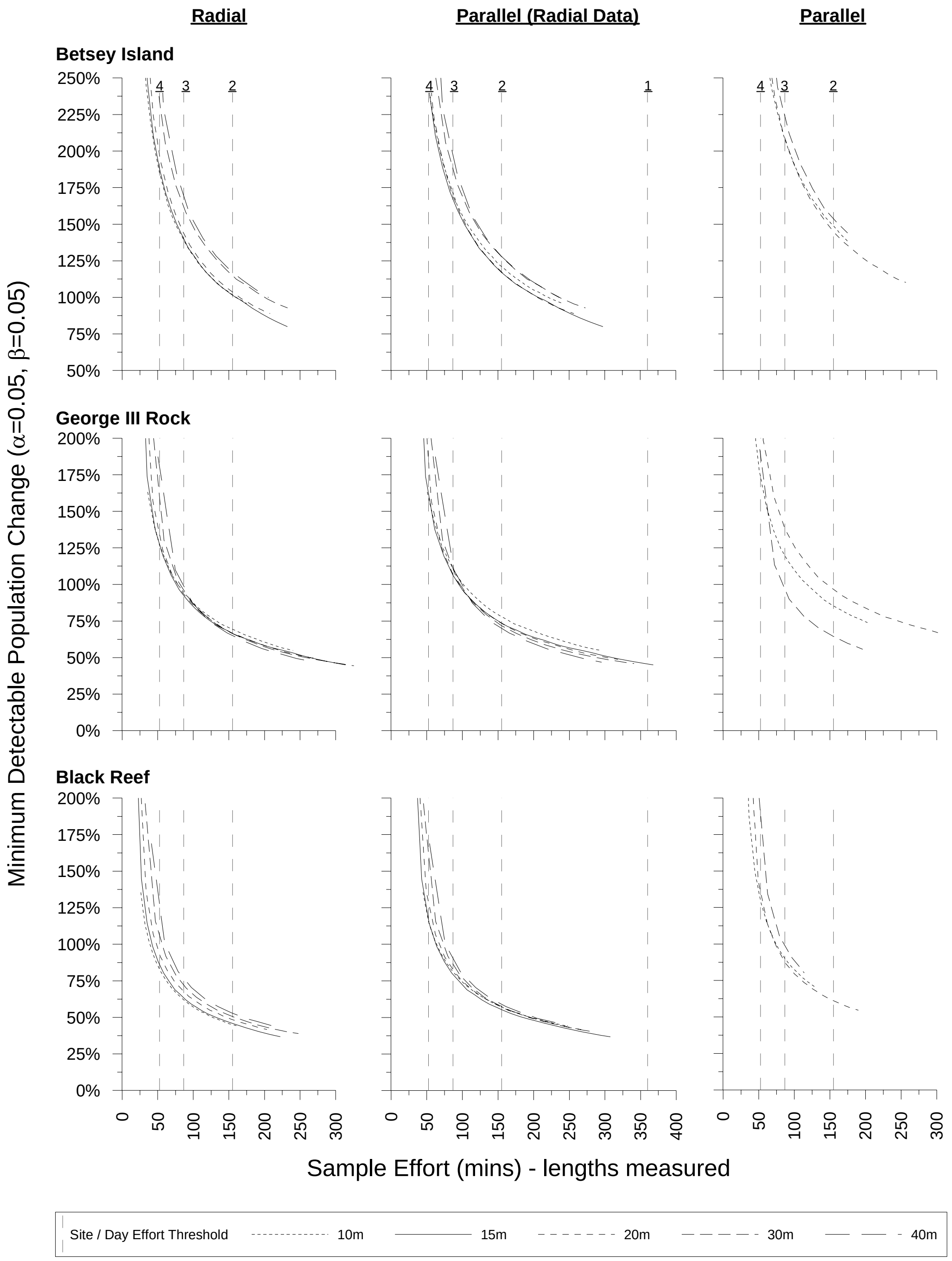

Figure 26. *Average minimum detectable effect size (α = 0.05, β = 0.05) from 5000 paired t-tests on randomly drawn sub-samples from blacklip abalone surveys at Betsey Island, George III Rock and Black Reef. Transect lengths range from 10m to 40m, and effect size is relative to scaled survey time (i.e. estimated time for measuring rather than merely counting abalone). Dashed vertical lines represent coarse effort thresholds, beyond which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset).*

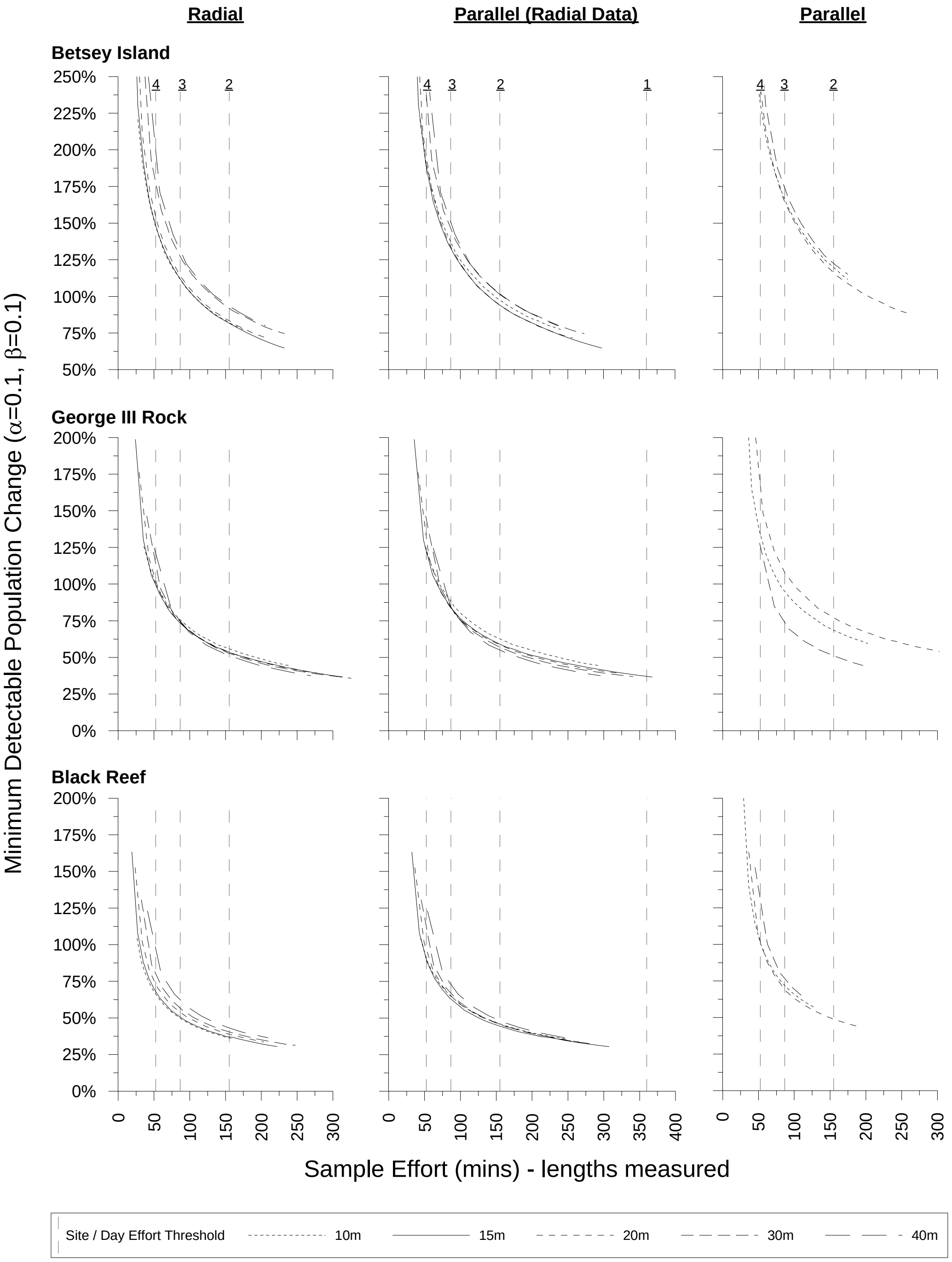

Figure 27. *Average minimum detectable effect size (α = 0.1, β = 0.1) from 5000 paired t-tests on randomly drawn sub-samples from blacklip abalone surveys at Betsey Island, George III Rock and Black Reef. Transect lengths range from 10m to 40m, and effect size is expressed relative to scaled survey time (i.e. estimated time for measuring rather than merely counting abalone). Dashed vertical lines represent coarse effort thresholds, beyond which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset.*

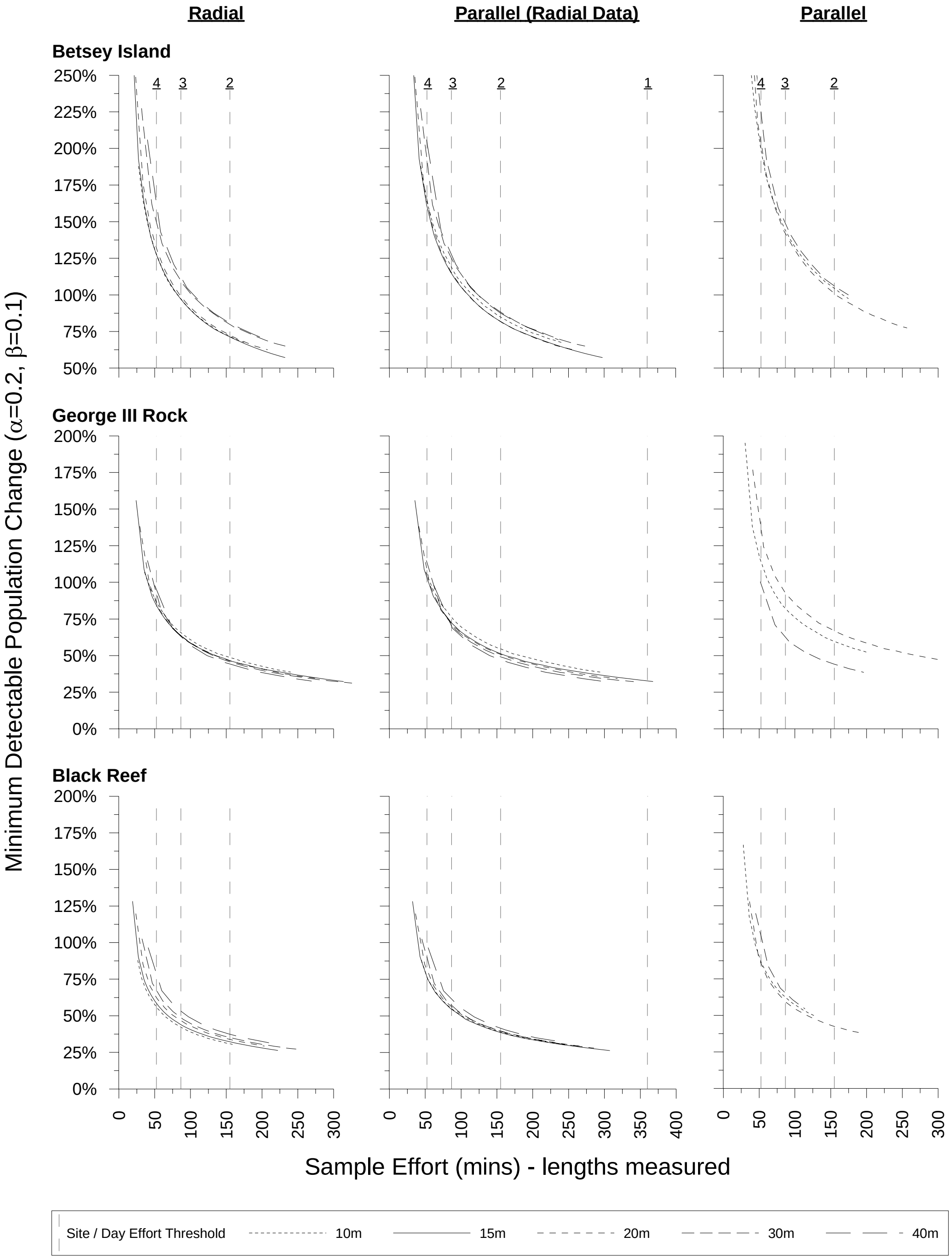

Figure 28. *Average minimum detectable effect size (α = 0.2, β = 0.1) from 5000 paired t-tests on randomly drawn sub-samples of blacklip abalone surveys at Betsey Island, George III Rock and Black Reef. Transect lengths range from 10m to 40m, and effect size is expressed relative to scaled survey time (i.e. estimated time for measuring rather than merely counting abalone). Dashed vertical lines represent coarse effort thresholds, beyond which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset.*

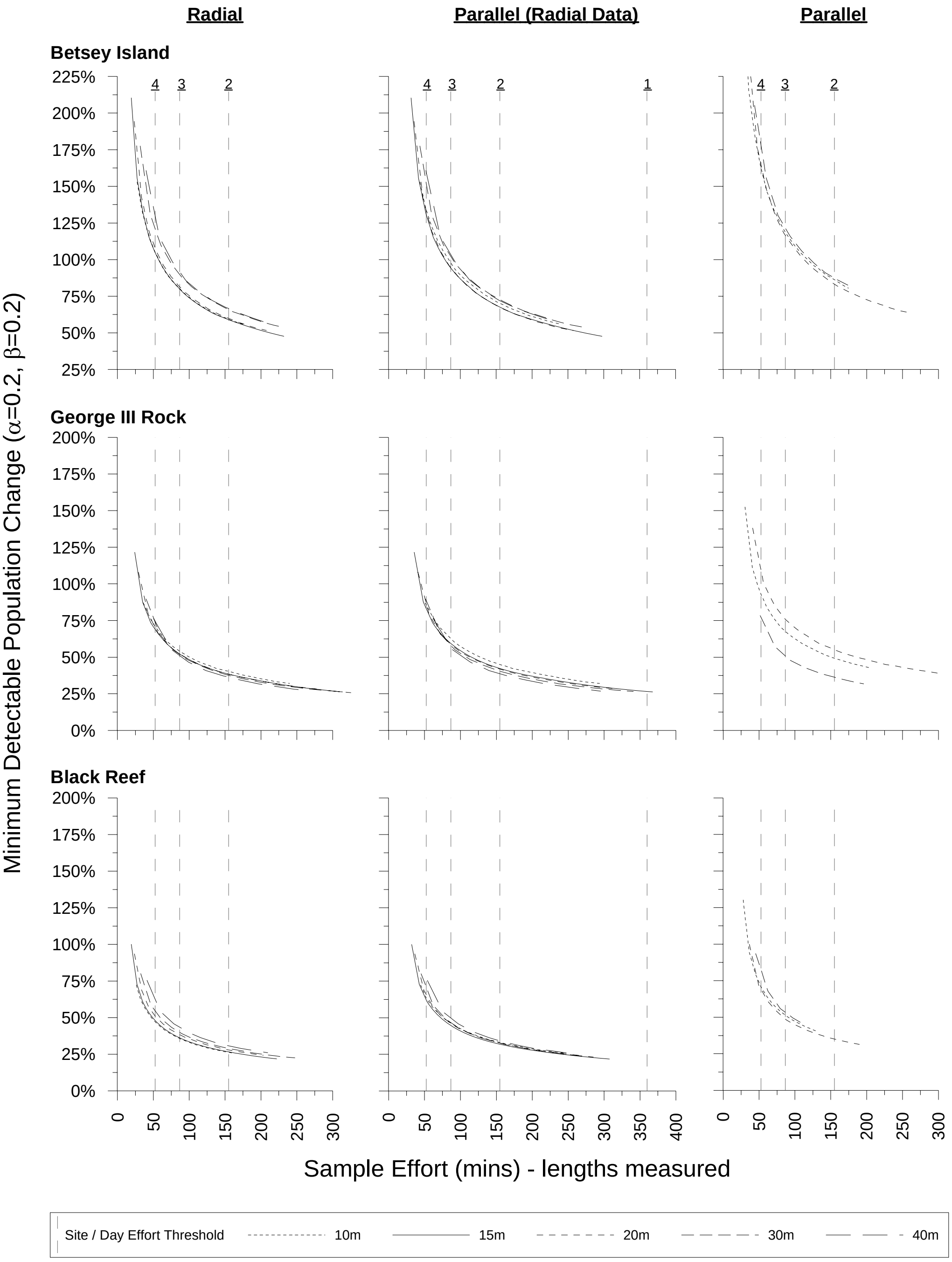

Figure 29. *Average minimum detectable effect size (α = 0.2, β = 0.2) from 5000 paired t-tests on randomly drawn sub-samples of blacklip abalone surveys at Betsey Island, George III Rock and Black Reef. Transect lengths range from 10m to 40m, and effect size is expressed relative to scaled survey time (i.e. estimated time for measuring rather than merely counting abalone). Dashed vertical lines represent coarse effort thresholds, beyond which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset.*

For the sake of completeness, the results for surveys in which abalone were counted but not measured are also presented (Figure 30 to Figure 36). These are unlikely to be as relevant to any potential Tasmanian survey program, since such surveys provide no information on the size distribution of the abalone encountered. Although associated free swimming length-frequency collections can be used to provide some information in this regard, these are known to be biased, both towards larger individuals (McShane et al. 1988, McClanahan and Muthiga 1992, Findlay and Willerton 1996, Hart and Gorfine 1997), and because collection effort is often concentrated in a relatively confined area which may not be representative of the entire site. Furthermore, free swim collections associated with transect surveys provide no error estimates for individual size classes. Although incorporation of such data into fisheries assessment models can assist synthesis of data from numerous sources, the inherent biases and lack of valid error estimates bring into question the value of such information, and the validity of output from models that rely on the same. Nevertheless, count-only surveys are used in a number of fisheries (Gorfine and Dixon 2002, Mayfield et al. 2004b), and as such these results may have wider relevance.

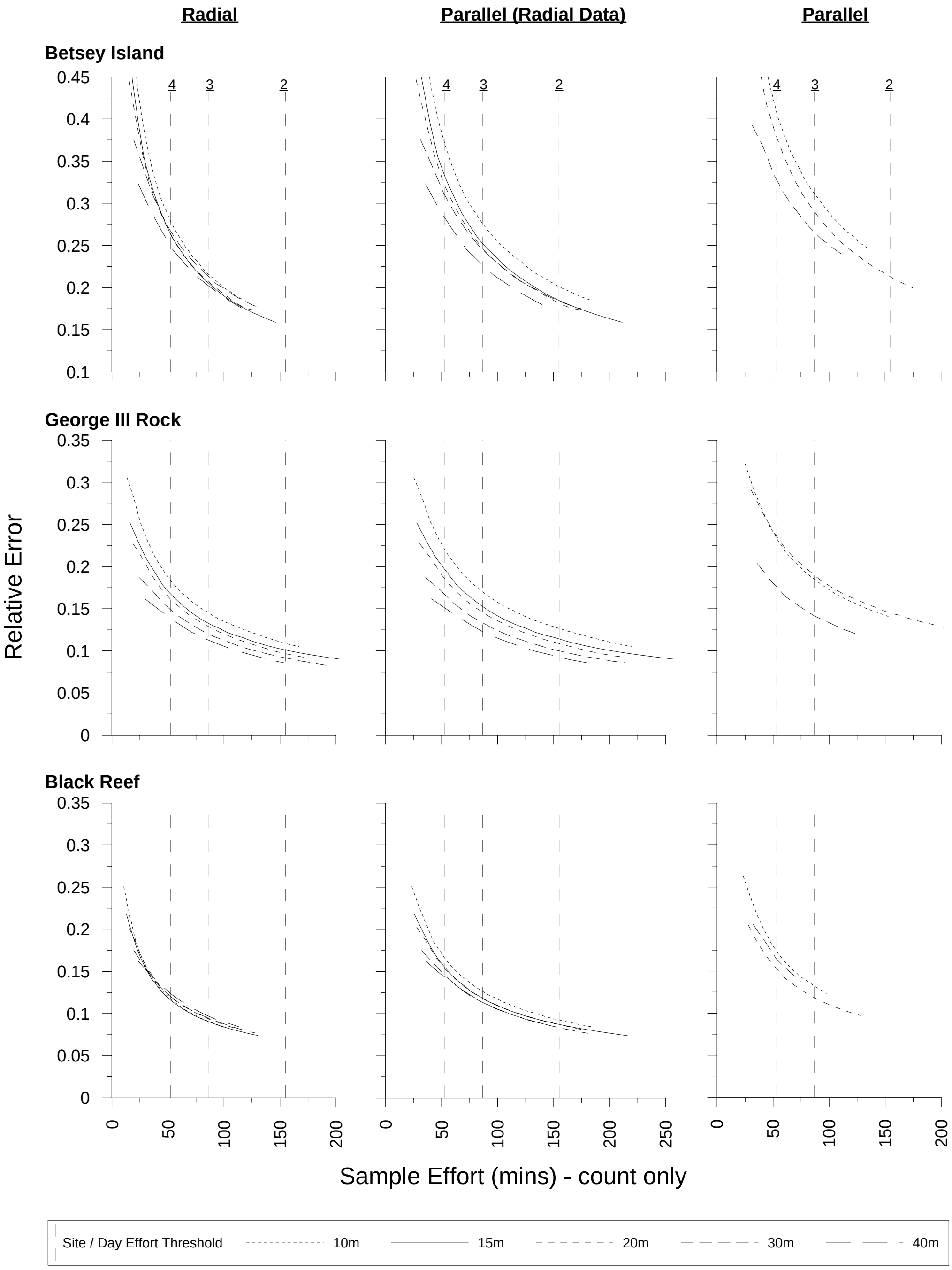

Figure 30. *Average relative error (S.E. ÷ $\bar{x}$) estimates from 10000 randomly drawn Monte Carlo sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from (1m x) 10m to 40m, and results are expressed relative to actual survey time. Dashed vertical lines represent coarse effort thresholds, beyond (i.e. to the right of) which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the relative error estimates calculated from radial transect data, and the right hand column uses data only from the limited parallel transect dataset.*

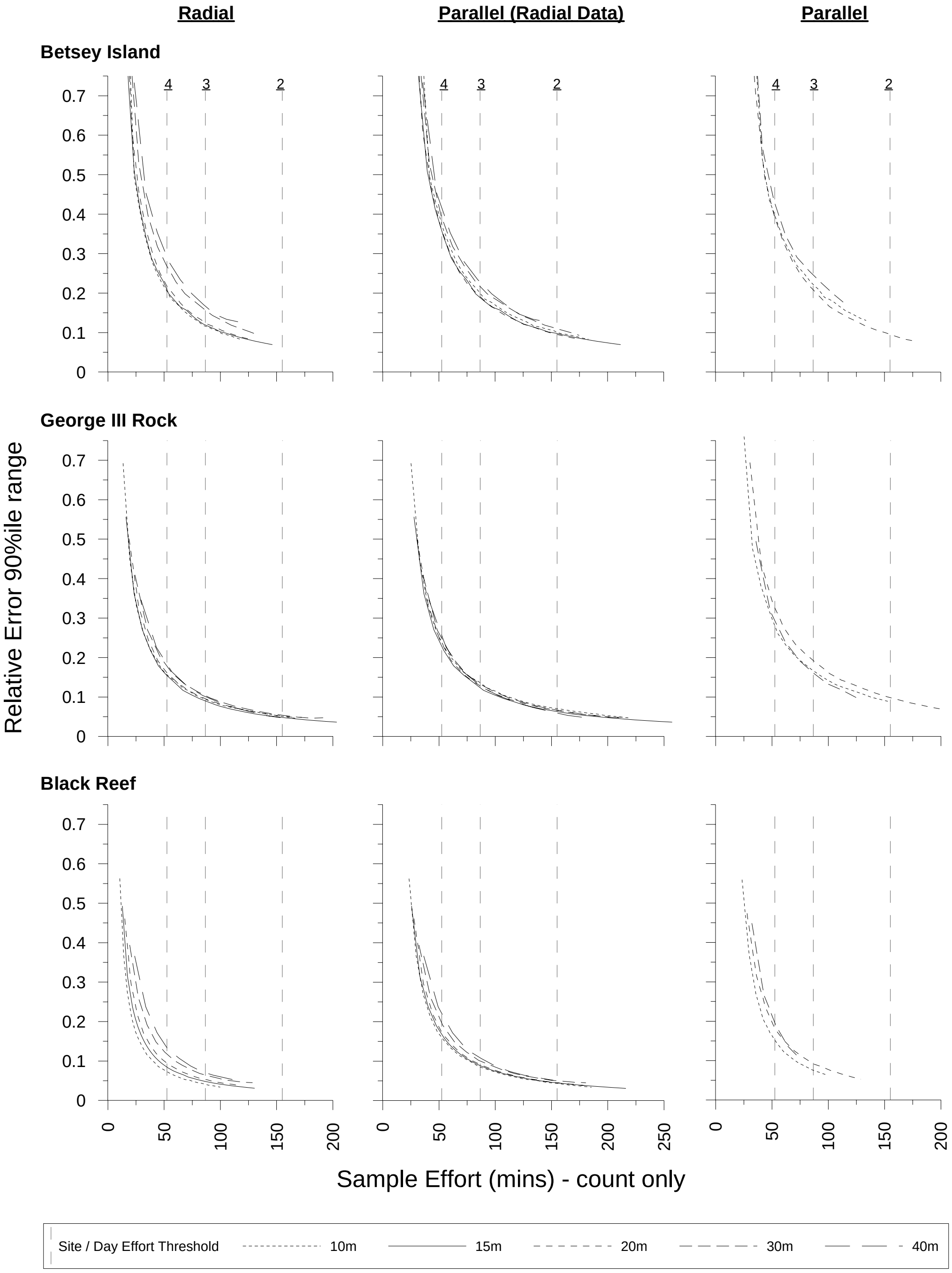

Figure 31. *Ninety percentile relative error (S.E. ÷ $\bar{x}$) range (two-tailed) from 10000 randomly drawn Monte Carlo sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from (1m x) 10m to 40m, and results are expressed relative to actual survey time. Dashed vertical lines represent coarse effort thresholds, beyond (i.e. to the right of) which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the relative error estimates calculated from radial transect data, and the right hand column uses data only from the limited parallel transect dataset.*

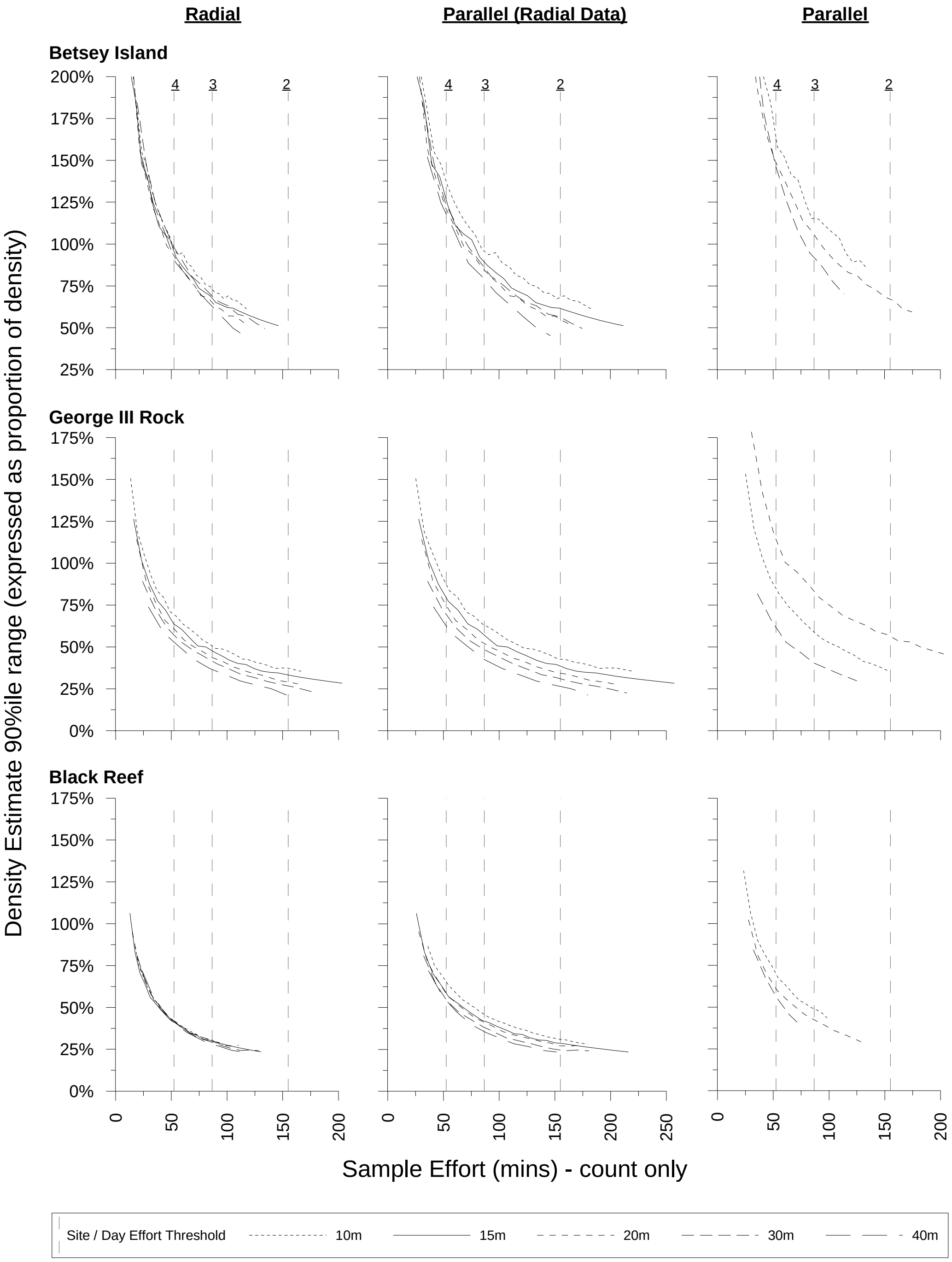

Figure 32. *Ninety percentile range (two-tailed) of density estimates from 10000 randomly drawn Monte Carlo sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from (1m x) 10m to 40m, and results are expressed relative to actual survey time. Dashed vertical lines represent coarse effort thresholds, beyond (i.e. to the right of) which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the range of density estimates calculated from radial transect data, and the right hand column uses data only from the limited parallel transect dataset.*

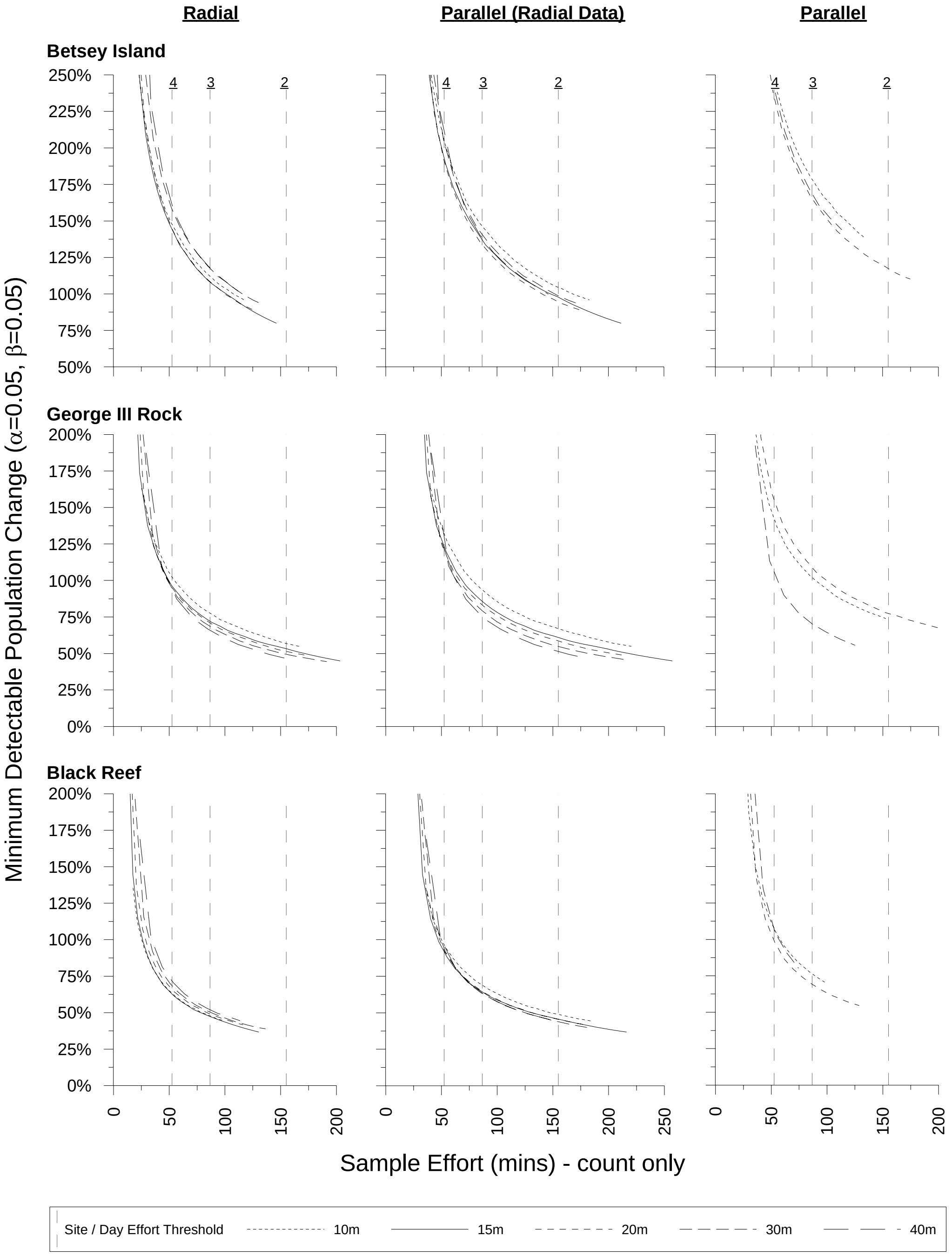

Figure 33. *Average minimum detectable effect size ($\alpha = 0.05$, $\beta = 0.05$) from 5000 paired t-tests on randomly drawn sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from (1m x) 10m to 40m, and effect size is expressed relative to actual survey time. Dashed vertical lines represent coarse effort thresholds, beyond (i.e. to the right of) which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset).*

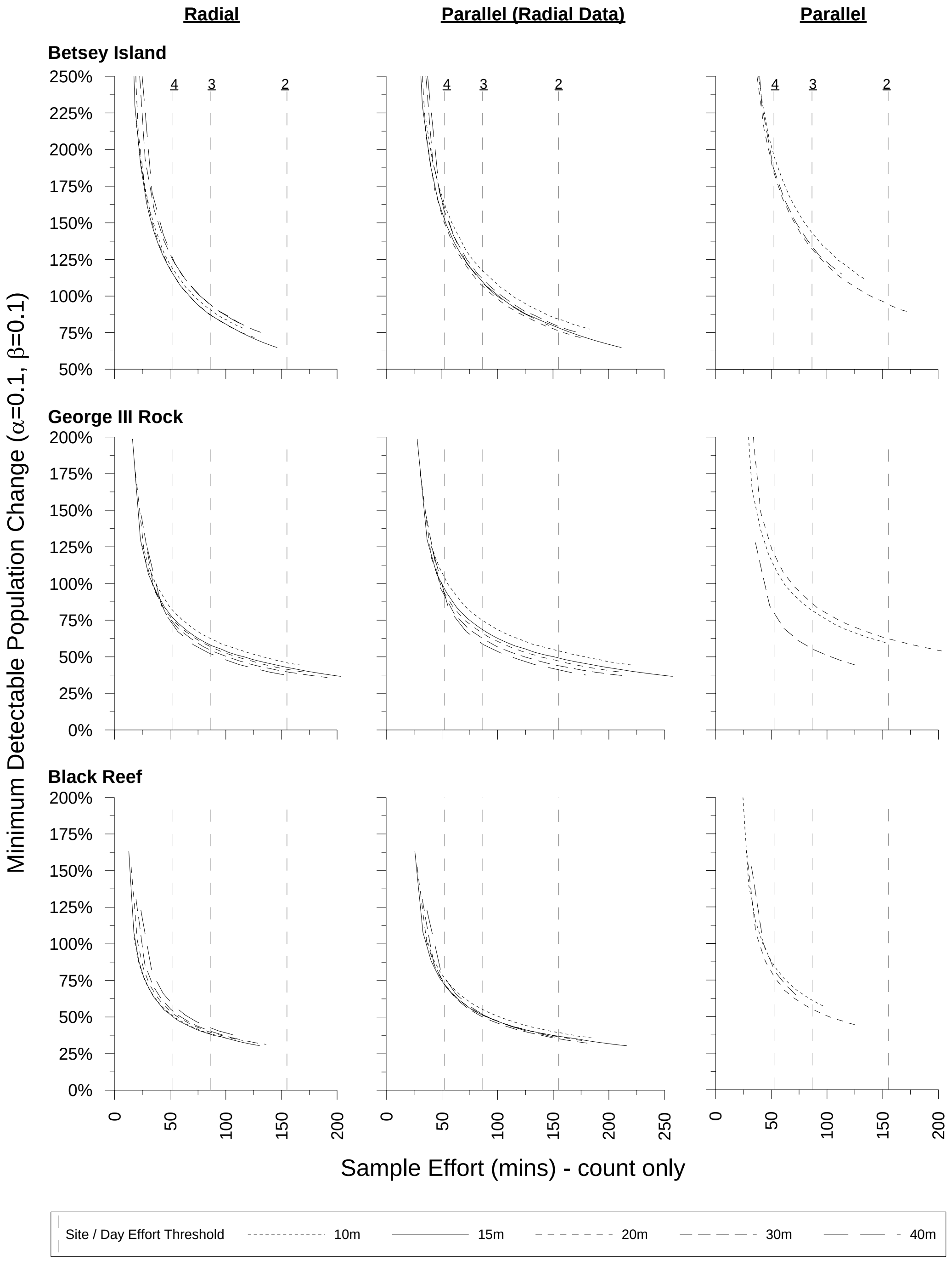

Figure 34. *Average minimum detectable effect size (α = 0.1, β = 0.1) from 5000 paired t-tests on randomly drawn sub-samples of blacklip abalone survey data colected at Betsey Island, George III Rock and Black Reef. Transect lengths range from (1m x) 10m to 40m, and effect size is expressed relative to actual survey time. Dashed vertical lines represent coarse effort thresholds, beyond (i.e. to the right of) which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset.*

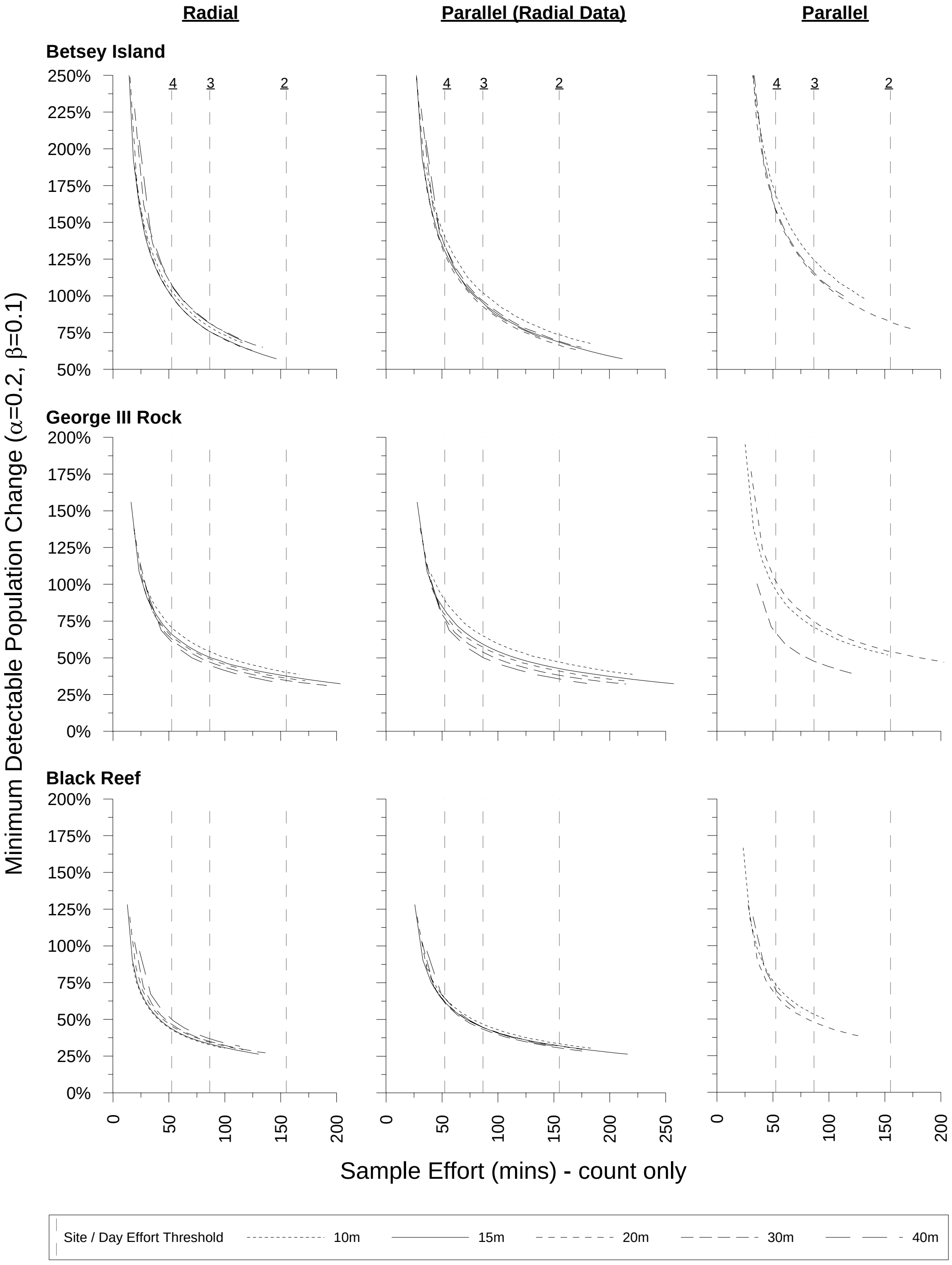

Figure 35. *Average minimum detectable effect size (α = 0.2, β = 0.1) from 5000 paired t-tests on randomly drawn sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from (1m x) 10m to 40m, and effect size is expressed relative to actual survey time. Dashed vertical lines represent coarse effort thresholds, beyond (i.e. to the right of) which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset.*

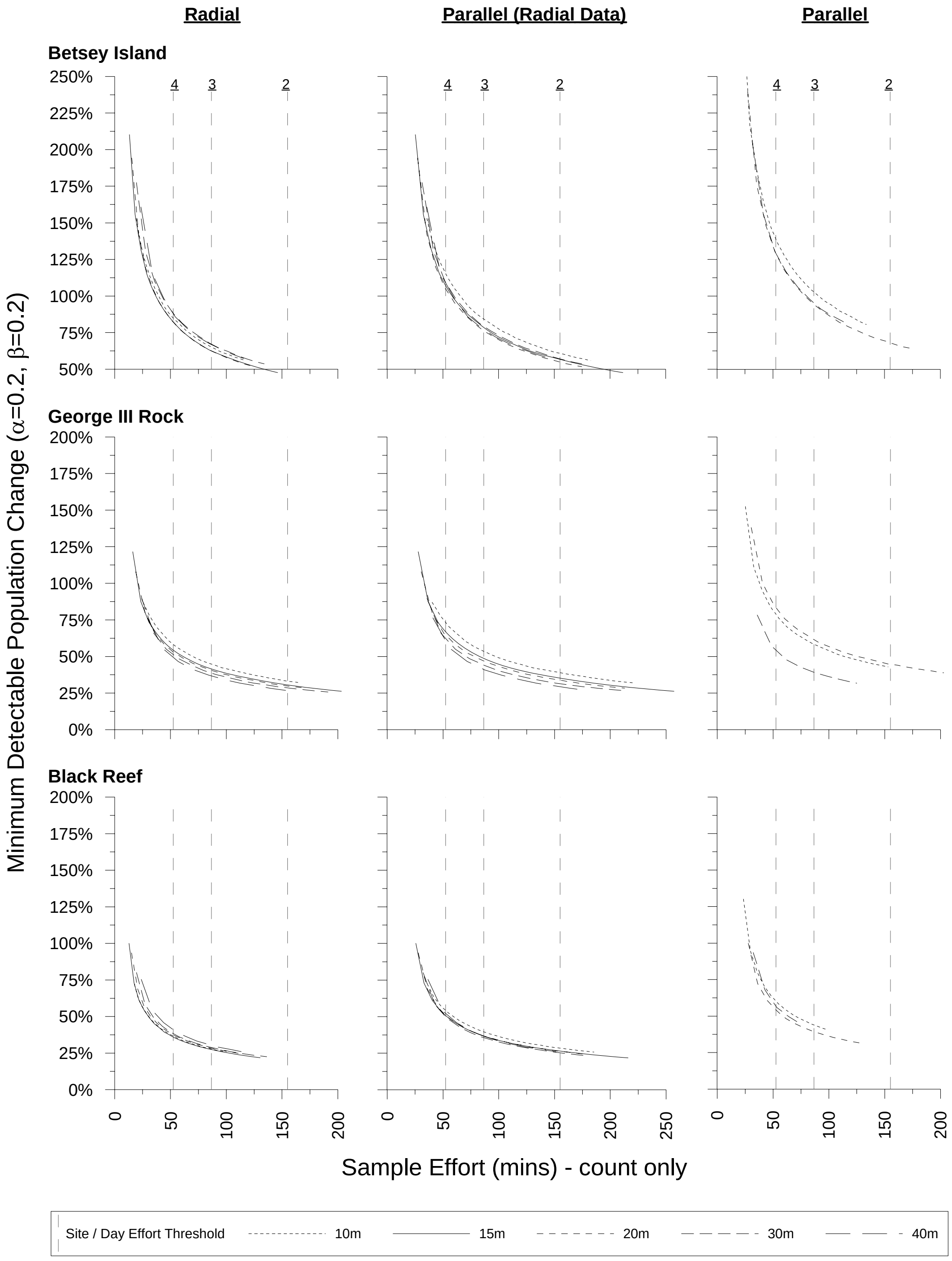

Figure 36. *Average minimum detectable effect size (α = 0.2, β = 0.2) from 5000 paired t-tests on randomly drawn sub-samples of blacklip abalone survey data collected at Betsey Island, George III Rock and Black Reef. Transect lengths range from (1m x) 10m to 40m, and effect size is expressed relative to actual survey time. Dashed vertical lines represent coarse effort thresholds, beyond (i.e. to the right of) which the number of sites sampled per day decreases by one (as per the labels in the top row of plots). Results for radial transects are shown in the left column. Two columns of plots are shown for parallel data: the centre column combines the times for sampling parallel transects with the effect size calculated from radial transect data, and the right hand column uses effect size data from the limited parallel transect dataset.*

In general, for surveys involving only counts rather than measurement of abalone, shorter transects (10m to 20m) are not quite as strongly favoured. The relative efficiency of radial over parallel transects is a little more apparent in such surveys, reflecting the greater proportion of time spent navigating between transects (which is where much of the efficiency benefit of radial transects lies).

Although count-only surveys are more efficient in terms of the number of transects that can be sampled within a given time, this does not generally translate into a substantial improvement in the variability indices over this period. This is because a considerable proportion of survey time is spent on tasks whose duration is independent of whether or not abalone are measured: specifically navigating between transect positions, and in the case of parallel transects, setting up and dismantling sites. Accordingly, estimates of appropriate levels of within-site replication do not differ greatly from those derived from surveys in which abalone were measured, although variability/precision is a little more favourable at each of these thresholds.

6.8.3. Optimum transect arrangement

Despite the conservative approach taken when comparing the performance of radial and parallel transects (i.e. assumption of rapid parallel transect setup and retrieval, and of equivalent search time to radial transects, despite evidence to the contrary), radial transects outperformed parallel units in all instances. When considered in the context of the other advantages of radial transect sampling, such as the broader range of conditions in which surveys can be applied (Callan et al. 1995, Gorfine et al. 1998), and their simplicity of operation, radial transects easily represent the preferred option. Further consideration of transect length and survey intensity is therefore confined to transects with radial arrangement.

6.8.4. Optimum transect length

When the results from the various methods applied for optimising transect length are considered collectively (particularly for surveys in which abalone are measured), 10m to 15m transects are the most consistently favoured, although 20m transects also performed well. However the relative performance of various length transects was not consistent across all sites, or according to all criteria.

At the George III Rock site in particular, longer transects appeared to be more efficient on the basis of a number of criteria (most notably Weigert's method, but also on the basis of relative error and the spread of density estimates). Survey conditions were most difficult at George III Rock, with swell, current and thick (generally 100%) cover of kelps (particularly *D. potatorum and P. comosa*). This hindered both searching and the time spent between transects, but to a differing extent (Table 4). Search time at George III Rock was 28% greater than at Betsey Island and 21% greater than at Black Reef. However, the period from the completion of one transect to the commencement of the next took 60% longer than at Betsey Island and 160% longer than at Black Reef (this was probably, due to the need to clear fouled transect lines from the kelp). Accordingly, the ratio of search time to that spent between transects was smaller at George III Rock than at the other sites. As a result, longer transects were favoured at this site, as the time spent between transects represented a smaller fraction of the total time required to survey such transects. Differences in the power of surveys conducted with different length transects, were less distinct than at George III Rock than at other sites when considered in relation to area surveyed (Figure 20 and Figure 21). This may reflect a difference in the spatial distribution of abalone at this (unfished) site, which would have also influenced the relative efficiency of various length transects.

Later experience with radial transect surveys in which abalone were measured, indicates that where abalone are highly abundant, the twofold scaling factor over surveys in which abalone are merely counted, may underestimate survey time. Abalone were present in relatively high densities at both George III Rock (0.90 abalone m^{-2}), and even more so at Black Reef (1.4 abalone m^{-2}). At Black Reef, and possibly at George III Rock therefore, search time may have been underestimated for scaled surveys. The effect of this would be to reduce the apparent efficiency of shorter transects, by increasing the ratio of time spent between transects to that spent searching. Thus if this was the case at either George III Rock or Black Reef (and it most likely was, at least at the latter), shorter transects would appear less efficient than they really were.

Shorter transects appear to be the most efficient at both Betsey Island and Black Reef. Although longer transects are more efficient according to some criteria at George III Rock, other criteria (particularly minimum detectable effect size) suggest that transect length makes little difference. Other considerations relating to radial transect length include that shorter transects can be used to sample radial sites in a far more representative manner than longer ones (Figure 8), and that shorter transects facilitate greater levels replication for a given survey effort, which improves robustness to violations of statistical assumptions (Harris 1985). Given all of these considerations, shorter radial transects were chosen as being more appropriate for blacklip abalone surveys in Tasmania. One disadvantage of using shorter transects however, is that a smaller total area is searched from a given survey effort. In terms of obtaining representative length-frequency distributions in conjunction with the surveys, this is a less desirable outcome.

There was little difference in the overall performance of transects ranging in length between 10m and 20m. However, the surveys upon which these results are based, required that abalone were counted rather than measured (measurement would have been too time consuming, given the size of the project), and thus the analyses subsequently undertaken related to the entire emergent population. In the context of an ongoing abundance monitoring program however, it is desirable that various sub-groups of the population (particularly pre-recruits and recruits) be analysed separately. Accordingly, the number of individuals from a particular sub-group encountered along each transect will be lower than the total number encountered. This is likely to result in inflated variability in results relating to sub-groups, relative to that for the total population. Furthermore, a general rule of thumb that has been suggested for maximising precision, is that the number of sample units which contain no individuals should not exceed the number which contains only one individual. At all sites surveyed during this phase of the work, 10m transects met this criteria. However, when the effect of selectively analysing sub-groups of the population was simulated by reducing the densities of abalone by 50% to 67% at each site[8], 10m transects at the Betsey Island site no longer meet the criteria relating to the number of transects containing zero individuals exceeding that containing one. Fifteen metre transects on the other hand, did meet this criteria. On this basis, 10m transects were eliminated from consideration.

Given that spatial bias in radial transect sampling is minimised and replication maximised by constraining transect length, the decision was taken to proceed with 15m transects over those of 20m length, for ongoing sampling of *H. rubra*. This is of particular significance given that sample units of large area (e.g 30m^2 – 100$^+$m^2) have been frequently applied in the estimation of blacklip abalone abundance. An additional benefit of short transects is that it allows smaller sites to be used, which in turn increases the versatility of the method for application on the narrow fringing coastal reefs which are common on the east coast of Tasmania.

6.8.5. Optimum within-site replication

Clear inconsistencies existed between sites, with regard to amount of effort required to yield “acceptably” precise results. On the basis of results from the low density Betsey Island site, survey intensity at the one to two site per day level (around 2.5 hours to six hours per site) was generally indicated, although three sites/day (~1.5 hours/site) can be surveyed if the relative error target were to be set at an average value of 0.25 (Gorfine and Dixon 2002).

Higher levels of replication were acceptable at the other sites, with sampling intensity at the two to three sites per day level generally appearing appropriate according to the criteria implied by (Bros and Cowell 1987). Where the target for relative error is set at an average value of 0.25 however, a sampling intensity of four or more sites/day (<55 mins/site) appears acceptable.

In general, the results from Black Reef were a little less variable than those from George III Rock, and thus it appears that less survey effort is required at this site to achieve a given level of precision. However, the abalone at this site were particularly dense (1.4 abalone m^{-2}), and as such, the scaling factor used to approximate survey time (assuming measurement of all abalone) may have underestimated the actual duration. As such, the relative efficiency of surveys at the Black Reef site may not be substantially higher than those at George III Rock.

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[8] This was achieved by dividing the numbers of individuals encountered in each 5m x 1m transect segment by two or three, as appropriate. Where this division yielded non-integer values, the results were rounded up or down to the nearest integer value, using a weighted random process. Thus for example, if the remainder of the quotient was 0.333, then there was a 2/3 chance that this value would be rounded down, and a 1/3 likelihood of being rounded up (this rounding process was performed numerous times, to ensure that the results obtained were not spurious).

Samples from lower density populations are typically more variable, in relative terms, than those where the survey subjects are relatively dense (Underwood 1981, Bland and Altman 1999). Since separate analyses are likely to be conducted on different size classes of abalone, densities of the individual size sub-groups will be lower than that for total abundance as considered here. The greater tendency of smaller *H. rubra* to aggregate around semi-cryptic habitats may further add to the variance of the pre-recruit size class (in southern and western Tasmania, large individuals of *H. rubra* are commonly found in fully exposed habitat such as on top of large rocks, and this may reduce variance when all size classes are considered together). Additionally, the densities encountered at the George III Rock and Black Reef sites are a little higher than would generally be expected throughout most of the fishery (the high abundance at Black Reef was unknown and expected when sites were being selected[9]). As such, a conservative assessment of the number of sites that can be surveyed in a day may be appropriate.

When all results are considered together, a general target of around two sites per day appears to be a reasonable starting point for a survey program, although if low variances are expected at those sites sampled on a given day, then a target of three sites for that day might be more suitable. However, the estimates of optimum within-site survey intensity developed here are coarse at best.

The optimum balance of within-site and among-site replication ultimately depends on a number of factors. Variability associated with results plays a major role in determining this balance. This may arise from a variety of sources, including within-site spatial variability, temporal variability within sites (i.e. the amount of noise associated with temporal abundance trends at each sites) and among sites (i.e. the consistency of trends across multiple sites). However, other factors also play a role. For example, site dimensions are important, since fewer transects can be used to sample a given proportion of the total area of small sites as opposed to large ones, and since populations are more likely to be homogeneous over smaller areas (the sites on which these results have been based, are approximately 2.5 times as large as the radial sites used in Victoria). Another important factor is the balance between the number of radial and other less efficient transect sites used (radial transects are unlikely to be universally suitable for application in narrow habitats such as fringing reefs). Where surveys are conducted at depths below about 9m, short bottom times may limit the number of transects that can be surveyed in a given day, and thus strongly influence the design. Finally, the scope, goals and resources available for the monitoring program are also critical considerations.

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[9] The Research Officer on this project was injured at the time, and was not able to participate in the surveys at this site. Accordingly, the site was not assessed until after the survey had commenced.

7. Application of the Modified Radial Transect Method: Initial surveys

With theoretical issues associated with application of the radial transect method addressed, and an "optimal" transect length of 15m (x 1m) identified, the focus of the work shifted from computer based assessment to practical field implementation of the method in a range of habitats. An important aspect of implementing any sampling schema to assess a real fishery is to locate the fixed sites, within which the random sample will be taken, at places that are representative of the fishery under observation.

7.1. Selection criteria for survey sites

A number of potential sites were identified for the initial field trials in the south-east of the state. This region was selected for a number of reasons, including proximity to the research base, the importance of the area to the fishery, concerns about stock depletion in this area, and that much of the region is characterised by steep narrow reefs which make the application of randomly positioned transects particularly challenging. Initial site selection was made largely on the basis of past research sampling, discussions with commercial abalone divers, observations of fishing activity, and importantly, from benthic habitat maps that had recently been developed for the area (Barrett et al. 2001b).

Upon initiation of these abundance survey trials, it quickly became apparent that the site selection process used for other sampling programs (e.g. growth, size at maturity) was inadequate for practical application. Relatively small positional differences (in the order hundreds of metres or less) frequently led to considerable differences in abalone abundance and in habitat type and continuity. Furthermore, areas considered good for fishing by abalone divers (who generally cover a considerable distance when fishing) were frequently found to be unsuitable for abundance assessment due to factors such as depth and the narrow or patchy distribution of suitable habitat or of abalone. In other areas identified by abalone divers as good abalone fishing grounds, few abalone were found, possibly indicating localised depletion. Although the habitat maps proved to be an invaluable resource in terms of site selection, the scale at which these maps were developed meant that they were often inaccurate at the relatively fine-scale required (metres).

A somewhat arbitrary decision was taken that the minimum site size required for a (semicircular) 15m x 1m radial transect site would be around 80m x 40m (primarily to constrain the ratio of transect length to site radius). In order to constrain variance to a "reasonable" level, and hence minimise the magnitude of the effect size that could be detected, sites were sought where abalone were distributed throughout most of the site. However, such deliberate selection of sites, raises issues about possible undesirable consequences on the results of a long-term survey program (Van der Meer 1997). One such issue is that where sites are placed specifically at those locations in which abalone occur across relatively wide areas (i.e. at least 40m x 80m); particularly in an otherwise depleted region; survey trends detected at these sites may differ from those in the broader population to which the inferences supposedly relate. For example, if distribution over a broad area is somehow indicative of the resilience of abalone at such locations, a conclusion of relative stability may be drawn, when in fact the broader stocks are trending downwards (Shepherd et al. 2001)..

The process of site selection is thus a critical aspect of the design of a long-term abalone survey program. This problem could be theoretically solved through random or spatially representative positioning of sites (Van der Meer 1997) (for fixed sites, this would refer to their positioning on the first survey occasion). However, this raises a second issue, the solution to which is diametrically opposed to that of the first; that is, completely random placement of sites leads to high among-site variances, requiring impractically large samples.

The risk of serious negative consequences arising from such hyperstability in survey results due to preferential site placement is, however, not likely to be great where strong depletion of surrounding stocks has already occurred. Indeed, in this situation, it is likely that any bias that does result from such a survey design would actually be in favour of detecting further decreases. Under a scenario where the fishery is depleted and fishing maintained at unsustainable levels, continued declines will manifest both in a reduction of the number of productive reefs, and in the density of abalone on the remaining productive reefs, as effort is displaced towards these areas (Prince and Hilborn 1998, Shepherd 2000, Gorfine and Dixon 2001). Under these circumstances therefore, such areas should be sensitive to negative trends in the surrounding fishery. However, this design may not be as sensitive to detecting recovery in the fishery. Should this occur, for example due to an appropriate reduction in fishing pressure or a broad-scale recruitment pulse, then recovery of previously depleted reefs which are not monitored will not be detected at least until such areas have been identified after the recovery has commenced (although the redirection of fishing effort into these areas should result in recovery at the survey sites). Although not an ideal scenario, this is consistent with the precautionary principle widely espoused as appropriate for successful fisheries management, in that if such bias does exist in the survey program it would be in favour of detecting depletion.

Although the placement of survey sites at locations were abalone occur across “reasonably” broad areas is less desirable than random site placement (Hilborn and Walters 1992, McShane 1998, Shepherd et al. 2001), there are mitigating factors for such a design beyond the practical necessity of minimising sample variances. For instance, areas with relatively consistent abalone distribution tend also to be those with “reasonable” abalone density. As such, the preferential placement of survey sites in these areas is likely to reflect the distribution of fishing effort, in that fishers tend to focus on areas where catch rate expectations are likely to be met (Prince 1989c, McShane 1998, Gorfine and Dixon 2001, Officer et al. 2001a).

In a fishery such as that for Tasmanian abalone, where all but the most optimistic assessments would concede either full- or over-exploitation throughout many (if not most) management areas; particularly in the Eastern Zone (Tarbath et al. 2005) where the survey effort was initially focussed; the distribution of fishing effort is likely to closely reflect the overall distribution of abalone stocks. As such, focussing sampling on these areas should provide both an indication of changes in the fishery, and the overall stocks. Such "preferential" targeting of locations with higher density is a reasonably common practice for haliotid surveys (Andrew et al. 1998, McShane 1995, Rodda et al. 1998a, Andrew et al. 2000a).

Furthermore, it is generally believed that the mechanism of overfishing of abalone stocks involves the serial depletion of abalone-producing reefs, until ultimately only the most productive (or isolated) reefs in the fishery continue to sustain consistent stocks (Prince 1989c, Shepherd 2000, Gorfine et al. 2001, Gorfine and Dixon 2001, Officer et al. 2001a). It is almost certain that the Tasmanian Eastern Zone fishery has experienced such serial depletion, and those reefs which continue to support reasonable stocks are particularly important to the fishery (Tarbath et al. 2003). If other reefs do not recover, then it is appropriate that survey effort focuses on the areas that continue to support "commercial" abalone populations. However, if recovery does occur, then "recovered" reefs can be identified for future surveys, whilst the longest time series of data would relate to those "core" areas which have proven to be most important to the fishery when stocks are depleted.

If spatial shifts occur in the overall distribution of abalone meta-populations , this could have a confounding effect on results, possibly leading to an interpretation of stock decline when, in fact, this is not the case (whether such shifts occur, and even whether broad meta-populations genuinely exist within the blacklip fishery however, is debatable). Should this occur, the consequences of such misinterpretation would again be on the side of caution, and would favour further recovery, or at worst, stock stability. As such, this would be unlikely to lead to any long-term damage to the fishery.

In the placement of sites for this project, an intermediate solution to the issue of random versus deliberate site location was chosen. This involved random (or haphazard) selection of survey sites from those identified as likely to be suitable (the method was haphazard in that weather and sea conditions influenced which sites would be selected on a given day). On a fine-scale, positioning of sites was done somewhat selectively in order to avoid areas of obviously unsuitable habitat or those with few abalone. This solution is analogous to the random selection of sites from those with "reasonable" densities in abalone surveys elsewhere, such as South Australia, Victoria, New South Wales and New Zealand (Andrew et al. 1998, McShane 1994, 1995, Rodda et al. 1998a, Andrew et al. 2000a), and is consistent with the need to randomise specifically at the lowest level of replication (i.e. the transect). Although weather conditions played a part in survey site selection during the pilot scale study, a more robust randomisation process would be desirable in the context of a larger ongoing monitoring program.

In depleted areas such as North Bruny Island, it is not possible to know whether the paucity of abalone at a given site is attributable to depletion, or due to the particular location being one in which abalone abundance is naturally low (as it is common to find areas that appear to contain suitable abalone habitat, but few, if any abalone). Thus it cannot be predict whether survey sites placed in such areas will be useful for detecting changes in relative abundance.

This problem is exacerbated by the fact that even when abalone are present in an areas, considerable variation in abundance can occur on the scale of tens of metres. In situations such as this, the best solution for site placement may simply be to take suggestions from divers who have historically fished the region, and to search within such locations for areas of habitat that appear to be suitable for abalone. Although this process is undoubtedly both subjective and somewhat arbitrary, it nevertheless probably represents the most (and perhaps the only) practical solution short of excluding unsuitable sections of the fishery from survey monitoring.

It may be that in some places, it is only possible to incorporate a limited number of survey sites. One such area may be the exposed southern end of the Tasman Peninsula (statistical sub-blocks 20C and 21A and 21C), which is a particularly steep area characterised by tall cliffs that rise from the waters edge. As a result of this topography, sufficiently shallow areas of reef in this region are particularly steep, narrow and exposed. Because dives beyond 12m depth[10] are considered impractical due to restrictions imposed by the Australian Standard for Scientific Diving (Standards Australia 2002), it may not be possible to survey multiple sites in each reporting sub-block in this area.

Although such depth restrictions on research dives mean that deeper water stocks will be (either largely or completely) excluded from abundance assessments, anecdotal evidence suggests that only a small proportion of the total catch (considerably less than 10%) is taken in deeper water throughout much of the fishery (more precise information on the depth at which catches are taken is unavailable due to the limitation precision with which this information has been reported, particularly prior to 2004). As such, any adverse effect on abundance estimation from failing to monitor "deep water" stocks is likely to be minimal in many areas.

7.2. Initial survey results

At those sites where the method was used (Figure 37), modified radial transects proved both effective and efficient (in relative terms) for estimating abundance of abalone. Some difficulties were encountered, including discontinuous habitat, the narrow sub-littoral distribution of abalone in many areas, prohibitive depths, patchy abalone distribution and an incomplete knowledge of the precise location of abalone "beds". However, these issues are not unique to the radial method, and are generally likely to be most problematic during initial surveys (after which, the same locations will merely be revisited).

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[10] Or 9m depth if the site is more than 2 hours away from a recompression chamber.

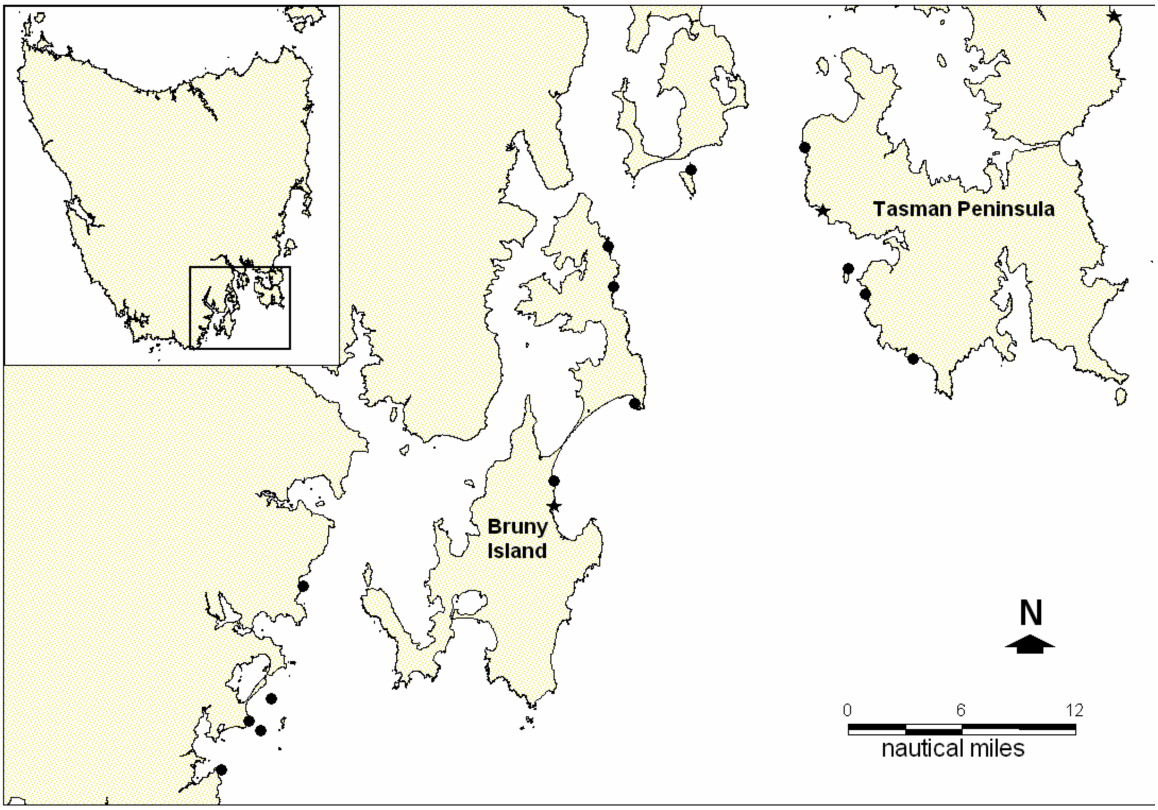

Figure 37. *Radial transect survey sites in south-eastern Tasmania. Circles (•) = sites surveyed during initial trials, stars (★) = sites added during subsequent surveys.*

The precision of the sample estimates was determined for five different categories of emergent abalone: recruits (>=136mm), pre-recruits (100mm – 135mm), juveniles (<100mm), all emergent abalone larger than 100mm and total emergent abundance. As expected, relative error (S.E. ÷ $\bar{x}$) was generally smallest for the total abundance of emergent abalone (0.13 to 0.46) and all abalone >100mm (0.13 to 0.45), and was highest (0.19 to 1.00) for juveniles (Table 5). However there was no consistent trend in terms of the precision of recruits and pre-recruits, other than that this was intermediate to that of the aforementioned groupings. Furthermore, the precision of results for individual size classes are somewhat erratic (for example pre-recruits at Fishers Point and Eliza Point, and recruits at Black Reef and Blighs Rocks).

Table 5. Estimated abundance and relative error estimates from initial abundance surveys (Means = Mean abundance; "Emergent" = all emergent abalone; "100mm to LML" = emergent abalone >100mm and <136mm; ">LML" = emergent abalone equal to or larger than legal minimum length of 136. Results are expressed as number of abalone per 15m^2 transect. Coefficients of Variation (CV) are presented in order to allow comparison with results from surveys undertaken in other fisheries, where precision was reported in these terms. All sites had a radius of 55m; those marked with an asterisk (*) were semicircular, and all others were circular.

Site (Reporting Block)	N	Means			Relative Error (S.E. ÷ $\bar{x}$)			CV		
		Emergent	100mm to LML	> LML	Emergent	100mm to LML	> LML	Emergent	100mm to LML	> LML
Fishers Point (13C)	12	3.7	0.4	2.1	0.16	0.46	0.22	0.54	1.60	0.75
Black Reef (13D)	12	25.9	12.5	0.6	0.13	0.11	0.39	0.44	0.37	1.36
Eliza Point (13D)*	12	5.2	1.8	1.2	0.19	0.39	0.22	0.67	1.34	0.77
George III Rock (14A)	12	16.7	7.2	7.0	0.14	0.16	0.20	0.48	0.57	0.69
Lady Bay (14B)*	12	4.2	1.7	2.8	0.30	0.48	0.24	1.04	1.67	0.84
Blighs Rocks (16B)*	12	3.8	2.4	1.1	0.20	0.22	0.41	0.70	0.76	1.42
One Tree Point (16D)*	12	9.6	5.3	2.2	0.18	0.21	0.26	0.61	0.72	0.90
Moorinna Bay (16C)*	10	1.1	0.6	0.4	0.50	0.34	0.41	1.45	1.79	1.29
Trumpeter Bay (16D)*	12	1.7	0.5	0.5	0.41	0.46	0.46	1.41	1.60	1.60
NW Betsey island (17A)	12	3.7	1.0	1.8	0.18	0.23	0.20	0.56	0.74	0.65
Black Jack Bight (17B)*	12	5.2	3.5	1.0	0.21	0.28	0.28	0.74	0.95	0.95
Wedge Island (20B)*	12	5.9	3.4	1.8	0.14	0.23	0.25	0.47	0.80	0.87
Crooked Billet Bay (20B)	14	6.0	2.8	1.9	0.23	0.28	0.37	0.87	1.04	1.37
Shipstern Bluff (20C)	12	7.0	4.4	2.3	0.24	0.31	0.23	0.82	1.07	0.78

Comparison of the precision of sample estimates from these surveys to results from haliotid surveys conducted elsewhere (Table 6) suggests that the results from this project are within the typical range experienced for work of this nature. Such comparisons however, provide only a rough indication of the relative success of the surveys, given the differing species, habitats, objectives, sample sizes and survey techniques used across the various studies. Moreover, although survey data may be relatively precise, they may also be inaccurate or biased, and as such misleading (Nash et al. 1995, Hart and Gorfine 1997, Hart et al. 1997b). Area-based methods are however, considered to be among the most accurate (Hart and Gorfine 1997, Hart et al. 1997b).

On the basis of the efficiency and comparable performance of the radial transect surveys, the technique was adopted as the method of choice for future surveys.

Table 6. Summary of precision values from haliotid surveys of *H. rubra* and other species. "Emergent" = all emergent abalone; LML = legal minimum length

Reference	Species	Location		CV		R.E. (S.E. ÷ $\bar{x}$)	
			Sizes (mm)	**Lower**	**Upper**	**Lower**	**Upper**
This study	*H. rubra*	Tas (Eastern Zone)	Emergent	0.44	1.45	0.13	0.46
			>=100mm	0.44	1.41	0.13	0.45
			<100mm	0.66	3.46	0.19	1.00
			100mm-LML	0.37	1.80	0.11	0.57
			>= LML	0.65	1.60	0.20	0.46
(Gorfine and Walker 1997a)	*H. rubra*	Vic (Eastern Zone)	80mm-LML			0.12	0.39
			> LML			0.06	0.41
		Vic (Central Zone)	80mm-LML			0.12	0.78
			> LML			0.20	0.67
		Vic (Western Zone)	80mm-LML			0.16	0.26
			> LML			0.20	0.27
(Rodda et al. 1998a)	*H. rubra*	SA (Western Zone)	Emergent	0.28	0.70		
			< LML	0.40	1.04		
			> LML	0.55	1.10		
		SA (Southern Zone)	Emergent	0.40	0.72		
			< LML	0.60	0.70		
			> LML	0.40	1.03		
(Shepherd et al. 1999)	*H. rubra*	SA (Western Zone)	Emergent			0.10	0.21
			< LML			0.11	0.28
			> LML			0.13	0.23
			Emergent			0.03	0.25
			< LML			0.09	0.27
			> LML			0.09	0.26
(Rodda et al. 1998a)	*H. laevigata*	SA (Western Zone)	Emergent	0.33	0.73		
			< LML	0.35	0.91		
			> LML	0.35	0.96		
(Shepherd et al. 1999)	*H. laevigata*	SA (Southern Zone)	Emergent			0.12	0.23
			< LML			0.13	0.30
			> LML			0.12	0.16
(Hart et al. 1999)	*H. laevigata*	WA (Zone 2)	Emergent	0.36	0.49	0.18	0.25
			<= 140mm	0.40	0.50	0.20	0.24
			141-150mm	0.28	0.56	0.14	0.27
			>= 150mm	0.59	0.61	0.29	0.31
(McShane et al. 1996)	*H. iris*	New Zealand	Emergent	0.57	1.53	0.08	0.30
(Campbell et al. 1998)	*H. kamtschatkana*	Canada (BC)	Emergent	0.44	1.48	0.14	0.58
(Tegner et al. 1989)	*H. rufescens*	USA (California)	All sizes			0.25	0.61
			>= 178mm			0.35	0.64
			>= 197mm			0.60	1.00
(Tutschulte 1976) cited in (McShane 1998)	*H. corrugata*	USA (California)	?	0.6	1.0		
	H. fulgens	USA (California)	?	0.8	1.7		

8. Maximising the Efficiency of *In Situ* Abalone Measurement

The ability to detect changes in abalone density is negatively affected by both spatial and temporal variability. In theory, variance arising from spatial sources can be reduced through stratification. In practice however, such stratification is impractical in the context on a broad-scale fisheries monitoring program, particularly at the within-site (i.e. transect) level. This is because the scale of knowledge required to assign such strata is unobtainable, in practical terms, on the scale of the Tasmanian fishery. Furthermore, implementation of such a sampling strategy requires a means to precisely locate and identify strata boundaries on each survey occasion, and assign sample unites accordingly.

Increasing replication, both spatially (e.g. the number of transects per site and sites per region) and temporally (i.e. survey frequency), is the most fundamental way to improve survey sensitivity. In a large-scale survey program, such as that proposed for the Tasmanian abalone fishery, the ability to maximise such replication strongly depends upon the efficiency with which surveys can be conducted. Although the radial transect method has been demonstrated to be both effective and efficient (Chapters 5 and 6), any further efficiency gains that can be made are valuable.

During the initial radial transect surveys, all abalone encountered along the transects were collected and taken to the surface where they were measured (Callan et al. 1995). Once measured, the abalone were then returned by hand roughly to the area from which they were taken. This was done both to reduce mortality, and minimise disturbance to the population at the fixed sites. Arguably the least efficient aspect of this procedure was the careful replacement of abalone.

It was suspected that *in situ* measurement may improve efficiency, however underwater recording of lengths by traditional means (such as slate and pencil) is relatively time consuming and difficult in rough conditions, and as such was unlikely to offer great efficiency gains. In South Australia, a manual underwater measuring gauge is used for *in situ* measurement of *H. laevigata* (Shepherd 1985). Because of the tendency of *H. rubra* to occupy cryptic or semi-cryptic habitat, these gauges have not been as widely used for blacklip abalone, as it has generally been considered more efficient to collect abalone for measurement at the surface. However, the South Australian applications, for which the gauge was developed, do not involve the use of fixed survey sites, and as such limited mortality or disturbance over a small area are not major concerns. As a result, abalone can be returned to a different area from which they came, and without any great need for special care. In the context of the methodology applied in this survey however, where the abalone are carefully returned to the approximate location from which they were taken, it was felt that these gauges may afford some efficiency improvements.

8.1. Accuracy of underwater measurement

Although an underwater measuring gauge had been used for collecting length-frequency data in South Australia for some time (Shepherd 1985), no published data were available on the accuracy of the measurements thus made. Measurement is generally more difficult underwater than that at the surface, and accuracy may be adversely affected by a number of external factors such as surge and weed. Unlike the measuring boards that are commonly used in Tasmanian abalone research, the jaws of theSouth Australian measuring gauge were narrow, and thus accurate measurement also depended on the ability of the diver to consistently determine the longest point of each asymmetrical abalone shell.

In South Australian surveys, where abalone cannot be directly measured without removal from the substratum (due for example to partial crypsis, or hindrance from weed or reef structure), the past practice was to estimate shell lengths. These estimates were recorded using the measuring gauge, and were thus indistinguishable from “true” measurements. Again, no published information was available on the accuracy of such estimates.

To this end, a small study was undertaken to assess the accuracy of underwater measurement with a gauge device similar to that used in South Australia[11].

8.1.1. Methods

Eight hundred tagged abalone of known length, were released into a bay near Blackjack Bight in south-eastern Tasmania (43° 1.2’ S, 143° 37.2’ E). These were given time to disperse, and then measured *in situ* by research divers. Because the South Australian gauge design does not lend itself to relating individual measurements to particular abalone, and due to the expense of making such gauges, Vernier callipers were used as an analogue, and the tag number, length and position of each abalone (cryptic, semi-cryptic or fully emergent) was recorded.

During this trial, the majority of abalone measured underwater were removed from the substratum prior to measurement, with the lengths of the remainder being either measured, or estimated, whilst still attached (depending largely on whether or not they were in a suitable position for measurement). This allowed the accuracy of measurements of abalone in each of these groups to be assessed separately.

8.1.2. Results and Discussion

The relationship between the measurements taken at the surface, and those measured or estimated underwater were generally tight (Figure 38). Circumstances were such that the

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[11] Inquires had been made into developing an electronic gauge / data logger, and a basic design was proposed, however the physical size of such the unit was prohibitive, and thus the “South Australian” gauge represented the best available option.

"underwater" measurements could not be made until a month following measurement at the surface, and it was feared that some growth may have occurred during this time, which would have confounded the results. If growth did occur however, it is not apparent in the results. Furthermore, given that the work took place during the slow growth season of late-May to late-June (unpublished data) when water temperature at the site was around 10°C, it is reasonable to assume that any such growth was indeed negligible[12].

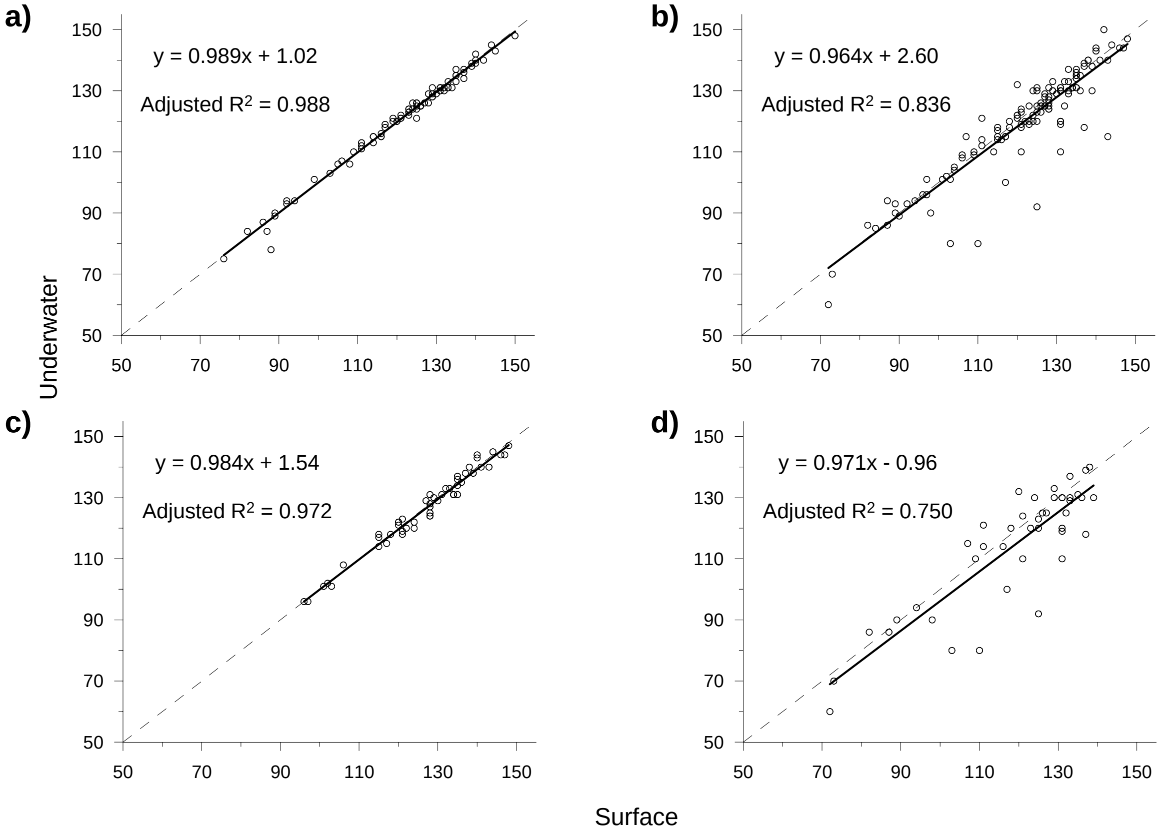

Figure 38 *Relationship between length measurements collected underwater (vertical axis), and those taken at the surface (horizontal axis). Surface measurements were taken one month prior to underwater measuremen: (a) abalone measured following removal from substratum; (b) abalone not removed from substratum (measured in situ where accessible, and lengths estimated where not); (c) emergent and accessible abalone measured without removal from substratum; (d) abalone lengths estimated due to inaccessibility of measuring gauge. Note: (c) and (d) are constituent sub-datasets of (b). The shorter dark line is the regression line, and the lighter dashed line is a provided as a reference at unity. The y variable relates to underwater length measurement or estimate, and the x variable the reference measurements made at the surface.*

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[12] Recent evidence from South Australia suggests that the stress associated with tagging *H. laevigata* at the surface may retard growth for a period (S. Mayfield, *pers comm*). If this is also the case for *H. rubra*, then this would further suggest that little growth had occurred.

The tightest relationships between length data collected at the surface and underwater, were for abalone that had been removed prior to measurement (not surprisingly) and for those which could be measured without removal. The tight regression coefficients ($R^2 = 0.988$ and 0.972 respectively) reflect the strength of this relationship, with the difference between surface and underwater measurements ranging from 2mm to -4mm (2% to -3%) for all but one of the abalone which had been removed[13], and 4mm to -4mm (4% to -3%) for those measured whilst attached. Importantly, the slopes of the regressions for surface versus underwater measurement were very close to unity (0.989 for removed abalone, and 0.984 for those accessible to measurement whilst attached), effectively indicating a 1:1 relationship

It was suspected that because abalone shells are asymmetrical, errors may have been made in determining their longest points if they were not first removed from the substratum. The effect of this would have been to place downward bias on measurements made in this manner. However, this was clearly not the case where the abalone were sufficiently accessible to allow measurement, as the close association between the regression and reference lines indicate (Figure 38c).

Although the regression coefficient and equation relating to abalone measured prior to removal are both slightly closer to unity than those relating to accessible abalone measured whilst attached, the difference is negligible. As such, given that removing the abalone prior to measurement reduces the efficiency of surveys, any possible minor improvements in accuracy that may be gained from removal are negated and so this is not recommended for accessible abalone.

When lengths determined underwater were estimated rather than directly measured; for example where the abalone was positioned such that the callipers could not be correctly placed across the shell; the relationship with data collected at the surface is somewhat weaker (Adjusted $R^2 = 0.750$, difference = 12mm to –33mm or 10% to –27%, gradient of regression line = 0.971 and intercept = 0.96) (Figure 38d). Nevertheless, the relationship between the two estimates was highly significant ($F_{1,41} = 126.7$, $p < 0.0001$). Although individual estimates were somewhat sporadic, on average where lengths were estimated rather than measured, such estimates were negatively biased by 3mm to 4mm over the range of lengths considered. Although this difference is not great, it was based only on estimates made by limited number of divers at only one site. Despite the existence of a relationship between the estimates and measured values, prudence dictates that such estimates are used only when measurements cannot physically be taken.

An alternative approach to increasing the efficiency with which length information is collected is to record the data in broader size classes, which would require less precision and hence less care on behalf of the survey divers. Presently, data is recorded to the nearest

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[13] One abalone appears to have "shrunk" by 10mm, which probably arose from misreading/misrecording one of the measurements.

millimetre for both length-frequency comparison, and analysis of abundance of different size classes, including legal and sub-legal categories. Legal minimum lengths differ throughout the fishery, and within a geographic area, through time. Indeed, since 1962 there have been at least 16 changes in the commercial size limit throughout the fishery (including ten in the last six years) (Nash 1994, Nash 1996, DPIWE 1997, 1999, 2000b, a, 2001, 2002). This is in addition to five temporary size limit reductions in the Bass Strait area (Nash 1996, DPIWE 1997), and various changes to recreational size limits (at present, there are five different commercial size limits throughout the state for *H. rubra*, two for *H. laevigata*, and four separate recreational limits). The decision to measure lengths in one millimetre size classes has been taken, in part, to accommodate this "fluidity" of size limits, such that historical data remain relevant following size limit changes. For example, data from years preceding such changes can be re-analysed for current size classes, in order to detect trends in the fishery and put current results in perspective. Although collecting data in 5mm or 10mm increments may lead to small improvements in the efficiency with which the data are collected, this benefit must be weighed against the loss of resolution in size data, and hence the reduced utility, that could result.

Merely counting rather than measuring the abalone that occur within transects, and then taking a small length-frequency sample from a nearby site may also prove to be a more efficient method of data collection, however this too has potential drawbacks. Taking a length-frequency sample from inside a radial site would lead to issues regarding the return of abalone, similar to those encountered when abalone are collected during transect sampling, and hence would not lead to efficiency improvements. Samples may be taken from areas nearby the survey site, and although this would largely eliminate the problem of careful return of the abalone, it raises new issues. Firstly, such collections will add to divers' bottom times, and as such efficiency gains may not be great (indeed, at sites with low abundance, this method may prove less efficient). Secondly, the size structure at neighbouring locations may not match that of the survey site, confounding interpretation of the results. Further, the length-frequency of abalone taken from a random collection is likely to be biased upwards relative to that measured along transects (McShane et al. 1988, McClanahan and Muthiga 1992, Findlay and Willerton 1996, Hart and Gorfine 1997). This is because larger emergent animals are almost certain to be more visible than smaller animals because of their size and emergent habitat preferences. Most importantly however, this method would not provide a true indication of the error about the estimates for the individual size classes of abalone, and consequently, appropriate confidence intervals could not be validly set (since error is likely to be higher for individual size classes than for total abundance). Valid inferences could not therefore be drawn as to temporal (or spatial) changes of individual size classes.

8.2. Field trials of an underwater measuring gauge

Following the success of this trial, a "South Australian gauge (Shepherd 1985) was borrowed from SARDI and trialled during radial surveys. The performance of this gauge was adequate, although it was less effective than had been hoped. The gauge was designed for surveying greenlip abalone, which tend to occur in relatively open habitat, and which can generally be measured without the need for removal from the substratum. Blacklip abalone habitat tends to be more complex, as because of this complexity, the gauge regularly fouled on both reef and weed, and most blacklip abalone were inaccessible to the gauge and thus required removal prior to measurement.

In response to this, a number of modifications were made to the design of the gauge. An old gauge was obtained from MAFRI (now PIRVic) to serve as a "prototype" for the modifications. The modifications included reversing the lanyard position, adding an elastic "return spring", and attaching wide plates to the jaws of the gauge. The modifications successfully eliminated the problem of fouling, and made the accurate measurement of "chipped" abalone (i.e. those removed from the substratum) easier, whilst still allowing the measurement of attached abalone where the reef structure permitted. This gauge was used in a number of surveys, and performed well.

Despite the modifications however, the efficiency of the gauge is still undoubtedly lower when measuring blacklip than greenlip abalone, as time must be spent removing most blacklip abalone prior to measurement. Because of this, and the relatively high cost of producing the gauges (around $300 per gauge), a simpler measuring board / slate device was also developed which incorporates both devices in the one unit (i.e. measuring board on one side and slate on the other).

8.2.1. Methods

In order to compare the efficiency and accuracy of both the measuring slate and gauge, a laboratory trial was conducted in which a group of 20 abalone shells, ranging in size from 66mm to 179mm, were measured by each of four observers using both devices. Reference values were obtained using a sliding measuring board, which contacts both ends of the abalone with flat plates, thereby allowing the longest axis to be determined with reasonable accuracy (this sliding board is considered too cumbersome for routine underwater measurement). The repeatability of measurements made with the gauge and the measuring slate were assessed in terms of the intraclass correlation coefficient (ICC), and the coefficient of repeatability (CR) described in Box 2 (Altman and Bland 1983, Bland and Altman 1986, 1990, 1999).

Box 2. Notes on the calculation and interpretation of measures of repeatability and agreement used during tests on the precision of abalone measurement eqipment

Measures of repeatability and agreement

Intraclass Correlation Coefficient (ICC)

The ICC is a widely used statistic for describing the level of repeatability of multiple measurements of a subject (Bartko 1966, Bland and Altman 1990, Commenges and Jacqmin

1994, Giraudeau and Mary 2001), and describes within-subject error in the context of the variance between subjects. Numerous forms of the ICC exist, with the appropriate form depending on both the purpose and design of the experiment (Bartko 1966, Shrout and Fleiss 1979). The version used here was based on the one-way analysis of variance model (Bartko 1966, 1976, Shrout and Fleiss 1979, Krebs 1999), and took the form:

$$R = \frac{MS_{\text{among sample units}} - MS_{\text{within sample units}}}{MS_{\text{among sample units}} + (k-1) \times MS_{\text{within sample units}}}$$

Where: MS = Mean square residual estimate from analysis of variance

k = Within groups level of replication

Meaningful values of the ICC range from 0 (no repeatability within replicate measurements), to 1 (indicating absolute repeatability). Negative values of ICCs are possible, but have no real meaning beyond an indication of zero repeatability (Bartko 1976, Giraudeau 1996, Zar 1999), and thus have been rounded to zero in these results.

The ICC (along with the Pearson Product-Moment Correlation Coefficient) has also been commonly used to attempt to describe agreement between two methods of measurement. This use of these statistics is not valid however as they do not describe biases or deviations from a relationship of unity between two methods of measurement, but rather merely expresses the strength of the association between the two (Bland and Altman 1990, Kuo 1994).

Coefficient of Repeatability (CR)

The CR was developed to provide a meaningful measure of repeatability in the same units as the subject of the measurement (Altman and Bland 1983, Bland and Altman 1986, 1999). The value of the CR indicates the likely range of differences between two repeat measurements at the level of interest (e.g. the 95% CR is the difference in value within which 95% of pairwise measurements would be expected to fall).

The coefficient of repeatability is calculated as:

$$CR = Z \times \sqrt{2} \times s$$

Where: Z = Z-table value corresponding to a confidence level of $\alpha/2$

S = within-subject standard deviation

The CR is generally robust to deviations from normality, but is affected by heteroscedasticity of residuals. Where log transformation is used to reduce heteroscedasticity, back transformation of the CR yields the coefficient of proportional repeatability. In this case, the CR_{prop} describes the maximum proportional difference expected between two measurements at the level of interest.

Limits of Agreement (LoA)

The LoA statistic is closely related to the CR, and provides a measure of the agreement between two methods in the same units as the original measurements (Altman and Bland 1983, Bland and Altman 1986, 1999). In this way, decisions on the agreement of two methods can be made based on perceived biological or clinical importance, rather than statistical significance (which depends heavily on the power and confidence of statistical tests). The LoA are the expected minimum and maximum values of a measurement taken by method B, relative to that taken by method A, at the level of interest (e.g. the 95% LoA are the range within which 95% of measurements taken with method B will lie, relative to a measurement taken with method A). The LoA are calculated by:

$$\text{LoA} = \text{diff}_{avg} \pm Z \times s$$

Where: diff_{avg} = average difference between measurements

Z = Z-table value corresponding to a confidence level of $\alpha/2$

S = within-subject standard deviation

As with the CR, the LoA are reasonably robust to deviations from normality but are affected by heteroscedasticity of the residuals. Log transformation and back-transformation have the same affect as for the CR. The LoA are also sensitive to the value of the CR.

The time taken to measure the shells using each device was analysed by one-way ANOVA. As the time taken for individual measurements was not recorded, the time taken to measure all 20 shells was used as the base-level replicate. As such, the degrees of freedom, and subsequently the power of the test, is somewhat limited.

Correlation between the reference measuring board values and those obtained from either the measuring slate or gauge were evaluated using the Pearson Product-Moment correlation coefficient. Agreement between the two methods was assessed in terms of the "percentage limits of agreement" (Altman and Bland 1983, Bland and Altman 1986, 1990, 1999).

Intraclass correlation coefficients were extremely close to unity for all devices (upper and lower 95% confidence limits were 1.000 for both the reference measuring board and from 0.999 to 1.000 for both the measuring slate and gauge), indicating extremely high repeatability of measurements with all devices under laboratory conditions.

Coefficients of repeatability were calculated by pooling measurements across operators. These were correspondingly high, with 95% of paired measurements within 1.3mm using the reference measuring board, 1.8mm with the measuring slate and 2.0mm with the modified gauge. The corresponding 50% coefficients of repeatability were 0.4mm, 0.6mm and 0.7mm respectively. The slightly higher repeatability for the reference measuring board is probably due in large part to the extra care with which measurements using this device were taken, as operators were aware that the values thus determined were to be taken as the reference values of the shells. When measuring with the other two devices however, operators tried to simulate field operation as much as possible, and worked more quickly than when using the reference device.

8.2.2. Results and Discussion

Both the measuring slate and gauge performed well in terms of accuracy, and performed similarly under laboratory conditions. Correlation coefficient (ρ) values of 1.00 were obtained for both devices against the reference value. Both devices had slight negative biases relative to the reference measuring board (-0.19mm for the measuring slate and -0.16mm for the gauge respectively). The 95% limits of agreement with the reference values were -1.81mm to 1.43mm for the measuring slate, and -1.79mm to 1.46mm for the gauge (with corresponding 50% limits of agreement of -0.75mm to 0.37mm and -0.72mm to 0.40mm respectively). These data show that both devices (the gauge and measuring slate) provide accurate measurements of abalone shell length under laboratory conditions . One way ANOVA of untransformed data revealed no significant difference ($p = 0.77$, d.f. 1,6) in the time taken to measure 20 abalone with the board or the gauge.

Despite the similar performance of the two underwater measuring devices in the laboratory, the gauge may outperform the measuring slate under field conditions, as shell fouling, protrusion of the epipodial muscle and parallax error can make accurate visual determination of the edge of the shell (required when using the slate) difficult, whilst underwater surge impedes the manual recording of lengths. As the modified gauge contacts both ends of the shell (thereby forcing back any protruding muscle and compressing fouling), and there is no need to manually record lengths, these problems are not likely to interfere with the accuracy or efficiency of this device.

A trial of the type described above would be prohibitively difficult to undertake under field conditions (due, for example, to the need to identify individual abalone and make multiple measurements on each, to relate particular measurements to the shells from which they came, and to the tendency of abalone to move epipodial muscles following disturbance). However, a simple trial was conducted to compare the relative efficiencies of the two methods under field conditions, in which two divers each measured 20 abalone using both the measuring slate and the gauge. The trial was conducted in an area of high abalone abundance, so as to largely eliminate the confounding factor of search time from the comparison. Both divers took approximately twice as long to measure with the board as with the gauge, suggesting that should a sufficiently broad monitoring program be implemented to justify the expense of producing gauges, then measurement and recording techniques should be re-examined in this context.

9. Site Considerations

9.1. Investigations of bias and variation associated with re-location of sites for temporal studies

Background

In the initial stages of this project, several survey designs were considered, including fixed or random transects within sites, and fixed or random sites within regions. Fixing the path of replicate transects within sites may serve to eliminate (or at least, greatly reduce) the variance associated with small-scale spatial differences in the distribution of abalone. With this design, any variation that remained would be attributable to temporal changes, thereby (in theory) improving the power of the surveys to detect trends in abundance. Problems with this design arose early in the project however, in the form of practical challenges (e.g. “fixed” marks moved in swell, marking chains were interfered with, and marks were difficult and time consuming to locate, due for example, to the heavy algal cover that characterises much of the fishery). However, the design of simply ‘fixing’ transects within sites by repeating the same bearing and starting point on each consecutive survey was not investigated.

The protocol adopted for a potential Tasmanian *Haliotis rubra* survey program was based to a large degree on the survey methodology used in the Victorian blacklip abalone fishery, and adopted the Victorian method of locating the position of fixed sites by GPS (Gorfine et al. 1996, Gorfine and Walker 1997a, Hart et al. 1997b, Gorfine et al. 1998, Gorfine and Dixon 2000), in addition to using distinctive topographical features such as bomboras, large rocks and gulches, for locating inshore sites (unlike the Victorian application, differential GPS was not used). The positioning of sites by these means is, however, imprecise, with the use of recognisable features probably having a precision of around ±5m to 10m, and GPS precision reportedly similar around Tasmania (Milbert 2000, 2001, 2004b).

9.1.1.1.Methods

In order to assess the “repeatability” of the abundance estimates from multiple surveys, a three-stage experiment was conducted in which slightly differing survey methodologies were applied during each stage. All stages of the work were designed around the modified radial transect protocol developed during this project, and involved repeating a series of three surveys over a two to three day period, at each of four sites. During stage one, site position (i.e. the buoyed reference line (i.e. a shot line) from which transects radiate outwards) was fixed and bearings and start points of individual replicate transects were retained on repeated survey occasions. During stage two, the shot line remained fixed, and replicate transect positions were re-randomised during repeat surveys. In stage three, the shot line, and hence site position was re-established using GPS and visual reference points on each re-survey occasion, and bearings and start points for each replicate transect were again randomised for each survey. This last stage represents the most efficient method of re-establishing sites through time, but has greater potential to confound spatial and temporal sources of variation depending on the accuracy with which the site is re-located.

The same pair of divers was used on all three repeat surveys within each combination of experimental stage and site. Where transects were fixed (stage one), all repeat surveys on a given transect were performed by the same diver.

In each survey, around 4 to 5% of the total area of each site was sampled, and as such large (55m radius) semicircular sites were sampled using more transects (12) than smaller (45m or 40m) sites (which could accommodate ten and nine replicate transects respectively). Accordingly, the number of replicates used to calculate the error term in analyses was unbalanced, and the analysis thus lacked orthogonality.

Stage one of this work involved undertaking repeated surveys of “spatially-fixed” transects. In the absence of obvious and clearly defined natural features to indicate the positions of individual transects, fixing transects must be achieved either through artificial means (such as marking positions with weights, buoys, stakes etc.) which proved to be problematic and unsatisfactory during earlier trials, or through navigation with respect to a reference position. The location of transect positions in this stage of the experiment were thus fixed in that the divers navigated along the same compass bearing, and the transect was positioned a fixed distance from the centre of the site. Divers took particular care in attempting to navigate to fixed sample unit positions during this phase of the work. The maximum distance from the reference position to the start of a sample unit was between 25m and 40m, depending on the size of the site. In order to minimise (and ideally eliminate) disturbance to the abalone, and thus reduce the likelihood of them moving between surveys during this stage of the experiment, shell lengths were estimated to the nearest 10mm rather than being directly measured. Estimation was aided through the use of visual references in the form of boards marked with 10mm increments. In an attempt to reduce the effect of diver memory on navigation and search pattern, the order in which the transects were swum was randomised for each repeat survey event.

Replicate surveys for each stage were conducted over a short period (two to three days). It was assumed that changes in abalone distribution over this period, due for example to movement of abalone or fishing, were minimal. This assumption was tested by comparing the differences in results from sequential surveys (i.e. the first and second, and the second and third surveys) to those of the first and third surveys, to determine if these increased with time.

The repeatability of surveys of “fixed” transects was determined by the intraclass correlation coefficient (ICC, See Box 2). The “coefficient of repeatability” (Altman and Bland 1983, Bland and Altman 1986, 1990, 1999) was also used to provide another perspective on the reliability of the fixed transect protocol (CR, See Box 2).

In stage two, the site position remained firmly fixed (using an anchored marker buoy as a central reference point), but transect coordinates were randomised on each survey occasion.

This allowed a test of the repeatability of surveys to be conducted using a standard protocol, whilst excluding the confounding effect of site “movement”.

In stage three3, the surveys also involved randomising transect coordinates for each survey, but additionally incorporated the removal of the site marker at the end of each survey, and its replacement assisted either by GPS (two sites) or in reference to topographical features (two sites), so as to introduce an element of imprecision in site position of an order similar to that expected during a monitoring program. This represents the most efficient approach to re-locating and re-surveying a site.

9.1.2. Results and Discussion

9.1.2.1.Stage one

Examination of ICCs for repeated surveys of “fixed transects”, reveals some degree of repeatability, particularly for total abundance and for abalone >= 100mm shell length (Figure 39), however the degree of repeatability was limited. Both total abalone numbers and total emergent abalone (100mm+) size classes appear to have approximately equivalent repeatability in terms of the ICC, which is unsurprising given that the 100mm+ size class data are merely a major subset of the total abundance dataset.

The repeatability of surveys for smaller abalone (<100mm) however, although also a (somewhat smaller) subset of the total abundance data, was generally lower than that for both total abundance and the 100mm+ size class at all but one site, and considerably so in least one instance (although at all individual sites there was some degree of overlap of 95% confidence limits, and substantial overlap at two). When abundance data were pooled across sites, the greater repeatability of the total abundance and 100mm+ size classes (ICC = 0.71 and 0.73 respectively) relative to that relating to those abalone with shell lengths <100mm (ICC = 0.27), is clear, with no overlap of 95% confidence limits (Figure 39).

In general, confidence intervals were reasonably wide, possibly reflecting the limited within-subject replication. As such, it was not possible to distinguish clear differences in repeatability between sites (such as may have been expected, for example, between large and small sites, those with moderate relief and those with low relief, or those with different exposure levels).

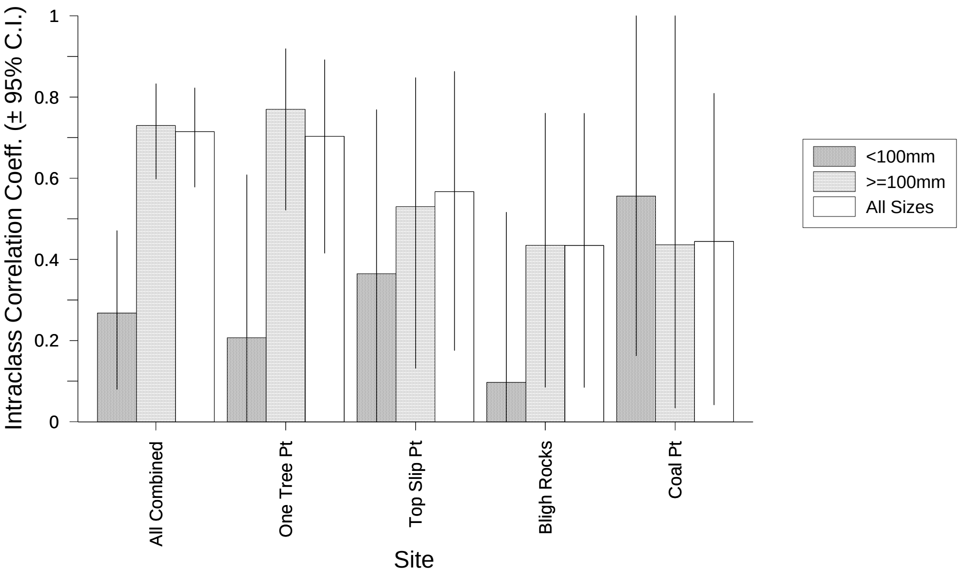


Figure 39. *Intraclass correlation coefficients with 95% confidence limits for total abundance and the composite <100mm and >=100mm size classes, for experimental stage one ("fixed" transect coordinates).*

It has been argued that comparison of ICC estimates should not be made where the data used were drawn from different populations, as has been done here with comparison of ICCs for different size classes and sites (Armitage and Berry 1994, Uebersax 2003). This argument is based on the premise that since the value of the ICC is strongly dependent on the between-subject variance (i.e. population variance), two samples with precisely the same within-subject variance, but drawn from separate populations, can give widely differing ICC values (Bland and Altman 1990, Uebersax 2003). This precaution has merit where the repeatability being tested is that of the assessment of a subject by different individuals (e.g. diagnosis of illness by different practitioners). In terms of this study however, where the ultimate purpose of the analyses is to assess the spatial repeatability of fixed sample units, a complete lack of repeatability of replicate samples would manifest as though each replicate sample from the "fixed" sample units were merely a random sample taken from the broader population of target organisms at the site. As such, the ICC in this instance may be considered an index of the randomness of replicate samples (with ICC = 0 indicating samples are completely random, and ICC = 1 indicating absolute interdependence of sample units). Therefore, comparison of ICC values has been made here, although this is not to suggest that the values calculated have definitive meanings.

Prior to calculating the repeatability coefficients (Table 7), plots were made of standard deviation versus mean abundance for each transect. When data were pooled across sites, there was a strong relationship between abundance and standard deviation. Because of this, repeatability coefficients are not reported for pooled data, as the value of the coefficient varies according to abundance. Statistically significant (95%) correlations between abundance and standard deviation were detected for abalone smaller than 100mm at three sites (Blighs Rocks, Trumpeter Bay and One Tree Point), and for total abundance at one site

(One Tree Point). Although not statistically significant at the 95% level, a high probability of correlation was also found for various size classes at two sites (One Tree Point and Blighs Rocks). The slopes of the regression lines for these significant and near significant (95%) relationships between mean abundance and standard deviation were generally small. Nevertheless, repeatability coefficients from these sites must be considered approximate and are most valid around the central abundance values (i.e. near the mean).

Table 7. Coefficients of repeatability (95% and 50%), data range and mean density (abalone per 15m^2 transect), for stage one ("fixed" transect coordinates). Crosses (X) in the top-right corner of a cell indicate that the relationship between standard deviation and abundance is significant at this site at the 95% level, whilst tildas (~) indicate significance at 80% level.

		One Tree Point	Top Slip Point	Blighs Rocks	Coal Point
All Sizes	95% CR	15.3 x	4.4	9.3 ~	3.7
	50% CR	5.3	1.5	3.2	1.3
	Mean Abundance	10.4	3.2	6.0	2.6
	Range	0 – 48	0 – 10	0 – 15	0 – 7
>= 100 mm	95% CR	8.5 ~	3.5	8.4 ~	3.2
	50% CR	2.9	1.2	2.9	1.1
	Mean Abundance	7.8	2.6	5.2	2.2
	Range	0 – 25	0 – 6	0 – 13	0 – 6
< 100 mm	95% CR	12.5 x	2.3 x	3.0 x	1.1
	50% CR	4.3	0.8	1.0	0.4
	Mean Abundance	2.6	0.7	0.9	0.4
	Range	0 – 27	0 – 4	0 – 4	0 – 2

Repeatability is generally greatest (i.e. repeatability coefficients are generally the lowest) in absolute terms, for abalone smaller than 100mm in length. However, when considered in relation to the mean abundance for that size class, this group always had the worst repeatability in relative terms. Similarly, in absolute terms, the size class of abalone with shell lengths of 100mm and greater had slightly higher repeatability than when all size classes were pooled, however when considered in relation to the mean abundance, these two groups were much closer together in terms of their repeatability.

At all sites and for all size classes considered, the 95% coefficients of repeatability were considerably greater than the mean abundance, indicating fairly poor repeatability in every case. In the case of abalone <100mm, these coefficients ranged from 289% to 484% of the mean, indicating particularly low repeatability (even 50% repeatability coefficients either exceeded, or at best approached equivalence to the mean for this group).

When considering the repeatability results for stage one surveys (fixed transects), it should be kept in mind that shell lengths were only estimated during this phase of the work, and as such there is likely to be some element of imprecision introduced in the results for the separate size classes due to this factor. Furthermore, as abalone within 10mm of the 100mm size class cut-off made up a greater proportion of the below 100mm size class than the 100mm+ group, this imprecision is likely to have had a greater effect on the precision of the smaller size class. Nevertheless, this is unlikely to have affected the general interpretation of the results.

In all repeatability calculations, the assumption is that the spatial distribution of abalone did not change between surveys (i.e. on a temporal scale of days). If this assumption does not hold, then poor repeatability values may reflect changes in abalone distribution, for example due to movement or fishing, rather than poor spatial repeatability, thereby confounding interpretations.

If changes in abalone distribution did strongly affect results, then provided that some proportion of abalone remained sedentary between surveys, the average relative absolute difference (ARAD) between surveys of the same transect would increase with increasing between-survey period (where ARAD is the average of the absolute values of the differences between repeated surveys of fixed transects, scaled for the mean of those transects). However, a consistent ARAD, regardless of the survey period, would suggest either that movement of abalone was having little effect on the results, or that virtually all abalone moved during even the shortest period between surveys.

In almost all cases, the ARAD of repeat surveys of transects was greater between consecutive surveys than between the first and third surveys for a given site and size class of abalone, indicating no general tendency for results from repeated surveys of fixed transects to become less similar through time. The only exceptions were at the One Tree Point site, where the ARAD of data for both total abundance and the 100mm+ size class were greater between the first and third surveys than between consecutive surveys. In both of these instances, comparison of ARADs by one-way ANOVA revealed no significant difference in ARADs from consecutive surveys or first and third surveys ($p=0.48$ and $p=0.56$ for all sizes and the 100mm+ size class datasets respectively).

These results suggest therefore, either that abalone movement did not noticeably affect repeatability results, or that abalone movement between each survey approached complete exchange of individuals. However, this latter explanation is unlikely since such broad movement is inconsistent with other research into this species (Prince 1989d, a, McShane 1990b, a, Dixon et al. 1998, Lansdell 2004). Furthermore, that some repeatability was noted in the survey results, considered in conjunction with the ARAD results, is inconsistent with broad movement over this time scale. It is reasonable to conclude therefore, that movement of abalone between survey events did not noticeably affect repeatability results.

The results for experimental stage one, when considered together, suggest that the repeatability of the “fixed” transects was achieved, albeit to a limited extent. In most cases (including all cases in which either total abundance or the 100mm+ size class were considered), results of repeat surveys of given transects were more similar than would be expected from random sampling alone. This is probably due in part to some limited amount of spatial repeatability in the sampling (i.e. some proportion of the fixed transect surveys did sample the same physical area). However, the results are also likely to be due in part to spatial autocorrelation of abalone distribution; that is the tendency of abalone in neighbouring areas of reef to occur in more similar densities than those which are spatially distant (Dixon et al. 1998). The conclusion of limited spatial repeatability is also supported by the perceptions of the survey divers, who reported that spatial repeatability was occasionally good, but more generally that repeat surveys were in the general vicinity of each other rather than specifically on the same strip of reef.

The existence of a degree of repeatability in the results for repeated surveys of fixed transects suggests that traversing fixed bearings does assist with removing the effect of small scale spatial variation in abalone abundance from estimates of temporal variation. However, such surveys would still be dependent on accurate location of the navigational reference point, and would be subject to all of the same philosophical, and a number of practical issues previously discussed for fixed transect monitoring (Section 4.1). Accordingly, and in light of the repeatability results for the other survey methodologies (described below), this method of spatially fixing transects was not pursued further.

9.1.2.2.Stages two and three

The overall repeatability of the surveys, regardless of individual methodology, was initially analysed by Model III ANOVA (ignoring that transects were theoretically spatially “fixed” during experimental stage one). Following examination of data for normality and the relationship between residuals and abundance, square-root transformation was applied to the data set for total abundance, and its composite size classes comprising abalone <100mm and those 100mm+. Normality was not achieved in any case, however this transformation did remove the relationship between residuals and abundance for both the total abundance data, and that component relating to abalone >=100mm. In the case of abalone smaller than 100mm, the relationship was improved, but homoscedasticity was not achieved. Because of the sensitivity of unbalanced ANOVA to heteroscedastic residuals (Underwood 1981), analysis was also performed on a dataset of <100mm abalone which was balanced by randomly removing “excess” replicates from larger sites (the appropriate transformation was once again square root, and again neither normality nor homoscedasticity were achieved).

Method and Method x Site interactions were of no interest in this analysis, as the aim was the assessment of repeatability of surveys. The Site term was of interest only in as much as it provided an indication of the power of each survey technique to detect a difference in abundance of the magnitude equivalent to that between sites. The Survey term however, provided an indication of the repeatability of replicate surveys, within each combination of Method and Site, and thus was the term of interest in the analysis.

The results of the analysis of variance models for total abalone abundance, and the composite 100mm+ and <100mm size classes revealed strong overall repeatability of replicate surveys, indicated by high probability values (p = 0.95 for all sizes combined, p = 0.83 for shell lengths (SL) >= 100mm, p = 0.93 for SL <100mm with unbalanced replicates, and p=0.64 for SL <100mm with replicates balanced through random removal). There was a highly significant effect of Site for each group analysed (p<0.0001 in all cases).

In order to provide an indication of the relative repeatability of each method, variance components were partitioned for separate two-way random effects ANOVAs (Site x Replicate Survey) for each method, using the SAS® "Proc Nested" routine. In every case, the Survey term accounted for effectively 0% of the variance in the dataset. The Site term generally accounted for some (< 30%) of the variance, with variation among individual replicates within sites accounting for the majority (> 70%) of the variation in the dataset (Table 8). This demonstrates that the effect of small differences in establishing the reference shot line (site) effectively contributes no variance to the overall dataset.

Table 8. Variance components calculated from separate two-way analyses of variance using the "Proc Nested" routine from SAS®. Components are presented as the percentage of total variance for the model contributed by the term of interest. There were four sites surveyed, and three replicate surveys undertaken by each method at each site. Survey methods were as follows: Method 1 = fixed site position and "fixed" transect coordinates, Method 2 = fixed site position with randomised transect coordinates, Method 3 = imprecise site location and random transect coordinates.

		Variance Component (percentage of total variance)		
Size Class	Survey Method	Site	Survey	Error
All Abalone	1	25.2	0.0	74.8
	2	29.5	0.0	70.5
	3	14.8	0.0	85.2
SL >=100 mm	1	27.6	0.0	72.4
	2	26.8	0.0	73.2
	3	14.0	0.0	86.0
SL <100 mm	1	9.6	0.0	90.4
	2	17.4	0.0	82.6
	3	16.5	0.0	83.5

The finding that spatial variation between transects was responsible for between 70% and 90% of total variance in the ANOVA model is particularly notable. This small scale variability is certainly the greatest challenge facing a potential abalone abundance monitoring program. Where stratification at the transect level is not practical, such variability can most effectively be addressed through maximising replication by optimising the efficiency with which surveys are conducted (as discussed in Section 6.7)

Finally, the repeatability of density estimates from each of the surveys was assessed by calculation of the limits of agreement (LoA) for each method (), using the mean density estimates from each survey and calculating across all sites. This was done, since in a broad-scale monitoring program, an error term used in analyses will relate to site density estimates rather than the counts of abalone from individual transects (Green and Montagna 1995). As such, determining the repeatability of density estimates provided an indication as to the relative merits of the different survey methodologies. Given the results of partitioning of the components of variance (Table 8), it is unlikely that any real difference exists in the repeatability of estimates determined using survey methods two or three (as replicate surveys contributed no variance to the models, whilst within-survey error was fairly large). This is not necessarily the case for survey method one however, as repeat surveys using this method were not independent of each other, as evidenced by the repeatability (albeit limited) of abalone counts from individual transects (Figure 39 and Table 7).

Relationships between mean density estimates and the standard deviations of these estimates were found for various combinations of survey method and size class. Logarithmic transformation removed these relationships, except in the case of abalone smaller than 100mm shell length assessed using methods one and three. Because of the logarithmic transformation (and subsequent back-transformation) of results, the 95% coefficients of repeatability are proportional rather than absolute (Altman and Bland 1983, Bland and Altman 1999). These analyses (Table 9) revealed that repeatability was slightly higher for surveys conducted using method one (fixed site position and “fixed” transect coordinates) than methods two or three which as expected, had roughly similar repeatability.

Table 9. Ninety five percent coefficients of proportional repeatability, for density estimates from repeat surveys (across four sites). Percentages indicate the range in which 95% of pairs of abundance estimates would occur (i.e. density estimate from one survey would be within the range X% to Y% of that from a second survey on 95% of occasions).

	Method 1	Method 2	Method 3
All Sizes	74% to 134%	61% to 161%	60% to 166%
>=100mm	79% to 125%	55% to 178%	50% to 197%
<100mm	N/A	34% to 289%	N/A

Although imprecise positioning of sites on repeated survey occasions did not have an effect on the results obtained here, this finding may not be universal. In situations were survey sites are positioned directly adjacent to distinct habitat boundaries (e.g. the sand/reef interface), imprecise positioning of the site on repeat survey occasions is likely to have a more substantial effect on survey results. However where such distinct boundaries exist, these can be easily used as one of the references that are used to aid positioning of the site. Where such boundaries occur at the outer curved edge of a site (as opposed to the flat edge of a semicircular site), this could slow the process of deploying the site, given that the distance to the central shot line (or reference line in the case of parallel transects) must be established, however this is only likely to add a few minutes.

Overall, the evidence clearly indicates that the precision with which “fixed” survey sites are re-established when using GPS and/or physical features has no noticeable effect on survey results. Accordingly, adoption of such methods to locate the position of such sites as part of a broader survey program should not lead to an artificial inflation of temporal variance estimates, and thus not reduce the power of such a survey program to detect temporal trends. Given that these methods are far more efficient than establishing and re-locating existing physical markers, these are clearly the preferable option.

9.2. Comparison of different transect site configurations

Two alternative configurations for implementing radial transect surveys are fully circular and semicircular sites. Prior to commencing surveys at sites throughout the state, consideration was given as to which of these configurations would be most effective for that location. In general, it was felt that semicircular, rather than fully circular sites would be preferable at most locations for three main reasons. Firstly, as semicircular sites occupy only half the area of circular sites (and half the distance in one direction), locations with sufficient “abalone habitat” to accommodate semicircular sites are more abundant than those required to accommodate circular sites. Secondly, in many locations along the coast, abalone tend to be most abundant in a narrow strip running roughly parallel to the shore. Therefore using semicircular sites allows sampling effort to be concentrated in this zone by following the contour of the shore (either by aligning the straight edge along the shore, or following the contour of “baylets” using the round edge), allowing survey effort to be focussed where the abalone are, rather than wasting survey effort in places where abalone are rare. Finally, for a given sampling effort (i.e. number of transects), the proportion of the total area sampled in a semicircular site is twice that from a circular site of the same radius. In general, this would be expected to lead to more precise estimates of abundance within sites. As such, semicircular sites might be used most frequently, with fully circular sites used only in areas where abalone distribution appears to be more or less continuous throughout the entire area circumscribed by the circular site, and where the reef does not drop sharply into deeper water.

A semicircular site was initially “trialled” at a single site to the south of One Tree Point, Bruny Island, by sampling both circular and semicircular sites. In this area, as with much of the rest of North Bruny Island, abalone are most abundant in a narrow strip of shallow water close to the shore. Because of this, a third survey method was also trialled whereby the coastline was divided into a series of approximately 30m sections, and a number of these sections were chosen at random. Within each randomly selected section of coast, a transect was situated parallel to, and around 5m to 10m from the shore (Figure 40).

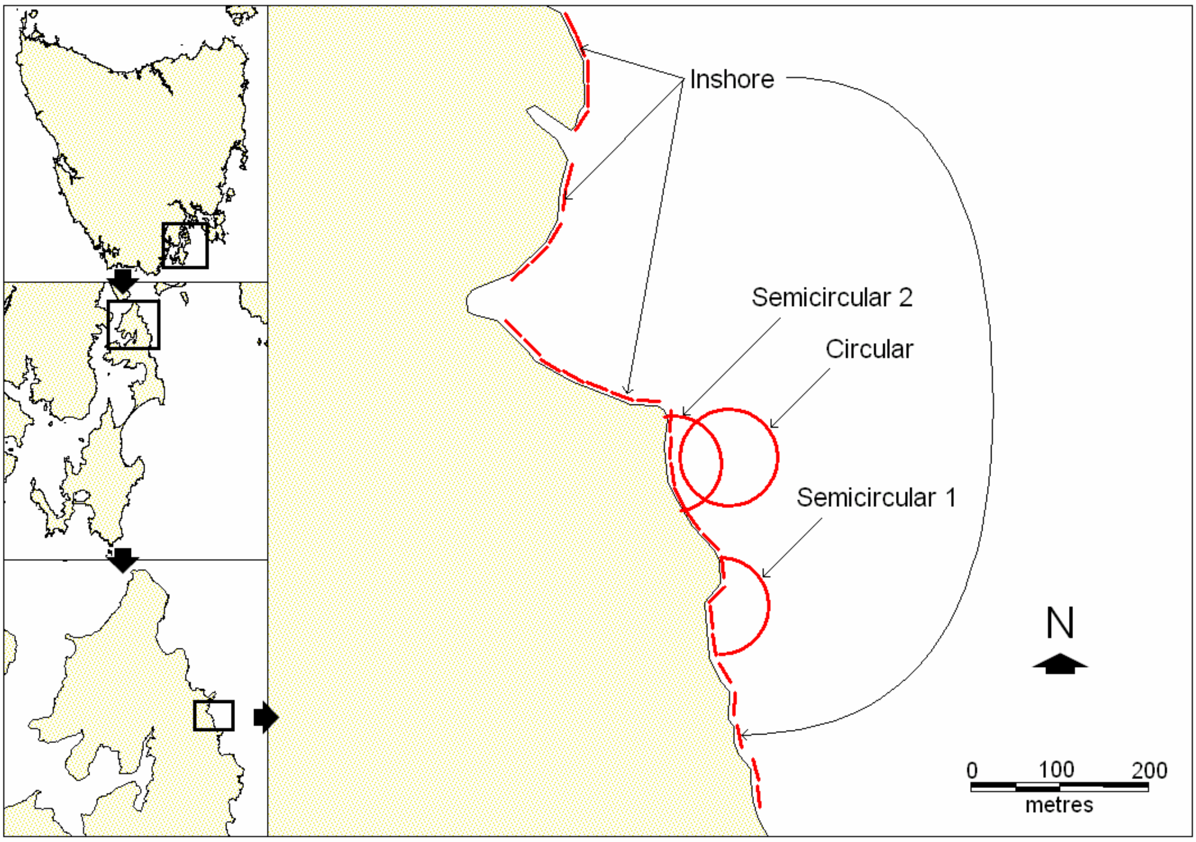


Figure 40. *Area to the south of One Tree Point, showing the position of the original semicircular (Semicircular 1) and circular radial survey sites, as well as the parallel inshore divisions and final semicircular radial site (Semicircular 2).*

Because the parallel inshore transects took considerably longer, and involved many more ascents for divers, it was more efficient to collect fewer, larger transects than were collected during the radial sampling. As such, a transect length of 20m x 1m was used for this sample (as opposed to 15m x 1m for radial transects). Nevertheless, a comparable total area was sampled, and the sample size was sufficient to gauge the relative effectiveness of the technique.

Given that the inherent properties of the different survey techniques are such that each samples a physically different area, it was not appropriate to compare density estimates. As such, comparison of the three surveys was done in terms of the precision of the results from each. The results of the comparison (Table 10) reveal that each technique had roughly similar, and relatively poor precision (note: the semicircular site sampled for comparison was that labelled "Semicircular 1" in both Figure 40 and Table 10). However, of the three survey methods, the parallel inshore transect sample was marginally more precise than the radial methods. There was no such general difference in the precision of the circular and semicircular radial samples.

Table 10. Sample size, area sampled and precision of survey results obtained using different transect configurations in the area south of One Tree Point, Bruny Island. The site labelled "Semicircular 1" was the original semicircular site surveyed, whilst that marked "Semicircular 2" was the site positioned on the basis of the knowledge gained during the inshore parallel sampling.

Sample Technique	N	Area Sampled (m^2)	SE/mean All emergent	SE/mean 100mm-LML	SE/mean > LML	CV All Emergent	CV 100mm-LML	CV >LML
Semicircular 1	10	150	0.47	0.71	0.54	1.48	2.24	1.70
Circular	13	195	0.48	0.44	0.68	1.71	1.60	2.44
Parallel Inshore	8	160	0.41	0.44	0.33	1.16	1.26	0.92
Semicircular 2	12	180	0.18	0.21	0.26	0.61	0.72	0.90

Collecting the parallel inshore transect sample involved diving along a considerable section (approximately 1km) of the coastline. Sampling in this manner provided researchers with a good overview of abalone distribution, and the knowledge gained was then used to position another survey site in an area with more consistent abalone habitat. This area occupied a similar width to a semicircular radial site, and so was sampled using this configuration ("Semicircular 2" in Figure 40 and Table 10). The survey results from this fourth sample were substantially more precise than those from any of the other survey samples collected in this area.

Given that each potential survey site around the state is unique in many ways, few generalisations can be drawn from this comparison in terms of a survey configuration that will be most appropriate at all sites (particularly given the absence of replication here). However, this work demonstrated a number of useful principles for setting up survey sites. Firstly, it showed that where abalone are distributed primarily in a narrow, shallow strip close to the shore (as is frequently the case for *H. rubra* in Tasmania), samples taken by concentrating sample units along a relatively long stretch of coast can yield results at least as precise as those taken over a much smaller and more clearly defined area. Secondly, and perhaps most importantly, it showed the influence of site position on precision, and survey sensitivity. Finally, the work similarly demonstrated the importance of selecting a survey configuration that is most appropriate to the site of interest.

9.3. Parallel transect sampling protocol

The radial transect method developed during this project has been demonstrated to be both versatile and efficient, however it is not entirely without shortcomings. The greatest of these is the practical requirement for survey sites to have minimum dimensions of around 40m (offshore) x 80m (alongshore). Because of the high proportion of steep and narrow reefs in eastern and south-eastern Tasmania, the tendency of abalone to aggregate close to shore, and the depleted abalone stocks here, this feature of radial transects has limited the number of potential locations which can be effectively surveyed in certain areas (such as outside North Bruny and South Maria Islands), where we have been unable to find a sufficient number of suitable sites for radial survey.

Since density estimates obtained through radial transect arrangements are statistically equivalent to those obtained through surveys using parallel transects (Section 6.2), both methods can be easily incorporated into a survey programme. However, as radial transects are the more efficient method, parallel transect surveys are recommended only at those locations where a radial configuration is not feasible (given that parallel transect sites can be narrower than radial sites in at least one dimension).

In order to facilitate parallel transect surveys, an algorithm and associated protocol were developed to generate “random” coordinates for transects aligned parallel to the shore. The algorithm is provided as an Excel spreadsheet macro (available from the authors).

9.4. Assessment of abalone ‘sightability’ and diver performance

Should a broad-scale abalone monitoring program be implemented, surveys are likely to be conducted by a number of different individuals, and over time the number of individuals involves will grow with staff turnover. In order for a survey program to be effective therefore, there must be reasonable agreement between survey results from different individuals.

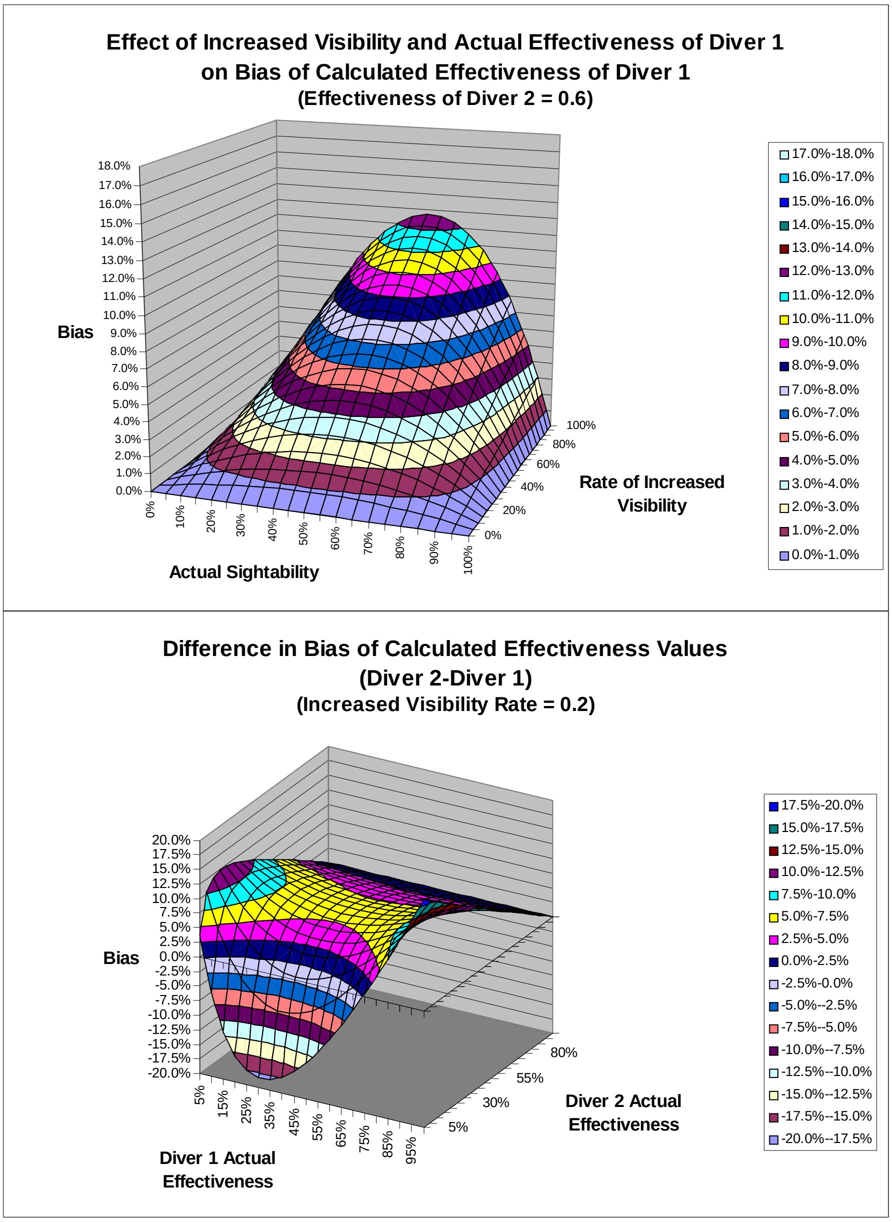
Pilot trials of a double-survey method for assessing diver performance and the sighting probability of abalone were successfully conducted, although no large-scale experiment was undertaken. The term sighting probability is used here to indicate the probability of an individual abalone on a transect being recorded by a diver during a survey. The double-survey technique involves repeated surveys of fixed transects by two different divers in immediate succession.

In addition to application in a standalone study of diver performance, if incorporated into the survey protocol, such double-surveys would allow the effectiveness of surveyors to be assessed on each survey occasion. Biases associated with variable sighting probability could then be taken into account, thereby improving survey accuracy and potentially reducing the variance associated with abundance estimates.

Twelve estimates of sightability were made during this pilot study, and for 11 of these the average sightability was 82% (range 67% to 100%), with a standard error of only 5%. The other estimate however, was 29%, which is a matter of some concern. There are doubts however over the validity of this last estimate, due to possible movement of the “fixed” transect and the method used to mark the individual abalone along this transect (a dark crayon which made marks difficult to identify).

The detection probability estimator is based on the well established Peterson mark-recapture statistic (Magnusson et al. 1978, Marsh and Sinclair 1989, Nash et al. 1995);, however its use for assessing surveyor performance and sighting probability is still relatively novel (Walter and Rusch 1997, Anthony et al. 1999, Jachmann 2002, Pollock et al. 2002). As such, no information could be found relating to biases inherent in this use of the statistic. To this end, a desktop investigation was made into the likely sources of bias: specifically loss of marked animals, increased visibility of marked animals, and the failure to recognise marked animals. The effects of the bias on the estimates for the first and second surveyor were investigated, as well as the interaction between the two.

In all cases, the magnitude of the bias on one surveyor’s estimate depends both upon the effectiveness of the diver in question, and the rate of occurrence of the source of the bias (e.g. the rate at which marked animals move from sight between surveys, or at which marking the abalone increases their detectability by diver two). In some cases however, the magnitude of the bias is also influenced by the effectiveness with which the other surveyor samples the transect. For example, where marking the abalone renders them more likely to be seen by the second diver, the calculated estimate of sighting effectiveness depends both on the rate at which detectability is increased, and the effectiveness of the second diver (Figure 41). Despite these confounding issues, double-survey estimates are reasonably robust over the levels of diver effectiveness and rates of bias likely to be encountered.



Effect of Increased Visibility and Actual Effectiveness of Diver 1 on Bias of Calculated Effectiveness of Diver 1 (Effectiveness of Diver 2 = 0.6)

Difference in Bias of Calculated Effectiveness Values (Diver 2-Diver 1) (Increased Visibility Rate = 0.2)

Figure **41**. *Effect of increased visibility of marked animals on estimates of diver effectiveness.*

10.Performance of Surveys in Remote Areas of Tasmania

Before any design for a state-wide fishery-independent monitoring program can be considered, it was essential that the performance and versatility of the preferred survey technique(s) be assessed in as representative a range of habitats as possible. To achieve this, research cruises were undertaken to the North-East, South- and North-West and Central Bass Strait Islands/Furneaux Group to evaluate the performance of the radial transect technique. A key objective of these cruises was to determine whether the inherent characteristics of the modified radial transect allowed its application on reefs throughout Tasmanian waters. Of particular interest was the statistical performance, particularly the precision, of transect surveys around the state (irrespective of the spatial arrangement of transects), whether the minimum site dimensions for modified radial transect samples (which have been set, somewhat arbitrarily, at 40m x 80m) were appropriate for application on the various reefs found throughout Tasmania, and the practicalities of using radial transects in different habitat types and kelp communities. Also of interest was the practicality of following a bearing and measuring shell lengths in the strong current conditions typical of the north-eastern and north-western “corners” of the state.

Several issues were associated with remote area surveys, that had not impacted upon the development work previously undertaken in the south-east of the state. Arguably the most significant of these was that restrictions imposed by the current Australian and New Zealand Standard for Scientific Diving (Standards Australia 2002), effectively prevent surveys below nine metres depth if it would take a diver more than two hours to reach a recompression chamber. Where such dives occur to depths of between nine and twelve metres, bottom time is restricted to a maximum of 70 minutes, following which divers must remain at the surface for at least six hours[14]. Where divers cannot access a recompression chamber for more than six hours, the maximum bottom time of such dives is further reduced to 60 minutes. For dives exceeding twelve metres, bottom times are even more restrictive.

This raises obvious issues in relation to the representativeness of surveys in areas where a substantial proportion of the abalone population occurs at greater depths than this. Indeed, in areas where few abalone are found at such shallow depths, then it may not be practical to conduct any meaningful abundance surveys at all. Given that the standard was only introduced in 2002, this issue had not been previously considered.

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[14] It is possible to slightly increase the total permissible bottom time by reducing the duration of individual dives. However individual dive times can thus become prohibitively short, and only relatively small gains are made in terms of overall dive times. This also requires that divers punctuate their dives with increasingly long surface intervals, which further detracts from the efficiency of surveys, and increases the number of ascents that a diver must make (multiple ascents are discouraged under University policy).

Another issue associated with remote-area surveys related to poor knowledge of the distribution of abalone and potential habitats in such regions. In the south-east of the state, where previous survey work had been focussed, investigation of suitable sites and allocation of these sites within regions had been simplified by local knowledge and the use of detailed habitat maps produced through SeaMap Tasmania (Barrett et al. 2001b, a). In more remote areas however, knowledge of the coast was poor, habitat maps were unavailable (although these have since been produced for sections of the North-East), and discussions with abalone divers did not provide sufficiently precise information on suitable site positions. As such, preliminary assessment of survey sites required a substantial fieldwork component.

10.1.North-EastCoast

The north-eastern region of Tasmania is of particular interest, as both catch and effort from this area have fallen to a fraction of their historical levels (Tarbath et al. 2001b). With little information about the state of stocks in this region, this decline has generally been interpreted as reflecting substantial stock depletion.

The restrictive dive rules in place for remote locations dictated that initial site assessments were necessarily done on snorkel to minimise dive times, and this added to the challenge of these assessments. On a research cruise to this region in November 2003, 24 sites between Cod Bay in the south and Clarke Island to the north were assessed for survey suitability. Of these eight were surveyed using radial transects (Figure 42). Of the 16 sites that were not surveyed, some were rejected because of low abalone numbers and a few due to narrow reef width, however a number of other sites were rejected on the grounds of depth.

These surveys highlighted several challenges, but provided a valuable opportunity to undertake abundance assessment in remote regions, where knowledge of reefs and habitats was poor or not available. Because of the extensive amount of sandy coastline in the area, it had been expected that the abundance of shallow abalone-carrying reef would be relatively low. In practice however, the abundance of such reef habitat was comparatively high (relative to areas in the south-east of the state), throughout much of the area visited.

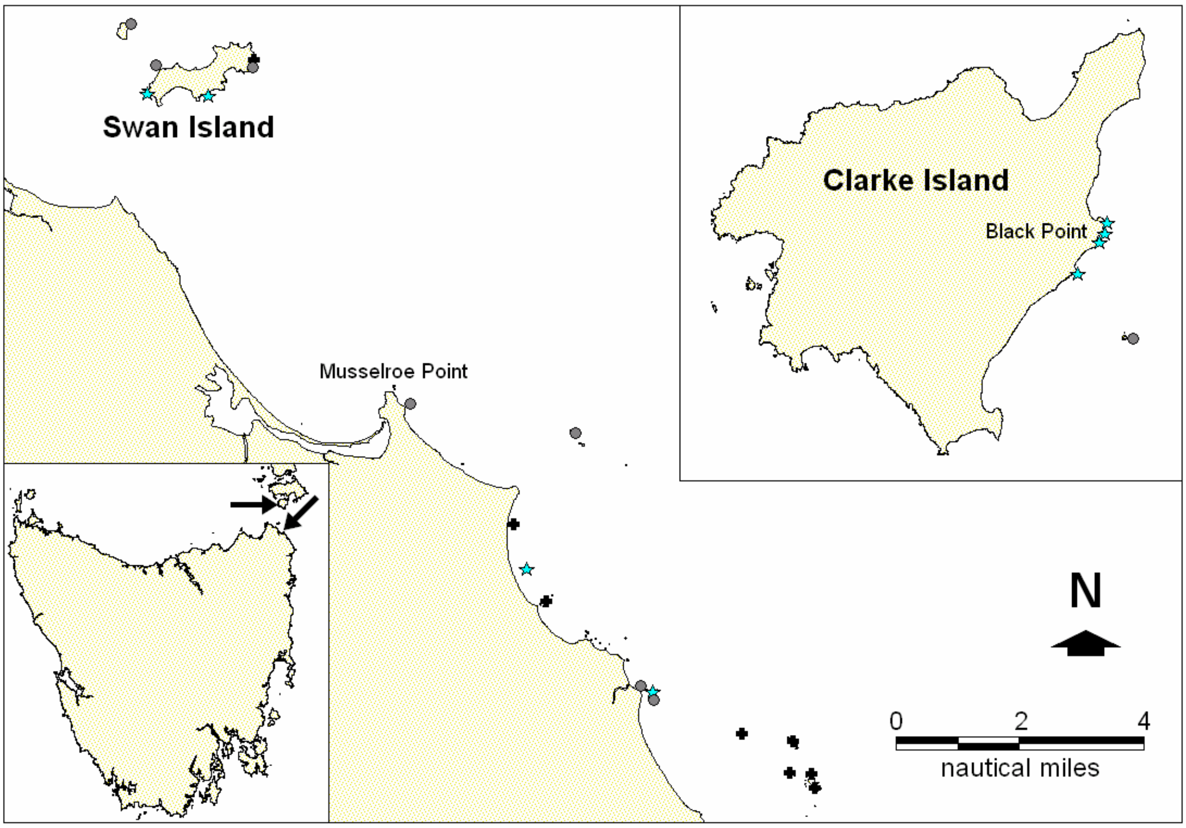

Figure 42. *Sites assessed for survey during the November 2003 research voyage to north-eastern Tasmania. Crosses (9) represent sites assessed as unsuitable, stars (∃) represent potentially suitable sites, and circles (#) indicate surveyed sites. Arrows in small inset map of Tasmania at the bottom left corner indicate the regions shown in the detailed maps. The inset at the top right corner (Clarke Island) has the same scale as the main map.*

The North-East (and the North-West) is subject to strong tidal currents of three knots or more, and it had been expected that such currents may preclude transect surveys. Strong currents were encountered during two of the surveys (at Musselroe Point and the north-west of Swan Island), and although this added to the difficulty of radial transect surveys, it did not prevent them from taking place. Under these conditions, it was found (unsurprisingly) that transects which were oriented roughly parallel to tidal currents were more easily surveyed than those oriented perpendicular to the direction of the flow.

With the exception of the data from the Swan Island reserve site, the mean abalone density estimates collected from the North-East (Table 11) were generally higher, and results more precise, than those from the south-east of the state (see Table 5).

Table 11. Abundance and precision estimates from blacklip abalone surveys in north-eastern Tasmania, November 2003. “Means” = mean abundance (per 15m^2) of abalone in emergent, pre-recruit 80mm+ and >LML size classes respectively; “Emergent” = all emergent abalone; “80mm to LML” = emergent abalone >80mm and <LML of 127mm or 136mm, depending on location (see **Figure 43**); “>LML” = emergent abalone equal to or larger than legal minimum length. All sites were semicircular, with site radius 45m, except Cobler Rocks Inshore, Swan Island Reserve and Low Islets sites where site radius was 40m.

Site (Reporting Block)	**N**	**Means**			**Relative Error** (S.E. ÷ $\bar{x}$)			**CV**		
		Emergent	**80mm to LML**	**> LML**	**Emergent**	**80mm to LML**	**> LML**	**Emergent**	**80mm to LML**	**> LML**
Cobler Rocks, South (31A)	10	14.7	10.9	2.3	0.18	0.17	0.35	0.55	0.54	1.12
Cobler Rocks, Inshore (31A)	9	20.9	17.2	2.6	0.41	0.42	0.44	1.23	1.25	1.25
Cobler Rocks, Inshore (31A)*	8	12.5	10.2	1.5	0.17	0.18	0.28	0.48	0.51	0.80
Black Reef, NE (31B)	10	15.7	13.9	0.7	0.22	0.21	0.30	0.70	0.68	0.96
Musselroe Point (31B)	10	16.2	12.9	0.3	0.16	0.19	0.51	0.51	0.60	1.61
Swan Island NW (31B)	10	26.2	17.1	2.6	0.19	0.20	0.43	0.60	0.65	1.37
Little Swan Island (31B)	10	19.9	14.4	2.0	0.16	0.17	0.32	0.50	0.52	1.00
Swan Island Reserve (31B)**	9	7.6	5.3	0.6	0.57	0.50	0.44	1.71	1.49	1.31
Low Islets (33A)	5	15.6	10.6	0.0	0.22	0.21	N/A	0.48	0.46	N/A

* Cobler Rocks Inshore, excluding one atypical replicate (containing 88 abalone), which strongly affected both the mean and precision estimates.

** Size limit for surrounding waters (fishing is prohibited at Swan Island Lady Bay Reserve)

An interesting finding was that even at relatively high density sites, an anomalously high number of abalone may still be encountered along a single transect, adding considerably to sample variance. A similar experience had been previously noted at lower density sites in the South-East, for example where a large number of abalone are encountered in a crack along a transect, at a site where all other transects contain two or fewer abalone. It was expected that results from high-density sites would be less sensitive to the influence of a transect passing through one or two “extra” aggregations, since this would generally represent only a relatively small proportion of the total abalone encountered. At one site however (inshore at Cobler Rocks), this was found not to be the case. One transect at this site lay precisely along a sand-strewn gutter (which is ideal blacklip abalone habitat in this region), within which abalone density was abnormally high (88 abalone were measured in this transect, as opposed to an average of 12.5 abalone in all other transects at this site). The results from this one transect heavily influenced both the density and precision estimates for this site (Table 11), demonstrating that the precision of such estimates can be poor, even when abundance is high.

The finding that abalone were present in reasonably high densities throughout the region was somewhat surprising, given the reduced catches from the area. It was apparent however, that although densities were generally greater than one abalone m^{-2}, only a small proportion of the population actually exceeded the minimum size limit (Table 11 and Figure 43). Whether this represents fishing mortality, or is a natural effect (e.g. due to small maximum size or natural mortality among larger fish) is not absolutely clear.

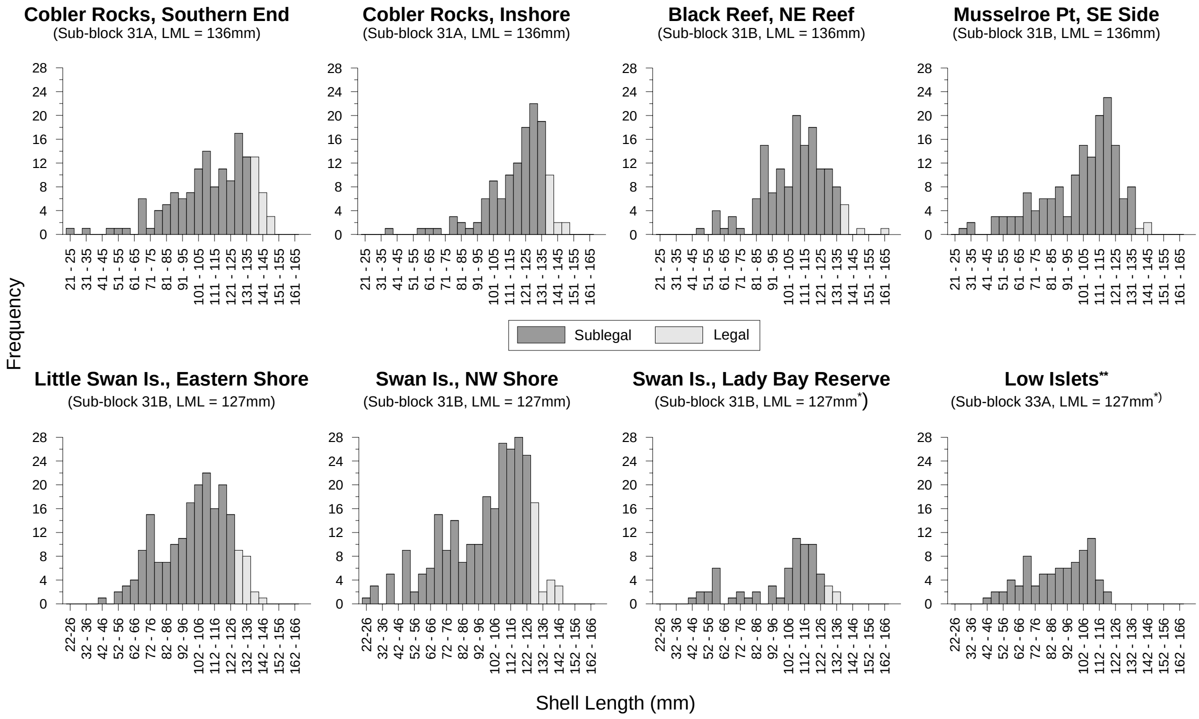

Figure 43. *Length-frequency histograms for sites surveyed in north-eastern Tasmania during the November 2003 research cruise. Shell lengths are grouped into 5mm categories. Legal minimum length (LML) is indicated in chart title and by a change in shading of histogram bars.*

* *Size limit for surrounding waters (fishing is prohibited at Swan Island Lady Bay Reserve)*

** *Graph shows only half of the data collected at the Low Islets site, as the balance was lost when the research dinghy capsized after surveying this site.*

Size limits in this area were reduced from 132mm to 127mm in 2001 (Anonymous 2000). This management change was followed by two years of increased catches (albeit still at a fraction of historical peak levels). The possibility exists therefore that the length-frequency pattern observed was due to growth overfishing. However, the apparently high overall abundance, and the limited catch and effort reported from this area suggest that other factors may have had greater influence.

A more satisfactory explanation for the limited number of legal sized abalone, is that size limits in this area are overly conservative. Abalone in this region are known to be slower growing, and to reach a smaller maximum size than those in more southern waters. That the modal size class in all samples was several groups below the legal minimum size limit (Figure 43), provides evidence for this hypothesis. As such, only a small proportion of the population may be available to fishing, thereby increasing the sensitivity to growth overfishing.

Before any conclusion on the appropriateness of size limits in the area can be drawn with confidence however, information on growth rates, size at maturity, and if possible, estimates of natural and fishing mortality must be considered. Such data would ideally be collected both at these and additional sites (only limited data are available at present, Tarbath and Officer 2003). Repeated surveys at these sites would also be useful to allow any modal progression to be tracked, thereby further aiding interpretation.

The unexpected results obtained in the north-east of the state highlight the value of such remote area surveys.

10.2. South-West and North-West Coasts

The West coast of Tasmania is one of the most exposed coastlines in Australia, with almost constant swell that rarely drops below two metres (it is difficult to work in shallow depths in such swells, particularly in this region). The period most conducive to abalone fishing (and research) on the West Coast is usually between November and April, when sea and wind conditions tend to be at their mildest, and periods of easterly winds are more frequent.

An anticipated problem with establishing sites and conducting surveys on the West Coast again relates to the current limitation of nine metres maximum depth imposed by remote area restrictions under the Scientific Diving Code (Standards Australia 2002). In higher-energy areas of the Tasmanian coastline, *H. rubra* are often distributed deeper than that in less exposed areas. Along much of the West and South-West Coast, the abalone fishery occurs primarily between 7m and 15m depth.

In March 2004, a research cruise was scheduled for the south- and central-West Coast. Adverse weather conditions prevented departure at the scheduled date, however an expected four day weather window eventually opened and was taken. The rapid onset of a frontal system reduced this window to only two days however, greatly limiting the potential for West Coast surveys. During these two days, four sites were surveyed between Window Pane Bay and Rough Bay near Bathurst Harbour, with approximately three to five sites assessed for every site that was considered suitable (Figure 44a). Reef structure varied from steep walls to large shelves, with a mix of quartzite boulders and slabs. To achieve the objective of assessing the radial transect technique in remote areas, sites were chosen where abalone appeared to be reasonably abundant. Insufficient abalone was the primary reason for rejecting the majority of sites assessed (again, it could not be determined whether such low abundance was because sites were depleted through fishing, or were not part of the fishery).

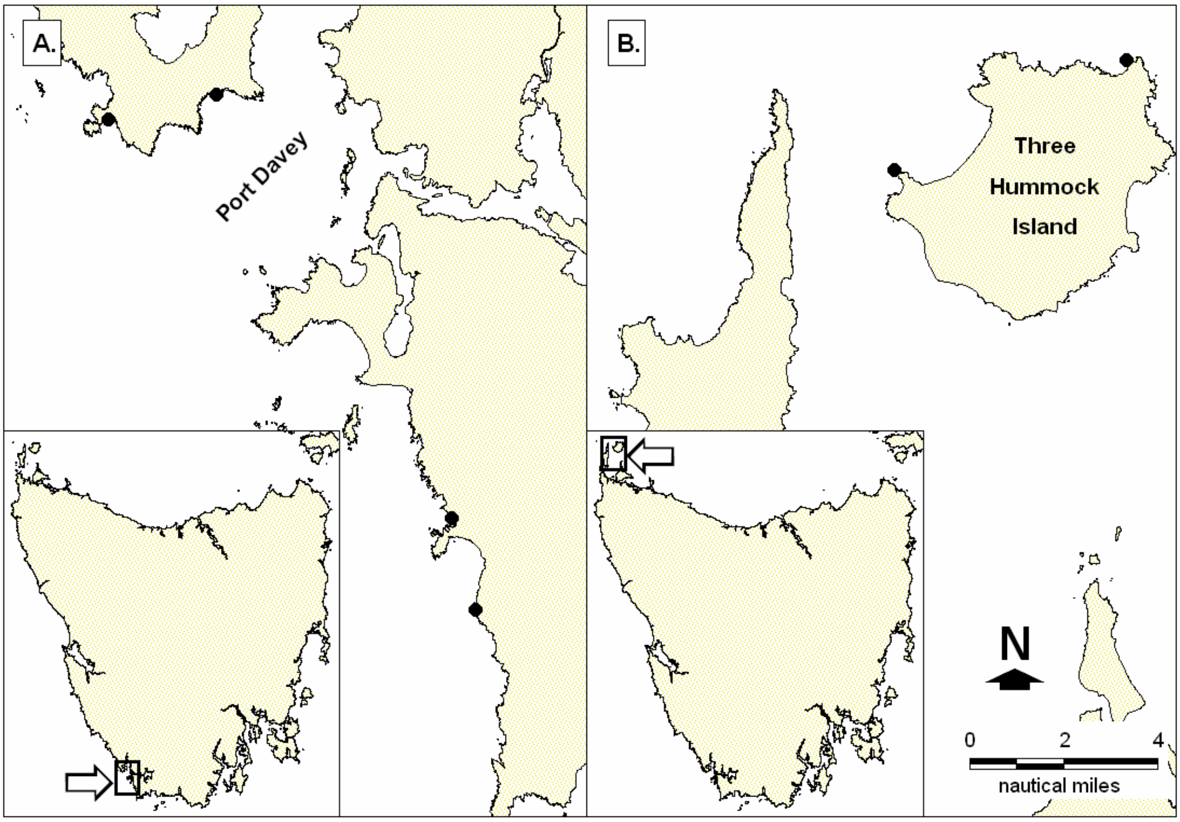

Figure 44. *West Coast sites surveyed using the modified radial transect method during the March 2004 research cruise: [A] South-West Coast (Port Davey Region) between Window Pane Bay (southernmost site) and Rough Bay (westernmost site); [B] Three Hummock Island.*

Adhering to the remote area restrictions imposed by the Australian Standard for Scientific Diving, and reflected in the University of Tasmania Dive Code presented a significant challenge during this cruise. Establishing sites that were primarily above 9m presented two problems. Firstly there were few reef areas of sufficient size above 9m depth to conduct a modified radial transect survey. Secondly, on reefs where these conditions were met, divers were challenged by surge, and by the presence and motion of a heavy canopy of bull kelp (*D. potatoratum*). In practice this greatly restricted the range of locations from which survey sites could be selected, and may invalidate inferences about broader stock health because sampling is only feasible from a small proportion of the active fishery. Importantly, this problem is not restricted to the current survey method, but is a generic issue for research in this region.

As weather conditions on the West Coast deteriorated, an opportunity was taken to evaluate radial transect methods in the North-West. With the time available, an assessment was made of the reefs on the northern shore of Three Hummock Island (Figure 44b). Site selection was slow in this area, as suitable abalone reef was patchy and often too small to conduct radial transect surveys. Abalone populations at the two sites on Three Hummock Island were particularly "patchy". The reef structure here was large granite slabs, interspersed with small grooves and shallow ledges. The abalone were generally distributed along these grooves. Consequently, individual replicate transects tended to contain relatively high densities when the transect followed a groove, but would result in low numbers (or zero) of abalone if the transect crossed perpendicular to the grove.

A series of reefs were also assessed on the northern mainland cost of Tasmania, but these were unsuitable largely because of the narrow and linear nature of the reef system (e.g. Circular Head), or there was insufficient shallow reef area to locate a radial transect site (e.g. Anniversary Point, Rocky Cape). In such areas, parallel transects, or those aligned to the shore, may represent a more appropriate, although less efficient survey option.

Abundances at the four central-West Coast sites (Table 12) were somewhat low in comparison to sites surveyed elsewhere (Table 5 and Table 11), and precision estimates were roughly comparable, or a little worse. At the two sites on Three Hummock Island however, abundance and statistical precision were roughly comparable to results from the north-east of the state (Table 11).

Table 12. Abundance and precision estimates from blacklip abalone surveys in western Tasmanian sites, March 2004. Means = mean abundance (per 15m^2) of abalone in emergent, pre-recruit 100mm+ (or 80mm+*) and >LML size classes respectively; Emergent = all emergent abalone; 100mm (or 80mm*) to LML = emergent abalone >100mm (or 80mm*) and <LML of 127mm or 140mm, depending on location**; >LML = emergent abalone equal to or larger than legal minimum length. Block 11 and 12 sites are around Port Davey, on the south/central West Coast, and the block 49 sites at Three Hummock Island. All sites were semicircular with 45m radius, except Burgess Point where the radius was 40m.

Site (Reporting Block)	**N**	**Means**			**Relative Error** (S.E. ÷ $\bar{x}$)			**CV**		
		Emergent	**100mm* to LML**	**> LML**	**Emergent**	**100mm* to LML**	**> LML**	**Emergent**	**100mm* to LML**	**> LML**
Window Pane Bay (12A)	10	7.9	3.4	4.4	0.30	0.46	0.24	0.94	1.45	0.74
Island Bay (12A)	10	2.7	0.5	2.2	0.28	0.80	0.21	0.89	2.54	0.67
Rough Bay (11C)	10	3.1	1.3	1.7	0.20	0.34	0.15	0.62	1.09	0.48
Saddle Bight (11E)	10	3.5	0.5	2.8	0.25	0.45	0.25	0.79	1.41	0.80
Burgess Point (49A)	10	12.9	5.4	6.8	0.24	0.36	0.24	0.71	1.09	0.71
Mermaid Bay (49A)	9	26.6	16.0	9.9	0.16	0.21	0.13	0.47	0.63	0.38

* 80mm to LML at Burgess Point and Mermaid Bay sites (Three Hummock Island)

** LML = 140mm at the block 11 and 12 sites, and 127mm at the block 49 sites

10.3. Bass Strait Islands and Furneaux Group

In May 2004, a third remote-area research cruise was undertaken to the Furneaux Group and Hogan Island (Bass Strait). This area was chosen to evaluate the modified radial transect technique as weather conditions precluded travelling to the West Coast, and since abalone size was generally smaller than in other areas in which surveys had been conducted (even the larger abalone in this area tend to be more cryptic, with few emergent individuals). Once again, the primary problem was locating reef areas of sufficient size in depths less than nine metres. Radial transect surveys were conducted at seven sites, and on each occasion the technique was efficient and practical (Figure 45).

Several days were also allocated to identifying suitable sites on the west coast of Flinders Island, and in Banks Strait in the south between Cape Barren Island and Clarke Island. No sites were found that were suitable, despite a significant greenlip fishery operating in this region. Abundant greenlip abalone were found below 9m and further offshore, where the habitat provides greater exposure to tidal currents. Again, the remote area restrictions prevented the establishment of sites in this region within the time available. On two occasions within a month of this visit, abalone divers recorded significant catches of blacklip abalone from deeper areas of reefs which were assessed, but rejected because there were insufficient abalone at shallow depths (<=9m).

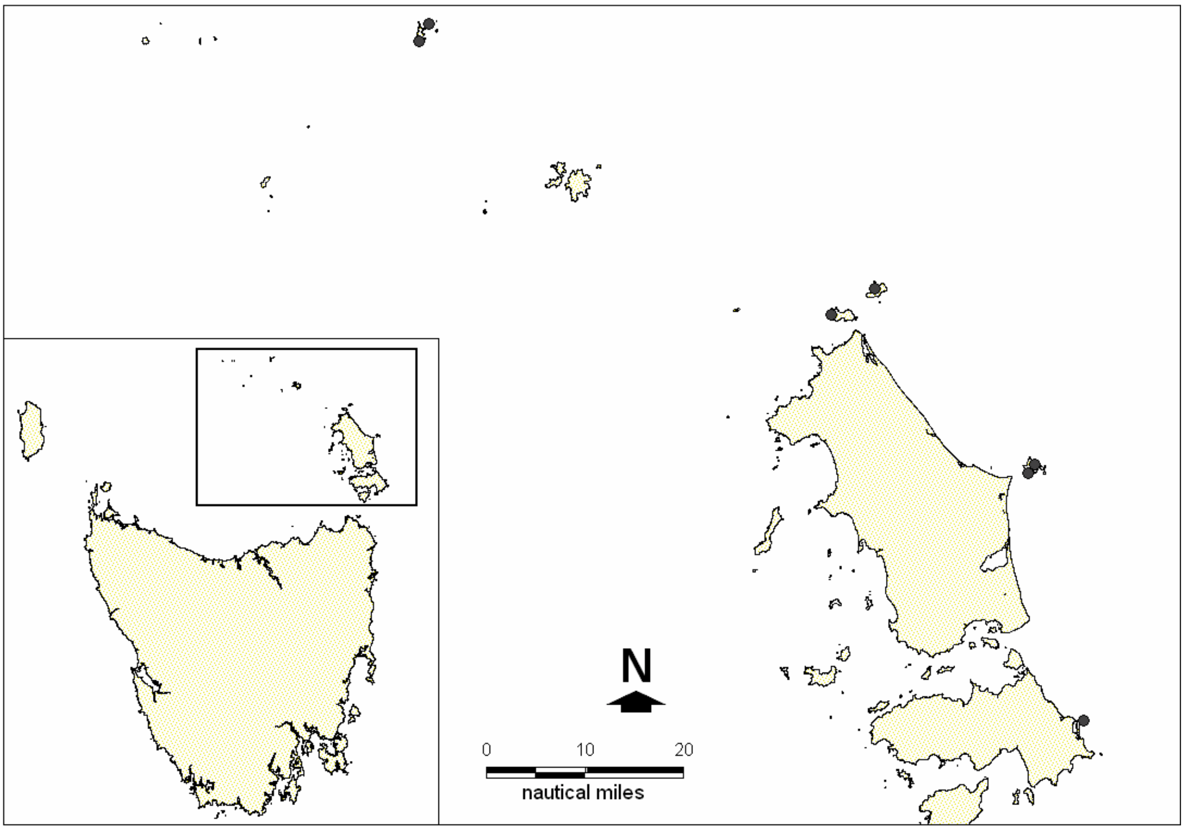

Figure 45. *Locations of sites surveyed during the May 2004 research cruise to the North-East and Bass Strait Islands.*

Abundances ranged from just over 0.5 abalone m^{-2} to around 1.4 abalone m^{-2} (Table 13), and at several sites, legal sized abalone accounted for only a relatively small proportion of the total population. Importantly, precision estimates were generally comparable to those from sites in other parts of the state.

Table 13. Abundance and precision estimates from blacklip abalone surveys in the Ferneaux Group and Bass Strait Islands (May 2004). "Means" = mean abundance (per 15m^{2}) of abalone in emergent, pre-recruit 80mm+ and >LML[*] size classes respectively; "Emergent" = all emergent abalone; "80mm to LML" = emergent abalone >80mm and <LML of 127mm or 114mm, depending on location[*]; ">LML" = emergent abalone equal to or larger than legal minimum length. All sites were semicircular with 45m radius.

Site (Reporting Block)	N	Means			Relative Error (S.E. ÷ $\bar{x}$)			CV		
		Emergent	80mm to LML	> LML	Emergent	80mm to LML	> LML	Emergent	80mm to LML	> LML
Harleys Point, Cape Barren Is (36A)	10	8.9	7.54	0.5	0.27	0.30	0.45	0.87	0.96	1.41
Moonlight Bay, Babel Is (38A)	10	19.2	14.1	3.2	0.28	0.31	0.27	0.87	0.97	0.86
Little Gulch, Babel Is. (38A)	10	16.0	10.8	3.3	0.27	0.29	0.38	0.85	0.92	1.20
Inner Sister Is., Reserve (37D)[**]	10	20.7	13.6	3.8	0.26	0.30	0.25	0.81	0.95	0.80
Hut Bay, Outer Sister Is. (37D)	10	8.4	3.6	1.1	0.31	0.40	0.37	0.99	1.26	1.17
Long Islet, northern tip (53)	10	8.6	4.6	3.0	0.22	0.27	0.30	0.69	0.86	0.96
Hogan Is., southern bay ()	10	12.3	4.9	6.4	0.13	0.25	0.14	0.40	0.78	0.46

* LML = 127mm at the block 36 and 38 sites, and 114mm at the block 37 and 53 sites

** Size limit for surrounding waters (fishing is prohibited at Inner Sister Island Reserve)

10.4. Remote area general discussion

The modified radial transect method generally performed well in habitats and conditions throughout the remote areas visited. Indeed, the technique was so successful that no attempt was made to use transects with any other arrangement. However, it is clear that the technique is not universally applicable.

Some inconvenience was encountered when working in high current areas, particularly for those transects which were oriented roughly perpendicular to the direction of water flow. It may be possible to alleviate this problem to a degree, by conducting surveys around slack tides, preferably during neaps, as much as possible at current affected sites. In reality however this is unlikely to always be possible due to factors such as limited weather windows, the need to survey multiple current affected sites on any given day, and the logistics of organising staff and equipment for extended field trips. In areas where current flow is particularly strong therefore, it may be more practical to employ a parallel, rather than radial transect arrangement. This may permit transects to be oriented appropriately with respect to the direction of water flow, if the orientation of the reef and distribution of abalone are so conducive.

In some locations, such as around Three Hummock Island, reefs were too narrow to accommodate radial transect sites (40m x 80m). In areas where this is the dominant reef pattern, then a less efficient parallel or shore-aligned transect arrangement may be more suitable, particularly if the area supports "reasonable" catches or contains moderate densities of abalone. At many locations throughout the state, reefs were physically wide enough to accommodate radial transects, but dropped below a workable depth, precluding radial transect surveys.

By far the greatest challenge faced during the remote area surveys was the restrictive dive rules imposed by the Australian (and New Zealand) Standard for Scientific Diving (Standards Australia 2002). This problem is not restricted to "remote" areas (i.e. those which are most easily reached using a larger research "mother ship") however. The only fixed recompression chamber facility in the state that is available for dive emergencies is based in the city of Hobart, in south-eastern Tasmania (although there is often a second, portable chamber based at a training facility at Beauty Point in the north of the State). University policy dictates that estimates of the time to reach a chamber must be based on the transportation method used to reach the dive site (i.e. no assumption of aerial evacuation). As such, the vast majority of the Tasmanian coastline is subject to these heavy restrictions.

In many parts of the coast, and particularly in high energy locations such as those typical of the West Coast, a large proportion of the abalone population are found deeper than nine metres. In such areas, there is little point in attempting any broad-scale fishery-independent monitoring program unless a solution can be found to allow more reasonable dive times. A solution applied to remote surveys in South Australia is to carry a portable recompression chamber and qualified operators on the research mother vessel during remote research cruises, however this is not currently practical for application in Tasmania, due to the smaller size of the research mother ship, availability of a chamber and operators, and expense. Other suggested solutions have included the use of mixed gases such as Nitrox (which are not covered by the Australian Standard), or bringing operations under a less restrictive standard. So far however, neither of these solutions have been implemented.

It is important to note that the abalone fishing industry does not fall under the scientific diving standard or university dive policy, and so is not constrained by the same restrictive dive rules. Accordingly, the fishery can, and frequently does, operate beyond survey depths.

Although a broad-scale and representative monitoring program is likely to be impractical or impossible to implement in remote areas, it may be worthwhile to implement a series of one-off "snapshot" surveys. It may, for example, be possible to implement one remote area survey per day in deeper water. Over the course of a ten day research cruise therefore, it may be possible to conduct eight or more surveys, which particularly if supplemented with shallow water surveys, can provide useful reference information about the state of the stocks in remote areas. By collecting small amounts of data in this way over a number of years, reference information about the state of stocks (in terms of abundance and size structure) in these remote areas can be accumulated. Such data is fundamental to sound long-term fisheries management (see Section 6.6.3).

10.5. Repeat surveys at established survey sites to assess temporal variability

With a practical and efficient sampling protocol now firmly established, it was appropriate to turn some attention toward the design of a potential abalone abundance monitoring program. The design of any such program depends upon a number of factors, including:

- the magnitude of effect that must be detected (i.e. the percentage change in abundance);
- the certainty with which an effect can be detected (statistical power);
- the certainty that any effect that is detected is real (statistical confidence);
- the relative importance of detecting an increase versus a decrease in abundance;
- an understanding of the variability in abalone abundance at different spatial scales (which affects the precision of abundance estimates); and
- the short-term temporal variability of abalone distribution at each site (which masks longer time trends in abundance).

The first three factors above are largely or entirely dependent upon availability of human, physical and financial resources, and inevitably there will be a trade-off between resources available and optimum sampling design. The last two factors however, are dependent largely upon natural (physical and biological) characteristics, and must therefore be determined through measurement (unless other means of estimation are available).

Within-site spatial variability has been measured throughout the course of this project at 35 sites, and the expected range of this factor is now reasonably well established. Estimation of temporal variability however, requires repeated measurements of abundance at a site over time, and therefore cannot be gathered rapidly (particularly when annual or bi-annual variation is of interest).

The data gathered during such repeat surveys provides important insight into the magnitude of temporal variation and the consistency of trends among sites. This data is important for determining the optimal allocation of resources to spatial and temporal replication, and survey power.

Repeating surveys at sub-annual intervals may also reveal seasonal trends in result. If, for example, no cyclical trend is detected in the data from four or more consecutive six-monthly surveys, then it would be reasonable to assume that there is no detectable seasonal signal of this period, due to either environmental or fishing induced changes. If this is found to be the case, then it will be possible to increase the power of surveys to detect changes in abundance throughout this part of the fishery, by increasing the frequency of surveys from yearly to six-monthly. Conversely, if a pattern is detected, further research will be required to determine whether the signal reflects a seasonal trend in abalone abundance (visibility), or seasonal fishing effort. The detection of a cyclical pattern may also provide an insight as to the most appropriate time of year to conduct surveys as part of an ongoing monitoring programme.

In order to understand the magnitude of temporal variation in abalone density, regular sampling using radial transect surveys at six monthly intervals (or more frequently) has been conducted at 12 established sites, and at 12 monthly intervals at five other sites in south-eastern Tasmania. The data gathered from these sites were examined to determine if there was a cyclical trend in abundance (such a trend was predicted on the basis of confirmed seasonal trends in catch-effort figures in this region).

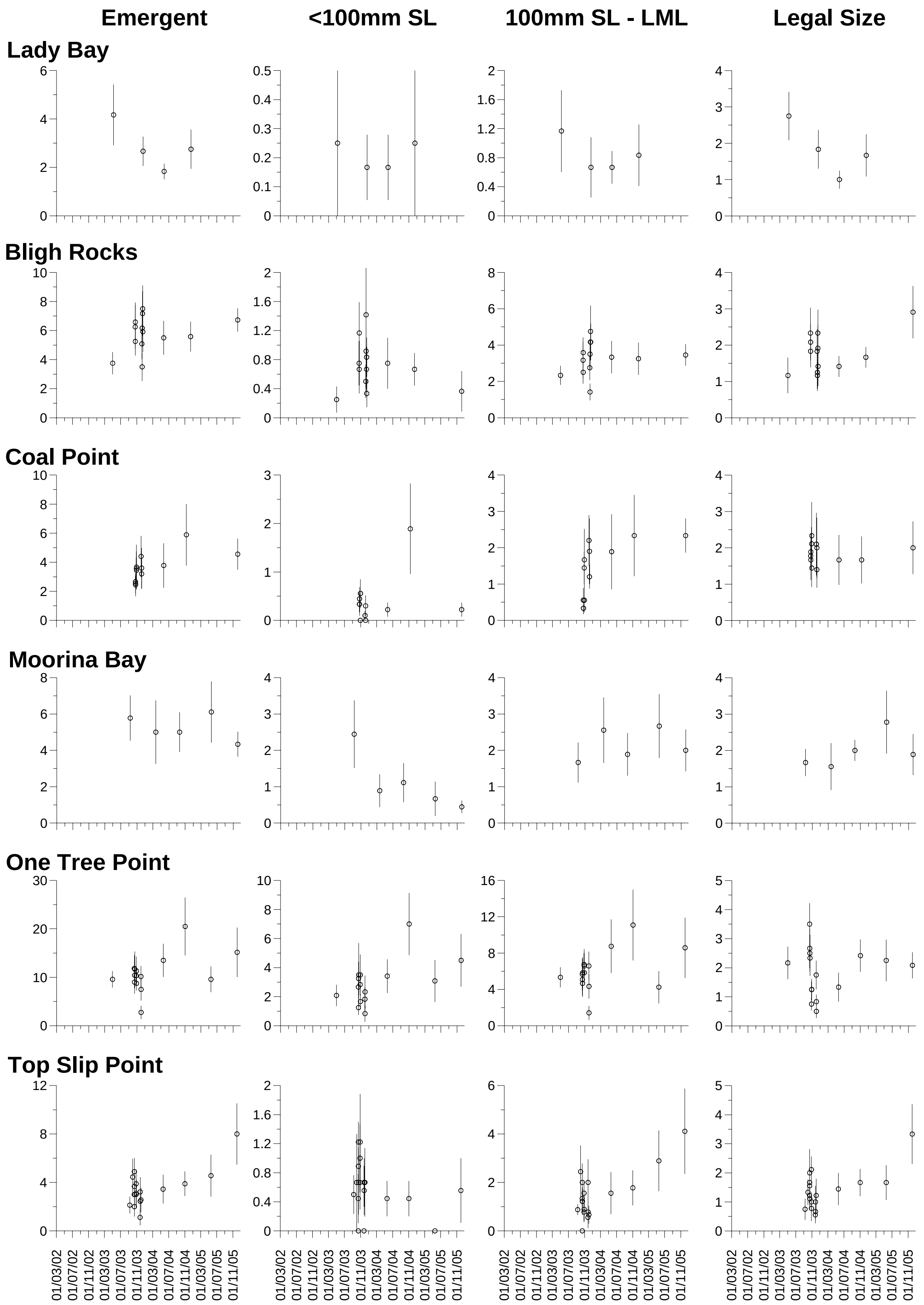

Figure 46. *Estimates of total abundance of abalone at fixed sites through time from four sites in south-eastern Tasmania. At One Tree and Top Slip Points, multiple surveys were conducted over a relatively short time period. At both sites (but particularly Top Slip Point) considerable variation was observed in the estimates from surveys conducted over a relatively short period.*

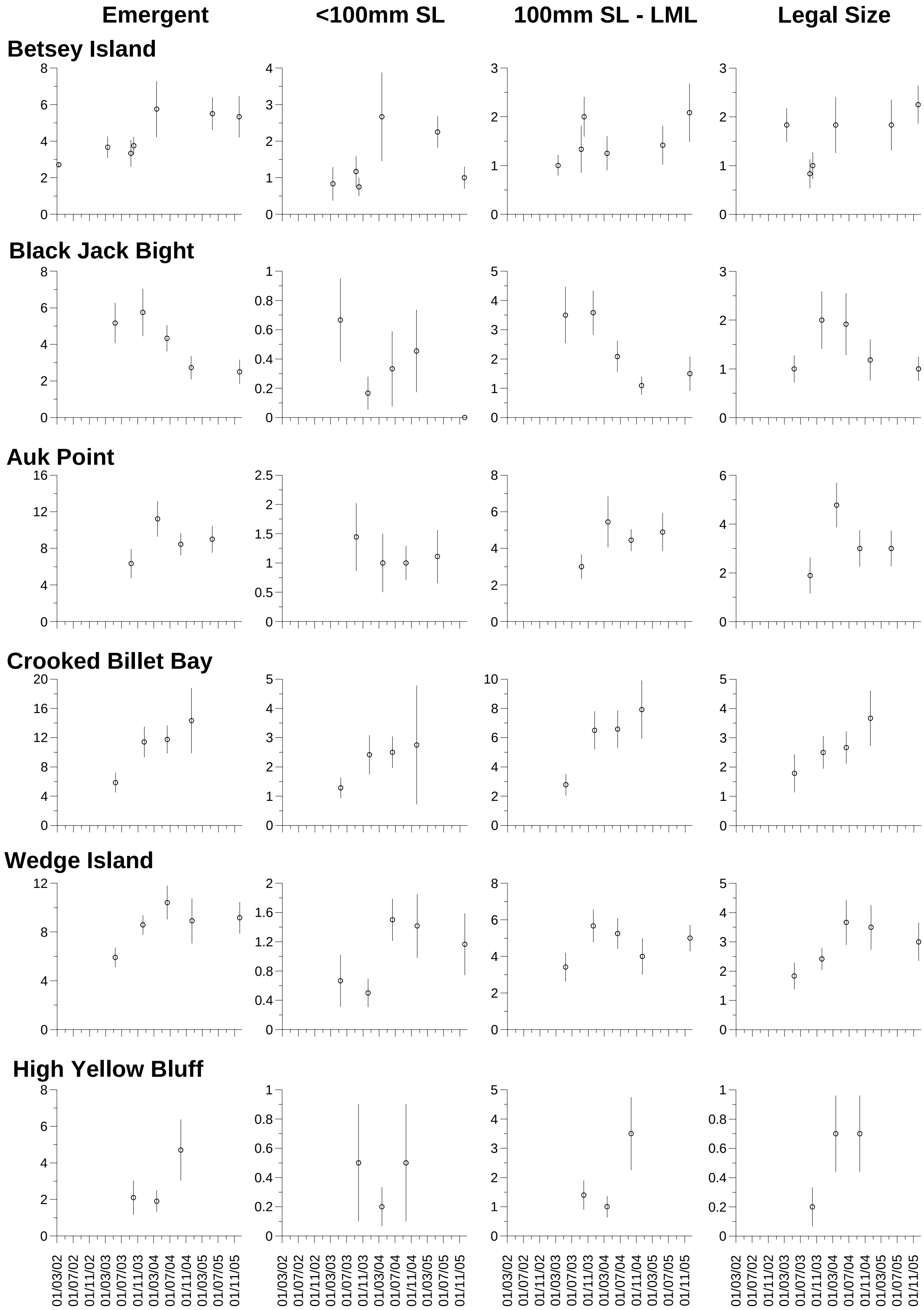

Figure 47. *Estimates of total abundance of abalone at fixed sites through time from four sites in south-eastern Tasmania. At One Tree and Top Slip Points, multiple surveys were conducted over a relatively short time period. At both sites (but particularly Top Slip Point) considerable variation was observed in the estimates from surveys conducted over a relatively short period.*

Although the ratios between standard error and mean for sample units within sites tend to be relatively low (generally in the range 0.2 to 0.3), the time series data gathered during this work shows that considerable variation in estimates of abundance exists between surveys (Figure 46, Figure 47). This is true even when these were conducted over a relatively short period. The consequence of this effect is, unfortunately, a reduction in power of any survey program to detect changes in abundance over time.

This work was preliminary in nature, and as such the conclusion of no cyclical trend is tentative. If it holds true however, it would be possible to reduce the survey frequency at each site from 12 monthly to six monthly (for example), with no confounding effect of season. This would enable more rapid and precise assessment of upward or downward trends in stock abundance, provided that sufficient resources are available.

11.Optimisation of Fishery-Dependent Data Sources

11.1.History of fishery – the rise & fall in the 1990/2000s

From 1975 to date, the Tasmanian fishery for blacklip abalone (*Haliotis rubra*), has exhibited some marked changes in total catches, catch rates, and availability of stock. To some extent, catch rate changes have been driven by the total catches reducing stock availability. The large catches taken in the early 1980s depleted stocks (Figure 48) and influenced catch rates until the early 1990s.

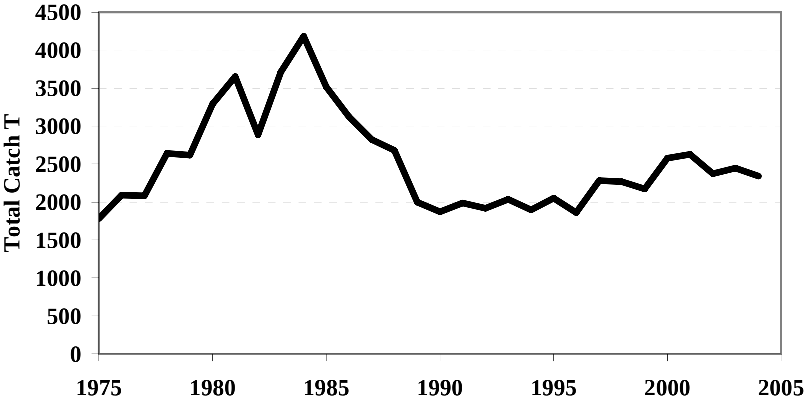

Figure 48. *Reported landings of blacklip abalone (H. rubra) from 1975 to 2004. Individual quotas and a Total Allowable Catch (TAC) were introduced in 1985. A large reduction in the TAC down to 2079 tonnes occurred in 1989.*

Detection of important trends in fishing patterns and the implied availability of stocks can be obscured if only the total State-wide catch is considered. Catch rates on the West Coast have always been higher than on the East Coast, but the West is more difficult to fish simply because of the harsher weather and sea conditions. Until the early 1990s the annual catch was similar on the East and West Coasts (Figure 49). However, a consideration of the differences between the catches from the two coasts demonstrates there was always a greater chance of more being taken from the East than the West (Figure 49, Figure 50).

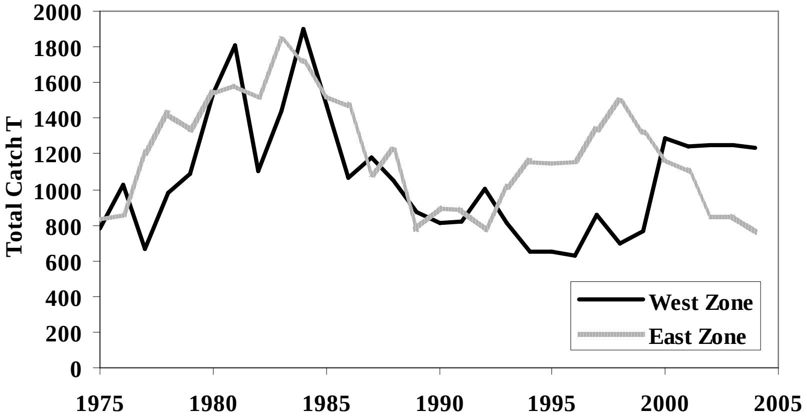

Figure 49. *Tasmanian blacklip abalone catches separated by East and West Coasts (East Coast defined as blocks 13-31; West Coast defined as blocks 6-12; these differ slightly from the current Eastern and Western Zones because the block boundaries do not coincide exactly with the zone boundaries).*

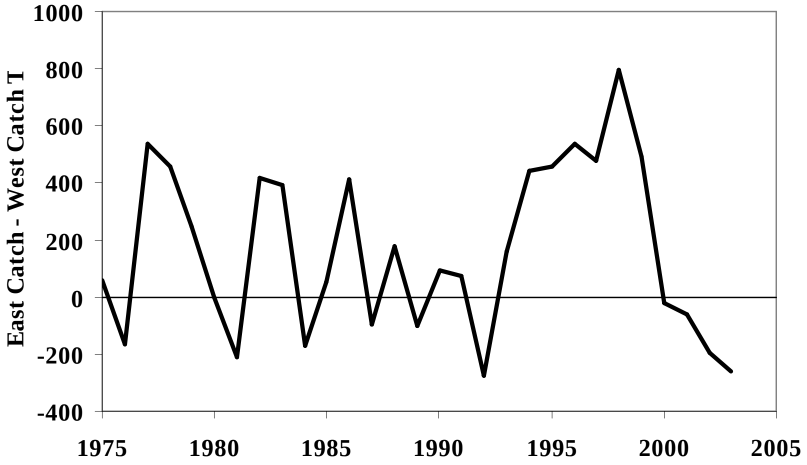

Figure 50. *The difference between Eastern Zone catches and Western Zone catches from 1975 to 2003. The bias towards catches from the Eastern Zone is apparent. The switch from 2000 onwards is due to the introduction of Eastern and Western Zones and separate TACs.*

Following the large quota reduction in 1989 (to 2079t) there was a period of three or four years of relatively low and even catches on both coasts, followed by a radical change in the distribution of effort. From 1994 consistently more abalone were taken from the East Coast than the West (Figure 49, Figure 50). Several factors are thought to have triggered this shift. The remoteness of the West Coast fishery requires a higher financial cost to the diver to catch a unit of quota. Although catch rates on the West Coast have always been approximately twice those on the East Coast (Figure 51, Figure 52), this incentive to fish the West Coast appears to be outweighed by the relative ease of fishing and recovery of the East Coast fishery. As the catch rate differential between the East and West diminished in the early 1990s (Figure 50) there was an economic incentive to shift effort to the East. The development of the live market may also have contributed to this shift, with an apparent market preference for the smaller East Coast abalone.

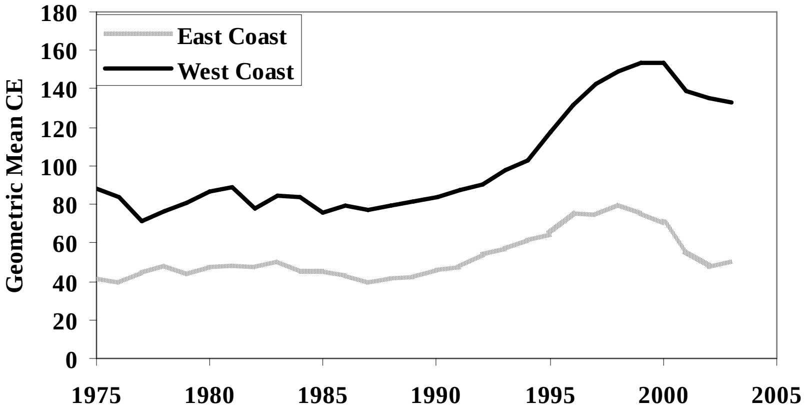

Figure 51. *A comparison of the geometric mean catch rates from 1975 to 2003 on the East Coast (blocks 13 to 31) and West Coast (blocks 6 to 12). A very similar pattern is seen using simple arithmetic mean catch rates.*

In 2000 when zonation of the available quota was introduced, the East Coast catch was reduced below that of the West Coast and that trend has continued to the present. Catch rates also started to decline from 1999 onwards on both the East and West Coasts. From the majority of diver reports, the catch rates and stocks on the East Coast appeared to reach unacceptably low levels for the catching sector. These deteriorating fishing conditions led to substantial quota reductions on the East Coast from 1190t in 2001 to 770t in 2004. The first signs of some recovery on the East Coast are now evident (Tarbath et al. 2005), with apparently rapid recovery in some areas.

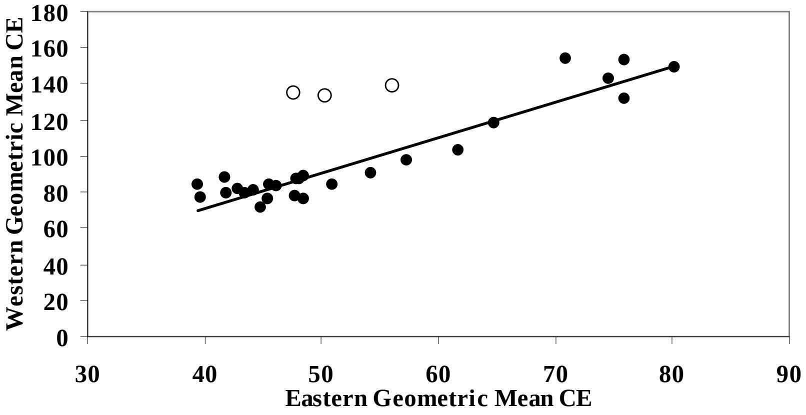

Figure 52. *The geometric mean catch rate on the West Coast plotted against the geometric mean catch rate on the East Coast for each year of the fishery from 1975 to 2003. The regression line is through the data for 1975 to 2000 with a gradient of 1.9609 and an intercept of -7.1137, describing 89.37% of the variation in the data. The three open circles on the graph are for the years 2001 to 2003, where the relationship broke down and the West Coast catch rates remained high while those on the East Coast dropped alarmingly.*

The large increase in catch rates across the State during the mid-1990s is thought to be a consequence of many independent factors. Firstly, the large reduction in TAC between 1985 and 1989 will have permitted recovery of stocks to some extent by the mid-1990s. Secondly, there were increases in the fishing efficiency of the fleet of divers. Fishing practices such as the use of GPS, the use of drop lines, and improved diving gear and boats would have contributed to the improved catch rates. The third factor is that the increase in catch rates were largely driven by several very successful recruitment pulses in the early 1990s. Divers reported that abalone availability during the last half of the 1990s was much higher than had ever been experienced on the East Coast. This was associated with the largest disparity of catches between the East and West seen to date (Figure 49, Figure 50).

11.2. Myths - two year rule/higher production when size limit at 127mm

The interpretation of changes in catch rates through time is complicated due to multiple and varied management changes, as well as changes to the fishing practices of the abalone divers (Tarbath *et al.* 2005).

When size limits were first introduced the legal minimum length (LML) was set at 127mm (or five inches at the time). One myth that persists within the abalone industry is that the stock was more productive when it was fished at a LML of 127mm, and that the very large annual catch taken in earlier years was sustainable. This myth is inconsistent with the widespread industry recognition that catch levels in the mid-1980s were clearly unsustainable. It was primarily industry concern that led to the introduction of a quota system and a TAC, with the TAC reduced in rapid steps down from a maximum of 3806t in 1985 to 2079t in 1989 (Tarbath et al. 2005). This level of catch was then maintained for eight years before increases were considered (Figure 48). The early fishing for abalone at 127mm will have altered the stocks in the East and West, although stocks in the North would have seen a reasonable level of protection.

Selection of a LML is necessarily a trade-off between competing demands. It is true that there are sub-populations of abalone in close proximity to one another that grow at different rates and as the LML is increased, slower growing sub-populations may become inaccessible to the fishery. To counteract this, there is a risk or potential cost that if the LML is too small insufficient spawning biomass of adults may be retained to produce sufficient recruits for future fishing across the full range of suitable habitats. On the other hand, if the LML is too large then the available exploitable biomass may be reduced and the total catch may be reduced with a greater fishing mortality rate on the larger abalone. While this may increase the resilience of the stock it may well decrease the economic resilience of the fishery as well as being a direct opportunity cost. Balancing this trade-off between conservation and risk is the difficult management decision required when setting an LML.

In Tasmania, to assist in making such decisions, an approximate “rule of thumb” has been developed empirically through considering the LML in various areas and comparing that against the size at maturity. In many places the LML was set at a size corresponding to what would be the case after approximately two or more years of growth following the size at

50% sexual maturity. The two years growth following maturity was really set as a minimum. However, since that early work many more samples aimed at determining the size at maturity have been made and there were numerous instances of sub-populations receiving both more and less than this guideline minimum protection.

11.3. Approaches to standardisation

11.3.1. Introduction

The assumption behind considering catch rates from any fishery is that this provides some insight into the relative amounts of available biomass through time. This assumption has often been challenged when considering abalone fisheries but the general trends of catch rate (Figure 51) do seem to follow the fate of the fishery in Tasmania so a more detailed examination was deemed worthwhile.

The catch and effort data available from Tasmania's commercial catch and effort database derives from a wide range of zones, blocks, and sub-blocks, divers, months, depths, and other factors that can be added such as moon phase, water temperature, and swell direction. It is well known that catch rates can be affected by all these factors (plus others unfortunately not recorded in any database). If the array of divers that fish, or the areas and depths that are fished, vary from year to year, or the season of maximum fishing varies from year to year, we may observe changes in catch-effort which have nothing to do with changes in the stock biomass. Rather, such changes would be related to fleet dynamics and the distribution of fishing effort. For the abalone fishery, therefore, we should not simply average the available data to obtain representative catch-effort figures through time. Instead we should attempt to determine catch-effort figures standardised in terms of the factors depth, fishing zone, month, and diver (plus any other factors we can obtain data for). After standardisation, the catch-effort data should then provide a better indication of the relative status of the stock upon which the fishery is based. In effect, standardisation acts to remove the effects, or at least reduce the obscuring effects, of the factors being included in the standardisation (e.g. depth, season, zone, etc). Once the effects of these factors has been neutralised the remaining variation, or at least that associated with a year or time factor, should provide a better representation of the relative changes in catch rates (as a proxy for relative abundance) through time.

As Kimura (1981, p211) says: "Since the 1950s it has been recognised that fishing power generally differs among vessels, and if c.p.u.e. is to be proportional to abundance, effort measurements must be standardised." The most commonly used method of standardisation is to include the various factors thought to effect catch rates into a Generalised Linear Model and to include Year as a factor, in this way the parameters derived for each year become the indices of relative abundance (Vignaux 1993, Klaer 1994).

After standardisation we are left with a set of yearly coefficients that represent the catch rate relative to some reference year (usually the first or last in the time series). Unfortunately, even if the standardisation accounts for a large proportion of the variability in the data there are no guarantees that catch-effort, even standardised catch-effort, can act as a good proxy for stock size. Instead of the success of the standardisation, one should be able to argue from the nature of the fishery whether or not there is likely to be even an approximate relationship between catch rates and stock size. This is an area of great debate and interest.

An obvious question to ask is whether the inferences it is possible to draw from the catch-effort information are consistent with the implications of abalone diver observations of abalone availability. When both data types are consistent then confidence tends to be increased in the assessment. If the different data are inconsistent then it becomes clear that some form of uncertainty is not being accounted for in the statistical modelling or data collection. Certainly, the general trends in catch rates (Figure 51, Figure 52) appear to follow the overall availability of abalone in the Eastern and Western zones. There is no denying that the low catch rates exhibited in the Eastern Zone fishery from 2000 were real expressions of a lack of availability.

11.3.2. Problems of dropline

Discussions with the divers indicated that one of the biggest factors to influence catch rates that they can remember is the advent of the droplines. These lines are used to pass full catch bags to the surface and receive empty ones in their place. By avoiding the need to surface and move large and heavy bags about the sea bed the catching efficiency of most divers increased enormously. Unfortunately, there are no records as to when each diver began to adopt the use of droplines in their operation so their effects cannot be analysed separately. Such changes that come about from alterations in how divers fish are often referred to as effort creep. In effect there is an increase in catchability, which if it is not identified, can easily be mistaken for an increase in availability.

11.3.3. Preliminary catch -effort standardisations

One of the objectives of this project was to develop methods of standardizing commercial catch and effort statistics on abalone to better represent any underlying changes in available stock biomass. Preliminary standardisations were conducted upon commercial catch-effort data from abalone statistical reporting areas 13 and 14 in the productive South-East region of Tasmania (Figure 53).

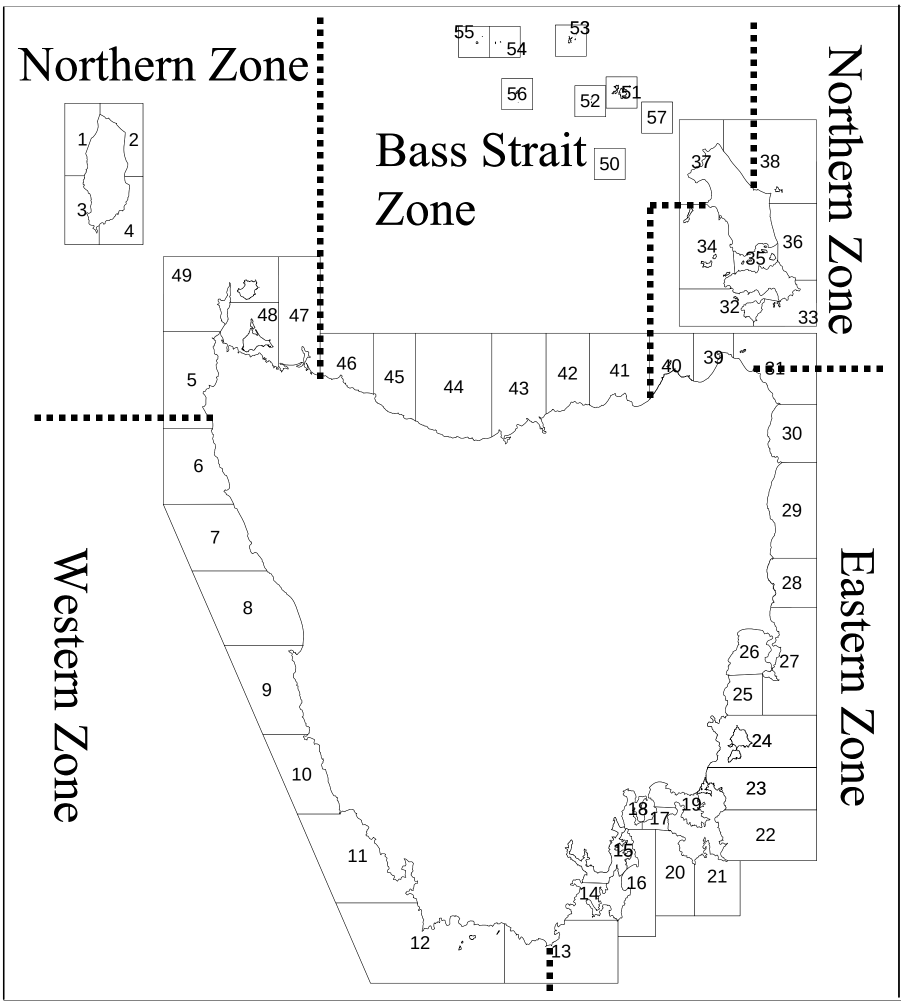

Figure 53. *Statistical blocks and zones used in the Tasmanian abalone fishery in 2004. Zones and zone boundaries may change from year to year. Zone boundaries are shown as dotted lines. The Greenlip fishery is not spatially-fixed, but mostly takes place on coasts included in the Northern Zone (taken from Tarbath et al, 2005).*

These preliminary studies were designed to determine the types of problems likely to be encountered when attempting to apply a classical Generalised Linear Model to standardise the available data. The optimum model, in terms of variation accounted for, for Block 13 was found to be:

$$Ln(CE) = Constant + Year + Month + Month^2 + Diver + Boat + Port$$

while for block 14 it was:

$$Ln(CE) = Constant + Year + Month + Month^2 + Diver + Boat + Port + Processor$$

Where the various factors are well identified by their names; Ln(CE) is the natural logarithm of the observed catch rates. The squared Month term is there as this is used to account for seasonality of catch rates.

There were important differences between the standardised catch rate trends and those based on simple summary information. The standardised data indicate that the trends in the catch rates were more extreme than the unstandardised catch rates would indicate. It was also clear that geographically adjacent statistical blocks could have different optimum statistical models. The potential importance of changes in the quality of fishing effort (effort creep) has also been demonstrated and this will continue to be investigated. These analyses provided insights into how to approach the analysis of the state-wide information.

11.3.4. Introduction of Generalised Linear Models

The standardisation of the commercial catch-effort data for blocks 13 and 14 led to trends in catch rate being perceived as more extreme than indicated by the unstandardised data. Because of this and the demonstrated potential significance of effort creep it was decided to include these preliminary analyses into the year 2000 and 2001 stock assessment reports (Tarbath et al. 2001a, Tarbath et al. 2002a). These reports were widely distributed among the Tasmanian Abalone Industry and were discussed in detail in the Abalone Stock Assessment group, which has members from all commercial sectors (divers, quota holders, processors, management).

After discussions with a selection of Tasmanian abalone divers, attempts were made to use Generalised Linear Models (GLMs) to standardise the commercial catch and effort information from different areas of the fishery (South-East and West Coast). Such standardisations are conducted routinely in NSW and Victoria (Worthington et al. 1998, Gorfine and Dixon 2000, 2002) and were suggested though not performed by (Gorfine and Walker 1997a, b). In Tasmania, only preliminary work has been attempted, although some of this led to improved perceptions of catch rate trends (Tarbath et al. 2001b, Tarbath et al. 2002b). That preliminary work indicated that standardisation of such commercial information for two of the most important statistical blocks in Tasmania (Tarbath et al. 2002b) provided useful insights into how catch rates have been influenced by factors other than stock biomass changes. This work on standardisation has been extended by adding a number of extra factors that intuitively may have effects upon abalone catch rates (e.g. wind speed, swell directions). To avoid the effects of effort creep that were apparent in the preliminary analyses the most recent GLM analyses were restricted to data from the last ten years (during which time most divers believe they have not varied their approach to fishing in terms of gear and searching patterns). However, the effects of the shifting emphasis to fishing for the live abalone market over the past five years have yet to be identified because divers do not yet report when they are fishing for the live market or the canning market. Most recently, fishing for the live market has led to divers being much more selective about the size of abalone collected. For example, on the Tasmanian West Coast, instead of taking the run of the fish, in many cases divers are only taking abalone between 140 mm and 160mm in shell length. Such selective fishing will have enormous effects upon their catch rates.

Unexpectedly, the most recently calculated standardisations made little impression on the catch rate trends based upon unaltered geometric mean catch rates. A wide range of different

GLMs were considered using as many different factors as were available (area, diver, month, landing site, processor, depth) but, to date, only minor changes to the unstandardised catch rates have arisen from the standardisation. This work will continue with a detailed consideration of the sampling distribution of catch rates through time (Tarbath et al. 2002b) and a consideration of other regions around Tasmania. In the Actaeon region of the fishery (the most productive part of the fishery, in the South-East region) there was a change in this sampling distribution from strongly log-normal during the 1980s and early 1990s, which is typical of fishery catch rates, to distributions which were far more symmetrical (similar to normal distributions) from 1993 onwards. Similar changes are apparent in parts of the West Coast. This radical change indicates that something remarkable occurred in the fishery at that time and will be investigated further. While the later distributions are less typically log-normally distributed the log-normal distribution still describes the distributions well; in effect, the earlier data simply had more extreme skewness than the later data.

In further future work, the GLM approach will also be applied to the 20 most productive statistical blocks in Tasmania on an individual basis. It is the case that ten of the statistical blocks often produce over 75% of the fishery so it is natural to focus attention on these areas.

11.3.5. Geometric average rather than arithmetic mean

In any discussion of catch rates it is normal to consider the average catch rates of a collection of observations (multiple divers and multiple days). The requirement is to obtain some indication of the expected catch rate for a particular combination of conditions (location, date, weather, etc). The simple arithmetic average (the sum of catch rates over the number of observations) rarely produces an adequate representation of an expected catch rate because the distribution of catch rates usually observed in many fisheries has a skewed distribution (often log-normally distributed). All this means is that catch rates do not distribute themselves symmetrically around some average but rather have a slewed distribution with a long tail to the right (i.e. only a few divers have really high catch rates, most have a lower catch rate and obviously there are no negative catch rates). It is still possible to calculate the arithmetic average of such a distribution but it would produce an estimate of the expected catch rate which was biased upward. Instead, it is more typical to use the geometric mean catch rate, which is far less influenced by extreme values skewed to the right.

$$\bar{x} = \frac{\sum x_i}{n} \qquad \text{arithmetic mean} \qquad (0.1)$$

$$\bar{x}_{GM} = e^{\sum Ln(x_i)/n} \qquad \text{geometric mean} \qquad (0.2)$$

An advantage of natural logarithm transformed catch rate data is that they are more symmetrically arranged about the average and are more amenable to ordinary statistical procedures, which generally require data to be normally distributed. Data that becomes normally distributed when log-transformed is known as log-normally distributed.

11.3.6. Frequency distribution of catch-efforts

The catch rates for an area can be summarised by plotting a frequency distribution of observed catch rates and comparing how the distribution alters through time (Figure 54). Note that with the untransformed data the distributions tend to exhibit some skewness to the right. Clearly, for the Actaeon region the catch rates declined seriously between 2000 and 2002. Since 2002, there has been a very slight improvement to 2003 but then indications of either a slight decline or no improvement (Figure 54 and Figure 55).

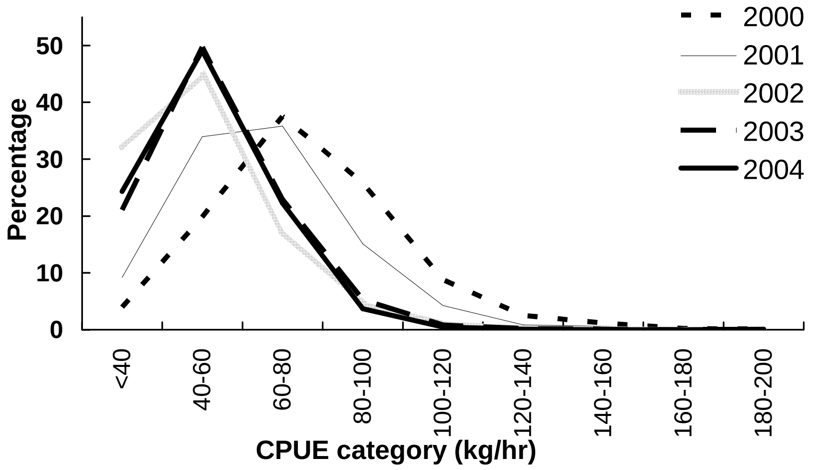

Figure 54. *Frequency distribution of abalone catch rates (kg hr^{-1}) for the Actaeons expressed as percentages of all observed catch rates.*

After natural logarithmic transformation the distributions are more symmetrical but show essentially the same relative patterns as the untransformed data (Figure 55), although a slight decline between 2003 and 2004 is more visible with transformed data.

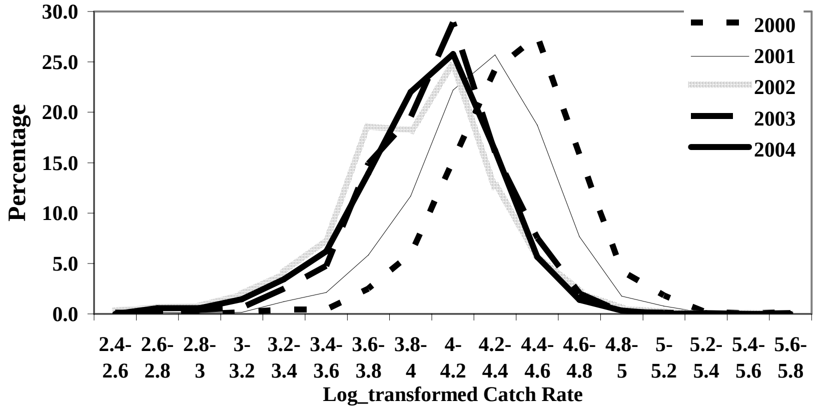

Figure 55. *Log-transformed abalone catch rates for the Actaeons exhibiting approximately normal distributions about the geometric means.*

11.4. Catch rate standardisation

11.4.1. Motivation for catch rate standardisation

The motivation for standardising catch rates is that fishers do not fish at random and their behaviour and other factors (e.g. wind speed and direction) can mask underlying depletion in a fishery. Catch rate data is fitted to a Generalised Linear Model where variables such as the Fisher, Vessel, Season and Region of fishing are included as categorical factors along with the Year. The coefficients for the Year terms in the statistical model correspond to the standardised catch rates and are compared to the catch rates from the simple geometric means. This allows for variation due to variables other than year to be included in the model.

11.4.2. Data used to evaluate GLM models

11.4.2.1. Minimum catch

Not all catch rate data should be included in a statistical standardisation. If some data is known not to be representative of typical catches it can validly be excluded. One decision rule for inclusion of data was that a diver had to exceed a minimum catch of 40kg for a record to be considered in the analysis. This was done for two main reasons, firstly catches of 0kg had to be excluded to make it possible to fit a Generalised Linear Model with a log link (one cannot log-transform a zero). Secondly, divers will often need to catch a small amount of quota at the end of the season or to complete catching a unit. It is assumed that these small catches are not representative of normal fishing effort so they need to be excluded from the analysis. This type of data is relatively evenly spread through the fishery so even if it were representative of general catch rates it would only have the effect of biasing the catch rates slightly high.

11.4.2.2. Catch per unit effort

The catch per unit effort, CPUE, or catch rate is measured in kilograms per hour of diving. The CPUE is calculated for each record as,

$$\text{CPUE} = \frac{\text{Weight of Catch}}{\text{Hours Dived}}.$$

11.4.2.3. Catch per day

There was some concern that divers may not be recording the dive time correctly; some may have reported time in the water while others may report time in the vessel. Because of this uncertainty an analysis just looking at the total weight per dive (or day) was also conducted. The catch per day in kilograms (CPD) analyses defined the Catch as

$$\text{CPD} = \text{Weight of Catch per Dive Day}$$

11.4.2.4. Area of analysis

The particular analysis described here included blocks 13 and 14 of the abalone fishery. Unfortunately this area spans both the Eastern and Western Zones of the fishery as block 13 was split between the Eastern and Western Zones when the Western Zone was introduced in 2000. The changing allocation of quota to the Eastern and Western Zones is something that cannot be allowed for in the analyses as we require a long time series of data to fit the models.

11.4.2.5. Selection of the dataset for Generalised Linear Model analyses

To reduce noise in the data it was also necessary to remove those divers that only fish part time or only have only dived occasionally in blocks 13 and 14 between 1987 and 2003. Their catch rates may be less likely to be as representative of the underlying dynamics of the stock and those divers who have only fished for one or two years have not provided sufficient data to permit a valid comparison of their data with other fishers. The data was therefore restricted to those divers that fished in blocks 13 and 14 for a minimum of three years and had a median catch of eight tonnes or more per year during that time. The divers that fit these criteria accounted for around 73% of the catch by weight, when excluding records under 40kg. If records under 40kg are included only 0.1% of the catch is unaccounted for.

11.4.2.6. Selection of the dataset for the mixed effects model analysis

An alternative to treating each diver as an independent level in a “Diver” factor is to treat divers as representing random variation around some overall average capability. To do this it is necessary to use what are termed mixed effects statistical models. When fitting mixed effects models to data, diver is treated as a random effect, so which diver caught the abalone is unimportant, only that the same method is used to select divers each year. The catch rate data of 20 divers in each year that caught the greatest catch, by weight, in blocks 13 and 14 for each year from 1987 until 2003 was used in this analysis. This accounted for around 74% of the total catch by weight during the 15 year period.

11.4.2.7. Variables included in the analyses

All variables in the Generalised Linear Model (GLM) analyses were treated as categorical factors. The variables that were included were the Year of the record, the Season, the Month, the Diver, the Block of fishing (either block 13 or 14), the Port of landing and the Processor.

To allow for the fitting of models with finer time resolution than the yearly scale it was decided to break the year up into four Seasons defined as;

Summer: January, February and March

Autumn: April, May and June

Winter: July, August and September

Spring: October, November and December.

11.4.2.8. Inclusion of weather data in the analyses

A series of Generalised Linear Models (GLMs) were fitted to the catch per unit effort (CPUE) data with the inclusion of weather data obtained from the Bureau of Meteorology in Hobart, http://www.bom.gov.au/. Data relating to the lunar phase was also obtained from the U.S. Naval Observatory website, http://aa.usno.navy.mil/data/ and included in the analysis. Both weather and lunar data was broken into categories and included as categorical factors in the GLMs.

The information on weather conditions at the Cape Bruny Lighthouse was obtained from the Bureau of Meteorology. Details of wind speed and direction in the morning (9am EST) and the afternoon (3pm EST). The wind direction was broken into three categories to represent ease of fishing. The categories were,

- E from 0° to < 135°,
- S from 135° to < 225°,
- and W from 225° to < 360°.

The wind speed was broken down into four categories,

- Light winds 0-5 knots.
- Moderate winds 5-20 knots.
- High winds 20-30 knots.
- Gale, over 30 knots.

The lunar data available was represented as the percentage of the disk of the moon illuminated. It was necessary to group this data into categories, four categories were created:

- New, less than 0.05 illumination.
- Waxing, between 0.05 and 0.95 illumination and increasing.
- Waning, between 0.05 and 0.95 illumination and decreasing.
- Full, greater than 0.95 illumination.

11.4.3. Statistical methods

11.4.3.1. The link function

With two types of catch-effort data, catch-per-hour (CPH) and catch-per-day (CPD), and a yearly analysis and a seasonal analysis there were four different kinds of analysis. A Generalised Linear Model (GLM) requires the statistical distribution that best represents the data to be identified and this is done via the link function. Thus, to identify which statistical distribution best represented the observed data we fitted Generalised Linear Models (GLMs) of the form

$$\alpha(\text{CPUE}) = \beta_0 + \beta_1\text{Year}, \quad \text{to the yearly CPD and CPH data}$$

$$\alpha(\text{CPUE}) = \beta_0 + \beta_1\text{Year*Season}, \quad \text{to the seasonal CPD and CPH data}$$

where 'α' is the link function of the GLM and β_0 and β_1 are the coefficients of the model. Five link functions were tested, the identity, log, square root, gamma and log gamma with the log-link providing the best fit to the observed data. A series of GLMs with log link functions were then fitted sequentially adding new factors to the models above until the optimal model was identified.

11.4.3.2. Catch per unit effort (CPUE) mixed effects model

As an alternative approach a series of mixed effect models were fitted with Diver being included as a random effect and the other factors such as Year, Month, Block, Port and Processor included as fixed categorical effects. The mixed effects models were fitted;

$$Ln\text{CPUE} = \beta_0 + \beta_1\text{Year} + \text{Diver},$$

where Diver was the random effect.

11.4.3.3. Statistical software

In all instances, the statistical package R versions 1.8.1 and 2.0.1 was used to generate the GLMs from which standardisations were derived. Both R 2.0.1 and Microsoft Excel 2003 was used for data inspection and plotting.

11.4.3.4. Model selection

The large number of observations in typical fisheries datasets means there is so much statistical power that it is often the case that selecting a model solely on the basis of a statistic such as AIC will result in the optimal model including all possible terms, including every possible interaction. In this analysis models were selected, primarily on lowest AIC, although attention was also given to the residual deviance or model divergence, degrees of freedom, standard errors of the model coefficients, and finally, the incremental changes to the trends through time of the parameters being standardised.

The AIC is the Akaike Information Criteria (Burnham and Anderson 1989), defined as:

$$AIC = -2L + 2K,$$

where L is the negative log likelihood and K is the number of free parameters.

The model divergence, the absolute differences between the various model fits, was considered when selecting models. Generally, changes tend to be large to start with and then quickly get smaller. There comes a point where the inclusion of additional parameters in a model no longer confers benefits or changes to the parameters in the model of interest (the yearly or seasonal parameters), even though the AIC may still be getting smaller.

11.4.3.5. Model validation

All models were validated using standard diagnostic visualisations, including QQ plots, plots of fitted vs observed values and Cook's distance plots (see Statistical Background section 11.6). These methods use residual information to determine how well a model fits the observed data. While a particular model may fit the observed data well, adding further factors may lead to a relatively poor statistical fit. Analysis of residuals can often identify when a model is providing a fit to the observed data consistent with the distribution assumptions made by the model.

11.4.4. Results

11.4.4.1. Contribution of weather data

The results of the Generalised Linear Models (GLMs) including weather data found that the inclusion of wind and lunar phase information did not add additional information to the models. Typically the lunar and wind terms were the last factors to be added to the models, there were benefits in terms of reduced AIC when adding lunar and wind information; however there was very little difference in standardised model coefficients. While different wind conditions will effect where and if a diver can fish this is not reflected in catch rate data as divers either don't fish in bad conditions, so we have no information, or they have sheltered areas in which they can maintain reasonable catch rates even when wind conditions are unfavourable. Further models were fitted without the inclusion of either wind or lunar phase data.

11.4.4.2. Yearly catch per unit effort analysis

The optimal yearly CPUE model in terms of lowest AIC and largest R^2 value, was determined to be,

LnCPUE = Year + Diver + Block + Month + Processor + Port + Diver*Block.

However, in terms of Model Divergence, the trends in the fitted models do not differ from the geometric means to any great extent, the standardised catch rates are slightly above the geometric means after 1996 (Figure 56).

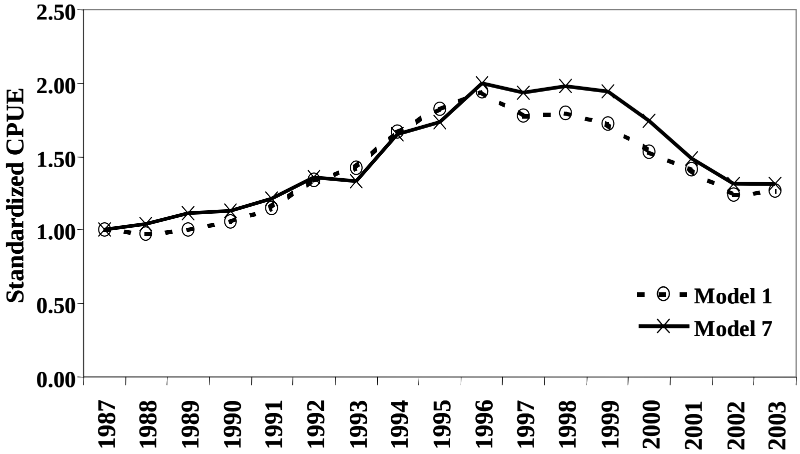

Figure 56. *Plot of yearly standardised CPUE in blocks 13 and 14 of the abalone fishery from 1987 until 2003. Model 1 is equivalent to the simple geometric means of catch rates and model 7 is the optimal standardised model.*

Table 14. Summary of statistical models used with the yearly standardised CPUE in blocks 13 and 14 of the abalone fishery from 1987 until 2003. Model 1 is equivalent to the geometric mean and Model 7 is the optimal model.

Model 1	Ln(Catch) =	Const + Year
Model 2	Ln(Catch) =	Const + Year + Diver
Model 3	Ln(Catch) =	Const + Year + Diver + Block
Model 4	Ln(Catch) =	Const + Year + Diver + Block + Month
Model 5	Ln(Catch) =	Const + Year + Diver + Block + Month + Processor
Model 6	Ln(Catch) =	Const + Year + Diver + Block + Month + Processor + Port
Model 7	Ln(Catch) =	Const + Year + Diver + Block + Month +Processor + Port + Diver*Block

	Model 1	Model 3	Model 4	Model 5	Model 6	Model 7
N	17833	17833	17833	17833	17833	17833
AIC	13454.16	9540.75	9068.94	8768.76	8671.97	8425.95
Res. Dev	2215.79	1771.43	1723.05	1682.17	1669.69	1639.81
DF	17816	17777	17766	17702	17684	17646
Adj. R^2	0.3263	0.4602	0.4747	0.4853	0.4886	0.4966

Table 15. Standardised catch rates for Blocks 13 and 14 CPUE from the abalone fishery from 1987 until 2003. Models are standardised relative to 1987 with standard errors (SE) included. Model 1 is equivalent to the simple geometric means and the Model 7 is the optimal standardised model (Table 13). The count column provides the number of records used in the analysis for each year.

Year	Model 1	SE	Model 7	SE	Observations
1987	1.000		1.000		1033
1988	1.032	0.015	1.038	0.014	1244
1989	1.126	0.016	1.118	0.017	840
1990	1.165	0.017	1.134	0.018	817
1991	1.181	0.016	1.212	0.021	825
1992	1.348	0.019	1.361	0.023	561
1993	1.413	0.016	1.328	0.022	897
1994	1.776	0.016	1.648	0.022	927
1995	1.854	0.016	1.732	0.021	1008
1996	2.061	0.015	2.002	0.021	1084
1997	1.973	0.015	1.931	0.021	1289
1998	2.021	0.015	1.982	0.020	1261
1999	1.995	0.015	1.946	0.019	1294
2000	1.839	0.015	1.747	0.020	1238
2001	1.555	0.015	1.488	0.021	1276
2002	1.380	0.015	1.314	0.021	1159
2003	1.414	0.015	1.312	0.022	1080

11.4.4.3. Yearly catch per day analysis

The optimal yearly CPD model in terms of lowest AIC and largest R squared value, was determined to be,

LnCatch= Year + Diver + Block + Month + Processor + Port + Diver*Block.

In terms of model divergence between the geometric means and the optimal standardised model, the trends in the fitted models are essentially the same as the geometric means (Figure 57).

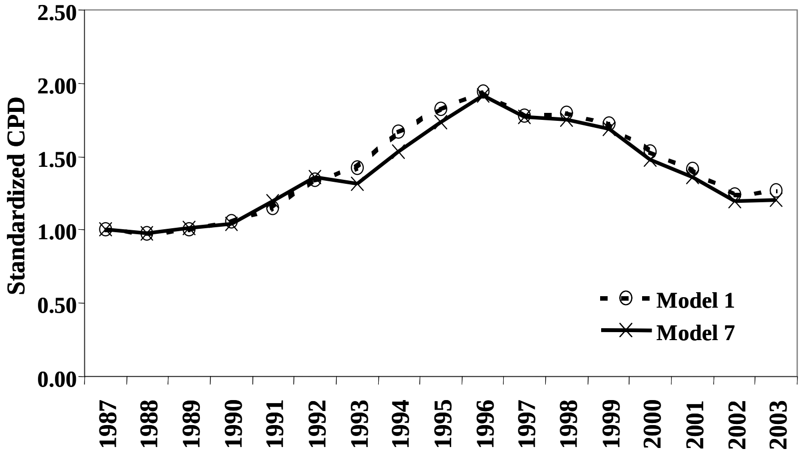

Figure 57. *Plot of yearly standardised catch per day (CPD) in blocks 13 and 14 of the abalone fishery from 1987 until 2003. Model 1 is equivalent to the simple geometric means of catch rates and model.*

Table 16. Summary of statistical models used in the standardised yearly Catch per Day analysis. Model 1 is equivalent to the geometric mean and Model 7 is the optimal model.

Model 1	Ln(Catch) =	Const + Year
Model 2	Ln(Catch) =	Const + Year + Diver
Model 3	Ln(Catch) =	Const + Year + Diver + Block
Model 4	Ln(Catch) =	Const + Year + Diver + Block + Month
Model 5	Ln(Catch) =	Const + Year + Diver + Block + Month + Processor
Model 6	Ln(Catch) =	Const + Year + Diver + Block + Month + Processor + Port
Model 7	Ln(Catch) =	Const + Year + Diver + Block + Month + Processor + Port + Diver*Block

	Model 1	Model 3	Model 4	Model 5	Model 6	Model 7
N	17833	17833	17833	17833	17833	17833
AIC	24115.61	22192.46	21961.19	21701.26	21666.19	21528.71
Res. Dev.	4028.75	3601.11	3550.32	3473.93	3460.11	3418.94
DF	17816	17777	17766	17702	17684	17646
Adj. R^2	0.1874	0.2721	0.2819	0.2948	0.2969	0.3038

Table 17. Standardised catch rates for Blocks 13 and 14 of the abalone fishery from 1987 until 2003 using Catch per Day data (CPD). Models are standardised relative to 1987 with standard errors (SE) included. Model 1 is equivalent to the simple geometric means and the model 7 is the optimal standardised model (

Table **16**). The count column provides the number of records used in the analysis for each year.

Year	Model 1	SE	Model 6	SE	Observations
1987	1.0000		1.0000		1033
1988	0.9764	0.0200	0.9975	0.0196	1244
1989	1.0040	0.0221	0.9996	0.0250	840
1990	1.0550	0.0223	1.0345	0.0254	817
1991	1.1501	0.0222	1.2015	0.0304	825
1992	1.3410	0.0249	1.3372	0.0335	561
1993	1.4200	0.0217	1.2982	0.0319	897
1994	1.6727	0.0215	1.5203	0.0315	927
1995	1.8272	0.0211	1.6817	0.0309	1008
1996	1.9450	0.0207	1.8576	0.0306	1084
1997	1.7763	0.0199	1.7331	0.0301	1289
1998	1.7982	0.0200	1.7713	0.0282	1261
1999	1.7259	0.0198	1.7222	0.0276	1294
2000	1.5319	0.0200	1.4906	0.0293	1238
2001	1.4127	0.0199	1.3799	0.0302	1276
2002	1.2388	0.0203	1.1892	0.0305	1159
2003	1.2726	0.0207	1.1800	0.0316	1080

11.4.4.4. Seasonal catch per unit effort analysis

The optimal seasonal CPUE model in terms of lowest AIC and largest R squared value, was determined to be,

LnCPUE = Year*Season + Diver + Block + Processor + Port + Diver*Block.

In terms of Model Divergence, the trends in the fitted models do not differ from the geometric means largely except in 2003 where the standardised catch rates are slightly below the geometric means (Figure 58).

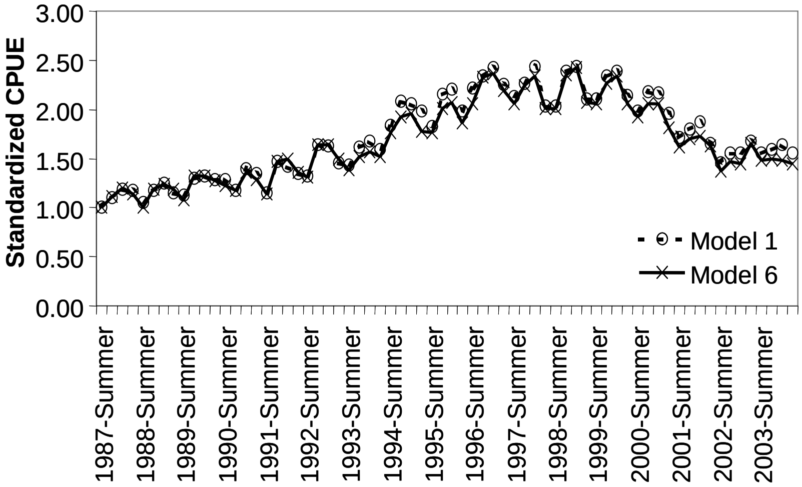

Figure 58. *Plot of seasonal standardised CPUE in blocks 13 and 14 of the abalone fishery from Summer 1987 until Spring 2003. Model 1 is equivalent to the simple geometric means of catch rates and model 6 is the optimal standardised model.*

Table 18. Summary of selected models and model statistics for the seasonal standardised CPUE data. Model 1 is equivalent to the geometric mean and Model 6 is the optimal model.

Model 1	Ln(Catch) =	Const + Year*Season
Model 2	Ln(Catch) =	Const + Year*Season + Diver
Model 3	Ln(Catch) =	Const + Year*Season + Diver + Block
Model 4	Ln(Catch) =	Const + Year*Season + Diver + Block + Processor
Model 5	Ln(Catch) =	Const + Year*Season + Diver + Block + Processor + Port
Model 6	Ln(Catch) =	Const + Year*Season + Diver + Block + Processor + Port + Diver*Block

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
N	17833	17833	17833	17833	17833	17833
AIC	13004.26	9429.15	8944.57	8631.2	8529.09	8281.23
Res. Dev.	2148.26	1750.53	1703.42	1661.77	1648.95	1619.28
DF	17765	17727	17726	17662	17644	17606
Adj. R^2	0.345	0.4651	0.4795	0.4904	0.4938	0.5018

Table 19. Standardised catch rates for Blocks 13 and 14 of the abalone fishery from 1987 until 2003 for the seasonal CPUE data. Models are standardised relative to 1987 with standard errors (SE) included. Model 1 is equivalent to the simple geometric means and the model 6 is the optimal standardised model (Table 18). The count column provides the number of records used in the analysis for each year.

Year/Season	Model 1	SE	Model 6	SE	Observations
1987-Summer	1		1		186
1987-Autumn	1.106	0.033	1.117	0.029	292
1987-Winter	1.191	0.032	1.196	0.028	334
1987-Spring	1.171	0.035	1.135	0.031	221
1988-Summer	1.05	0.033	1.009	0.029	297
1988-Autumn	1.171	0.032	1.188	0.029	301
1988-Winter	1.253	0.031	1.241	0.028	398
1988-Spring	1.153	0.034	1.185	0.03	248
1989-Summer	1.126	0.037	1.076	0.034	161
1989-Autumn	1.3	0.034	1.32	0.033	225
1989-Winter	1.318	0.032	1.32	0.03	310
1989-Spring	1.284	0.039	1.275	0.036	144
1990-Summer	1.282	0.036	1.224	0.034	180
1990-Autumn	1.18	0.036	1.17	0.034	184
1990-Winter	1.4	0.032	1.362	0.03	307
1990-Spring	1.345	0.038	1.288	0.035	146
1991-Summer	1.152	0.034	1.14	0.033	248
1991-Autumn	1.471	0.037	1.464	0.037	166
1991-Winter	1.421	0.033	1.49	0.034	262
1991-Spring	1.342	0.038	1.36	0.037	149
1992-Summer	1.317	0.039	1.307	0.038	144
1992-Autumn	1.636	0.039	1.646	0.038	142
1992-Winter	1.624	0.036	1.645	0.036	194
1992-Spring	1.456	0.046	1.5	0.044	81
1993-Summer	1.427	0.035	1.379	0.036	222
1993-Autumn	1.615	0.037	1.513	0.037	172
1993-Winter	1.683	0.031	1.565	0.033	378
1993-Spring	1.592	0.04	1.514	0.041	125
1994-Summer	1.833	0.038	1.759	0.037	160
1994-Autumn	2.084	0.035	1.923	0.036	210
1994-Winter	2.054	0.033	1.962	0.033	289
1994-Spring	1.981	0.033	1.77	0.034	268
1995-Summer	1.823	0.037	1.758	0.037	163
1995-Autumn	2.15	0.032	2.012	0.033	310
1995-Winter	2.202	0.031	2.072	0.032	387
1995-Spring	1.983	0.038	1.861	0.038	148
1996-Summer	2.211	0.036	2.062	0.036	191
1996-Autumn	2.341	0.034	2.321	0.034	241
1996-Winter	2.428	0.031	2.367	0.032	361
1996-Spring	2.249	0.033	2.195	0.034	291
1997-Summer	2.129	0.033	2.062	0.034	265
1997-Autumn	2.263	0.032	2.236	0.033	311
1997-Winter	2.431	0.031	2.339	0.032	389
1997-Spring	2.029	0.032	2.014	0.033	324
1998-Summer	2.03	0.034	2.013	0.034	226
1998-Autumn	2.386	0.032	2.346	0.032	299
1998-Winter	2.432	0.03	2.422	0.031	474

Year/Season	Model 1	SE	Model 6	SE	Observations
1998-Spring	2.109	0.033	2.075	0.033	262
1999-Summer	2.111	0.032	2.054	0.032	317
1999-Autumn	2.339	0.032	2.268	0.032	307
1999-Winter	2.385	0.031	2.335	0.031	366
1999-Spring	2.14	0.032	2.058	0.032	304
2000-Summer	1.982	0.033	1.927	0.034	261
2000-Autumn	2.186	0.033	2.052	0.033	260
2000-Winter	2.167	0.031	2.052	0.032	359
2000-Spring	1.964	0.031	1.817	0.032	358
2001-Summer	1.713	0.033	1.619	0.033	296
2001-Autumn	1.796	0.033	1.698	0.033	284
2001-Winter	1.876	0.032	1.727	0.033	321
2001-Spring	1.648	0.031	1.63	0.032	375
2002-Summer	1.462	0.032	1.376	0.033	325
2002-Autumn	1.557	0.034	1.471	0.034	255
2002-Winter	1.555	0.032	1.447	0.032	341
2002-Spring	1.683	0.034	1.649	0.035	238
2003-Summer	1.557	0.035	1.485	0.035	218
2003-Autumn	1.593	0.033	1.493	0.034	288
2003-Winter	1.644	0.032	1.483	0.033	335
2003-Spring	1.551	0.034	1.451	0.036	239

11.4.4.5. Seasonal catch per day analysis

The optimal seasonal CPD model in terms of lowest AIC and largest R squared value, was determined to be,

LnCatch = Year*Season + Diver + Block + Processor + Port + Diver*Block.

The trends in the fitted models do not differ from the geometric means to any great extent, the standardised catch rates are slightly below the geometric means in 2003 and in the period between 1993 and 1996 (Figure 59).

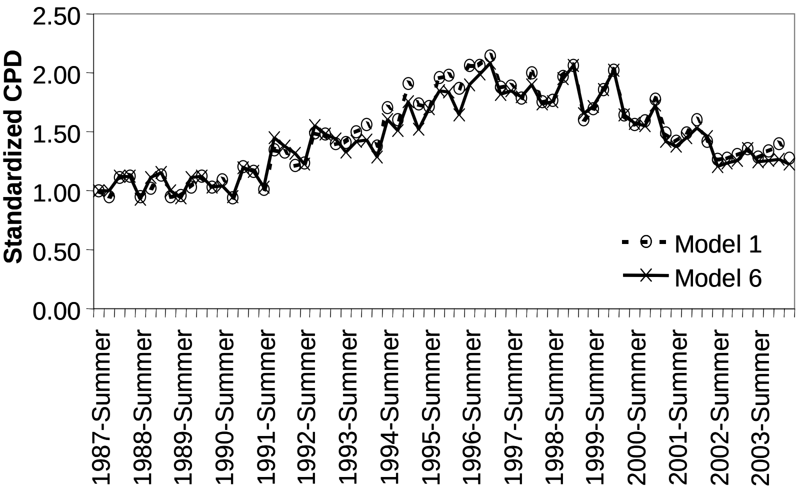

Figure 59. *Plot of seasonal standardised CPD in blocks 13 and 14 of the abalone fishery from Summer 1987 until Spring 2003. Model 1 is equivalent to the simple geometric means of catch rates and model 6 is the optimal standardised model.*

Table 20. Summary of selected models and model statistics for seasonal standardised CPD data. Model 1 is equivalent to the geometric mean and model 6 is the optimal model.

Model 1	Ln(Catch) =	Const + Year*Season
Model 2	Ln(Catch) =	Const + Year*Season + Diver
Model 3	Ln(Catch) =	Const + Year*Season + Diver + Block
Model 4	Ln(Catch) =	Const + Year*Season + Diver + Block + Processor
Model 5	Ln(Catch) =	Const + Year*Season + Diver + Block + Processor + Port
Model 6	Ln(Catch) =	Const + Year*Season + Diver + Block + Processor + Port + Diver*Block

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
N	17833	17833	17833	17833	17833	17833
AIC	23829.06	22218.27	21879.09	21599.52	21566.92	21432.86
Res. Dev.	3941.92	3586.16	3518.2	3438.7	3425.5	3385.39
DF	17765	17727	17726	17662	17644	17606
Adj. R^2	0.2026	0.273	0.2868	0.3004	0.3023	0.309

Table 21. Standardised catch rates seasonal CPD data for Blocks 13 and 14 of the abalone fishery from 1987 until 2003. Models are standardised relative to 1987 with standard errors (SE) included. Model 1 is equivalent to the simple geometric means and model 6 is the optimal standardised model (Table 20). The count column provides the number of records used in the analysis for each year.

Year/Season	Model 1	SE	Model 6	SE	Observations
1987-Summer	1		1		186
1987-Autumn	0.953	0.044	0.995	0.042	292
1987-Winter	1.111	0.043	1.125	0.041	334
1987-Spring	1.125	0.047	1.125	0.045	221
1988-Summer	0.946	0.044	0.924	0.042	297
1988-Autumn	1.018	0.044	1.116	0.043	301
1988-Winter	1.135	0.042	1.153	0.04	398
1988-Spring	0.953	0.046	1.004	0.043	248
1989-Summer	0.957	0.051	0.936	0.05	161
1989-Autumn	1.033	0.047	1.109	0.048	225
1989-Winter	1.125	0.044	1.12	0.044	310
1989-Spring	1.036	0.052	1.033	0.052	144
1990-Summer	1.089	0.049	1.042	0.049	180
1990-Autumn	0.934	0.049	0.949	0.049	184
1990-Winter	1.2	0.044	1.192	0.044	307
1990-Spring	1.166	0.052	1.167	0.051	146
1991-Summer	1.007	0.046	1.027	0.048	248
1991-Autumn	1.342	0.05	1.447	0.053	166
1991-Winter	1.326	0.045	1.376	0.049	262
1991-Spring	1.21	0.052	1.312	0.054	149
1992-Summer	1.232	0.052	1.225	0.055	144
1992-Autumn	1.492	0.052	1.555	0.055	142
1992-Winter	1.48	0.048	1.482	0.052	194
1992-Spring	1.402	0.063	1.444	0.064	81
1993-Summer	1.41	0.047	1.327	0.051	222
1993-Autumn	1.501	0.05	1.423	0.053	172
1993-Winter	1.564	0.042	1.425	0.047	378
1993-Spring	1.38	0.054	1.282	0.059	125
1994-Summer	1.702	0.051	1.601	0.054	160
1994-Autumn	1.604	0.047	1.511	0.051	210
1994-Winter	1.907	0.044	1.757	0.048	289
1994-Spring	1.739	0.045	1.521	0.05	268
1995-Summer	1.717	0.051	1.694	0.053	163
1995-Autumn	1.961	0.044	1.843	0.048	310
1995-Winter	1.981	0.042	1.838	0.047	387
1995-Spring	1.864	0.052	1.643	0.055	148
1996-Summer	2.066	0.049	1.902	0.052	191
1996-Autumn	2.061	0.046	1.985	0.05	241
1996-Winter	2.138	0.043	2.078	0.047	361
1996-Spring	1.878	0.044	1.816	0.049	291
1997-Summer	1.888	0.045	1.848	0.049	265
1997-Autumn	1.781	0.044	1.792	0.048	311
1997-Winter	1.999	0.042	1.9	0.047	389
1997-Spring	1.754	0.043	1.737	0.047	324
1998-Summer	1.766	0.047	1.759	0.05	226
1998-Autumn	1.972	0.044	1.953	0.047	299
1998-Winter	2.057	0.041	2.064	0.045	474

Year/Season	Model 1	SE	Model 6	SE	Observations
1998-Spring	1.605	0.045	1.653	0.047	262
1999-Summer	1.692	0.044	1.713	0.046	317
1999-Autumn	1.862	0.044	1.857	0.047	307
1999-Winter	2.019	0.042	2.017	0.044	366
1999-Spring	1.641	0.044	1.646	0.047	304
2000-Summer	1.562	0.045	1.576	0.049	261
2000-Autumn	1.588	0.045	1.553	0.048	260
2000-Winter	1.775	0.043	1.724	0.046	359
2000-Spring	1.487	0.043	1.416	0.046	358
2001-Summer	1.419	0.044	1.373	0.048	296
2001-Autumn	1.49	0.044	1.452	0.048	284
2001-Winter	1.597	0.043	1.526	0.048	321
2001-Spring	1.422	0.042	1.463	0.047	375
2002-Summer	1.261	0.043	1.2	0.048	325
2002-Autumn	1.276	0.045	1.236	0.049	255
2002-Winter	1.306	0.043	1.257	0.047	341
2002-Spring	1.356	0.046	1.356	0.05	238
2003-Summer	1.29	0.047	1.244	0.051	218
2003-Autumn	1.333	0.044	1.258	0.048	288
2003-Winter	1.399	0.043	1.269	0.048	335
2003-Spring	1.28	0.046	1.222	0.051	239

11.4.4.6. Mixed effects analysis

The optimal annual model when using mixed effects, in terms of lowest AIC and largest R squared value, was determined to be,

LnCatch = Year + Diver + Block + Month + Port.

This relates to Catch as this is catch per day. However, in terms of Model Divergence, the trends in the standardised catch rates are slightly below the geometric mean from 1993 until 2003 (Figure 60).

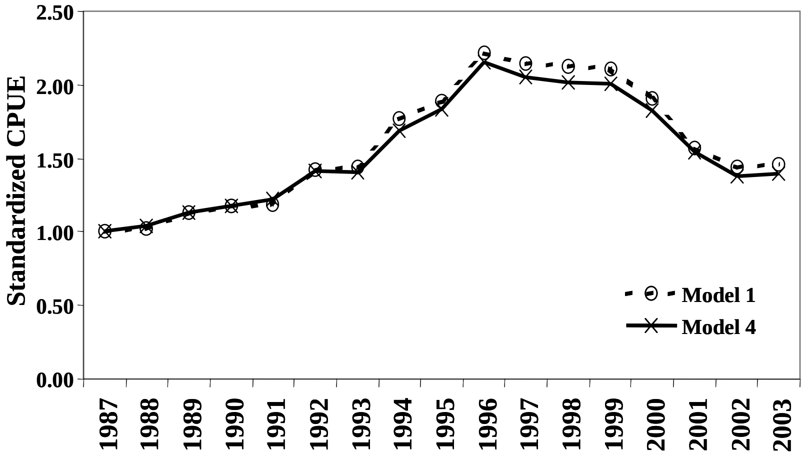

Figure 60. Plot of annual standardised CPUE in blocks 13 and 14 of the abalone fishery 1987 until 2003 using a random effects model. Model 1 is equivalent to the simple geometric means of catch rates and model 4 is the optimal standardised model.

Table 22. Summary of selected models and model statistics for the annual standardised CPUE data using a mixed effects statistical model. Model 1 is equivalent to the geometric mean and model 4 is the optimal model.

Model 1	Ln(Catch) =	Const + Year + Diver
Model 2	Ln(Catch) =	Const + Year + Diver + Block
Model 3	Ln(Catch) =	Const + Year + Diver + Block + Month
Model 4	Ln(Catch) =	Const + Year + Diver + Block + Month + Port

	Model 1	Model 2	Model 3	Model 4
N	19715	19715	19715	19715
AIC	15374.86	14876.12	14459.33	14327.12

Table 23. Annual standardised catch rates for Blocks 13 and 14 of the abalone fishery from 1987 until 2003 using a mixed effects model. Models are standardised relative to 1987 with standard errors (SE) included. Model 1 is equivalent to the simple geometric means and model 4 is the optimal standardised model (Table 22). The count column provides the number of records used in the analysis for each year.

Year	Model 1	SE	Model 4	SE	Observations
1987	1.000		1.0000		1480
1988	0.9764	0.0141	0.9975	0.0139	1712
1989	1.0040	0.0152	0.9996	0.0150	1132
1990	1.0550	0.0158	1.0345	0.0156	1010
1991	1.1501	0.0162	1.2015	0.0160	987
1992	1.3410	0.0181	1.3372	0.0179	655
1993	1.4200	0.0167	1.2982	0.0166	938
1994	1.6727	0.0167	1.5203	0.0166	972
1995	1.8272	0.0171	1.6817	0.0169	1001
1996	1.9450	0.0171	1.8576	0.0170	1053
1997	1.7763	0.0166	1.7331	0.0166	1209
1998	1.7982	0.0167	1.7713	0.0167	1227
1999	1.7259	0.0165	1.7222	0.0166	1300
2000	1.5319	0.0167	1.4906	0.0167	1234
2001	1.4127	0.0168	1.3799	0.0166	1287
2002	1.2388	0.0175	1.1892	0.0174	1273
2003	1.2726	0.0180	1.1800	0.0179	1245

11.4.5. Conclusions to the standardisation procedures

Standardising abalone catch rates from some of the most important statistical catching blocks in Tasmania only led to minor alterations in the trends described by the simple geometric means of catch rates. In all fitted statistical models there was little difference between the simple geometric means and the standardised catch rates.

The yearly Catch per Day (CPD) analysis and both the seasonal Catch per Unit Effort (CPUE) and seasonal CPD analyses show standardised catch rates slightly below the simple geometric means of catch rates in 2003.

The yearly CPUE analysis and the mixed effects analysis both showed the standardised catch rates slightly above the simple geometric means of catch rates in 2003.

The idea of used a mixed effects statistical model treating the variation relating to divers as representing random variation around some population mean led to standardised trends that were almost coincident with the original geometric mean catch rates trends.

Despite large changes in catch rate occurring over the time period selected for this study, the standardisations would have an almost negligible effect upon any assessment. This surprising result may be due to a number of causes. It may simply be a confirmation of the oft repeated refrain that catch rates with abalone contain little or no information about the stock status. However, the decline in catch rates from 1996 to 2003 was very real and very marked; so there was definitely some signal in the data. Alternatively, the divers may be so similar in their operations and fishing behaviour that implementing the standardisation is effectively unnecessary.

It was especially disappointing that factors such as wind speed and swell direction had no perceptible effect upon the yearly or seasonal factors used. It seems likely that these factors as raw data are overly simple and further information would be required before these factors could have an effect. From discussions with divers it seems likely that there is a strong interaction between wind speed and swell direction and fine-scale location of diving (sheltered waters getting more effort in rough conditions than in fine conditions. This illustrates that the results of any GLM need to be interpreted carefully. Just because no effect is seen does not mean all possible effects have been explored.

The catch rate standardisation process needs to be applied in other areas that contain more extensive amounts of abalone bottom that may not be known so well by the divers. Now that some areas on the East Coast appear to be recovering somewhat from the depressed catch rates experienced in recent years the contrast in the data may be enough to produce informative results.

11.5. Overall conclusions

When considering the outcomes of the catch-effort standardisations we are faced with anomalous results. From the simple history of the fishery on the East Coast in recent years it is obvious that catch rates can have some relationship with the relative abundance. Classically, abalone catch rates are deemed to be hyperstable, with divers able to maintain catch rates when stock sizes are declining until eventually an apparent catastrophic collapse appears to occur. In addition, it is well known among divers that some are much more efficient than others. What is unusual is that the standardisation indicates that none of the factors available are influencing the observed catch rates away from the unstandardised annual or seasonal trends. While the diver term in the standardisations usually accounts for a large proportion of the variation described by the GLM it nevertheless, fails to alter the trend of catch rates through time away from the unstandardised data.

The main possibility is that somehow informative aspects of the data from the divers are being neutralised by the current process and resolution of reporting. Typical catch rate data from the Actaeons on the east coast of Tasmania (from 1993 to 2003) show regularities that in all likelihood stems from rounding errors on the part of divers rather than reality (Figure 61). The data clearly exhibit regularities for each hour and in many cases each thirty minute interval. This relates directly to the divers estimating their dive times in round numbers of hours or minutes. Interspersed in among the rounded data are a scattering of other data for which it is assumed the divers refer to a dive computer for their diver times. Such categorising will act to obscure any real trends in the data except for very large ones.

It would be asking a great deal to expect the divers who are undertaking physically demanding and dangerous work to take especial care over their catch-effort recording. Because these are a valuable species under quota there is every reason to expect that the reporting of catch is accurate, so the main problem derives from the description of effort. In addition to the lack of resolution in the effort data there is an obvious lack of geographical resolution in the use of statistical sub-blocks. This is a relatively complex system of lines on the water which could easily confuse abalone divers out at sea. Again there is undoubtedly some approximating when deciding in which sub-block any effort is expressed. Clearly, if catch rates, indeed fishery-dependent data in general, is to have value in stock assessment what is needed are better and automatic ways of collecting effort and location data.

Alternatives considered and rejected during this project included using observers on industry vessels, more details log books, and even diver interviews. However, observers on vessels would primarily be restricted to the larger vessels and perforce be restricted to a very small fraction of the fishing effort that occurs in the very large Tasmanian abalone fishery. This is certainly a method that could be used to generate detailed fishery-dependent data but it would only be practical for particular and special questions and would prove too unwieldy and intrusive on industry to contribute in a practical way to standard assessments. Similarly, more detailed log books would place an intolerable burden on an industry who already have a plethora of pre-reporting and post-reporting conditions to fulfil. The real risk arises that more detailed log books would lead to a lower quality in industry provided data. Fortunately, in Tasmania, there is excellent cooperation between industry and scientists and most divers provide data as best they can. A more complex or detailed log book was considered to be too great a further impost on divers and was rejected as a positive way forward. Finally, diver interviews are used already to obtain first hand impressions of stock conditions on the abalone grounds. If the modelling or other observations in the assessments are inconsistent with the observations of divers on the ground then the modelling is considered suspect. However, beyond that it is difficult to use diver interviews in any quantitative way.

A far more inventive and informative possibility was finally hit upon during this project that may hold the potential to provide accurate effort and location data along with improved length-frequency data. As described later, a combination of depth and temperature loggers attached to divers (to provide real time effort in the water) and self-contained GPS units attached to data loggers to provide accurate positional data appear to solve the problem of obtaining adequate resolution to fishery-dependent data. They, of course, retain their own problems with respect to handling the very large amounts of data involved, but at least the data is truly representative of what is happening in the fishery and there is very little approximation involved. Indeed, one of the problems is then to decide at what resolution to use the data generated.

In addition to these innovations, which are still being explored and developed, sets of electronic measuring boards have been developed that contain data loggers and are water resistant and robust. When these are deployed in the field, either on mother boats or research trips, the rapid data acquisition they permit generates high quality length-frequency information almost irrespective of who is operating the device. With these the quantity and distribution of length-frequency information it is possible to capture is increased.

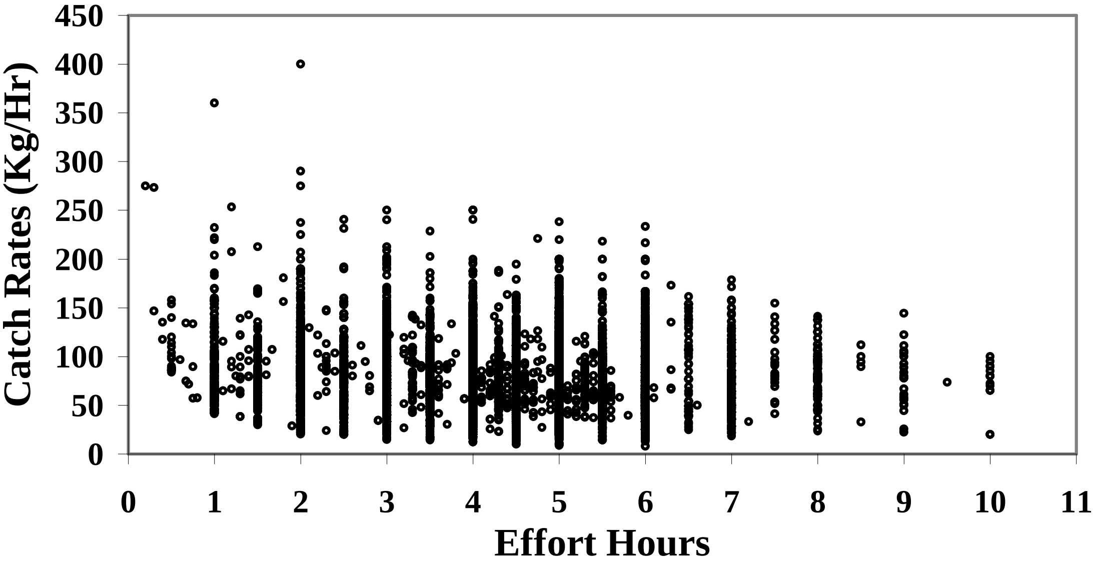

Figure 61. *The catch rates, in kg per hour, from the Actaeon statistical blocks for the years 1993 to 2003. The regular intervals correspond to half hourly intervals.*

Currently, fishery-dependent data from the abalone fishery around Tasmania is compromised by the extremely large scale of the fishery, the limitations imposed by the fact that most fishing occurs from relatively small vessels, and the difficulty in obtaining reliable effort and location data. The size frequency of the catches can be obtained from a number of processors but this tend to lead to biased samples that fail to obtain accurate estimates of West Coast catches. None of the innovations initially envisaged in this project were or are effective in improving the value of fishery-dependent data (though interviews with divers, even relatively informal interviews, have proved to be of great value in the annual assessment process). Instead, wholly new ideas have enormous potential to improve our knowledge of real effort and location of effort. These innovations lead to the possibility of producing novel performance indicators for abalone fisheries that involve the use of spatial detail and real amounts of effort required to obtain set catches. While these ideas are outside the scope of the current project they are nevertheless being investigated.

Standardisation of fishery catch rates may still be a useful took but only with the improved catch rates deriving from the new tools whose development began during the period of this project.

11.6. Statistical Background

When applying statistical models it is unsatisfactory to choose the model that explains the greatest amount of variation in the data or has the smallest AIC without an examination of the residuals. Residual plots indicate the correspondence of the fitted model with the observed data under the assumptions made in the model. In this analysis four separate residual plots have been used. Plots of the residuals vs the fitted values and standard deviance of residuals are used to identify any pattern in the residuals of the model. A pattern in the residuals indicates that the assumptions underlying the fitted model are not being satisfied. This may be due to the use of the incorrect link function or statistical distribution in the analysis. A Q-Q plot is another method of determining the fit of the model (and its underlying assumptions) to the observed data. The diagonal line x = y indicates good fit to the data, deviations from the line x = y show a poor fit to the observed data (Venables and Ripley 2002). The Cook's distance plot relates to the influence exerted by each observation on the fit of the model. A data point with a Cook's distance that is high relative to the Cook's distances of the rest of the data indicates that it is exerting a large amount of influence over the fit of the model.

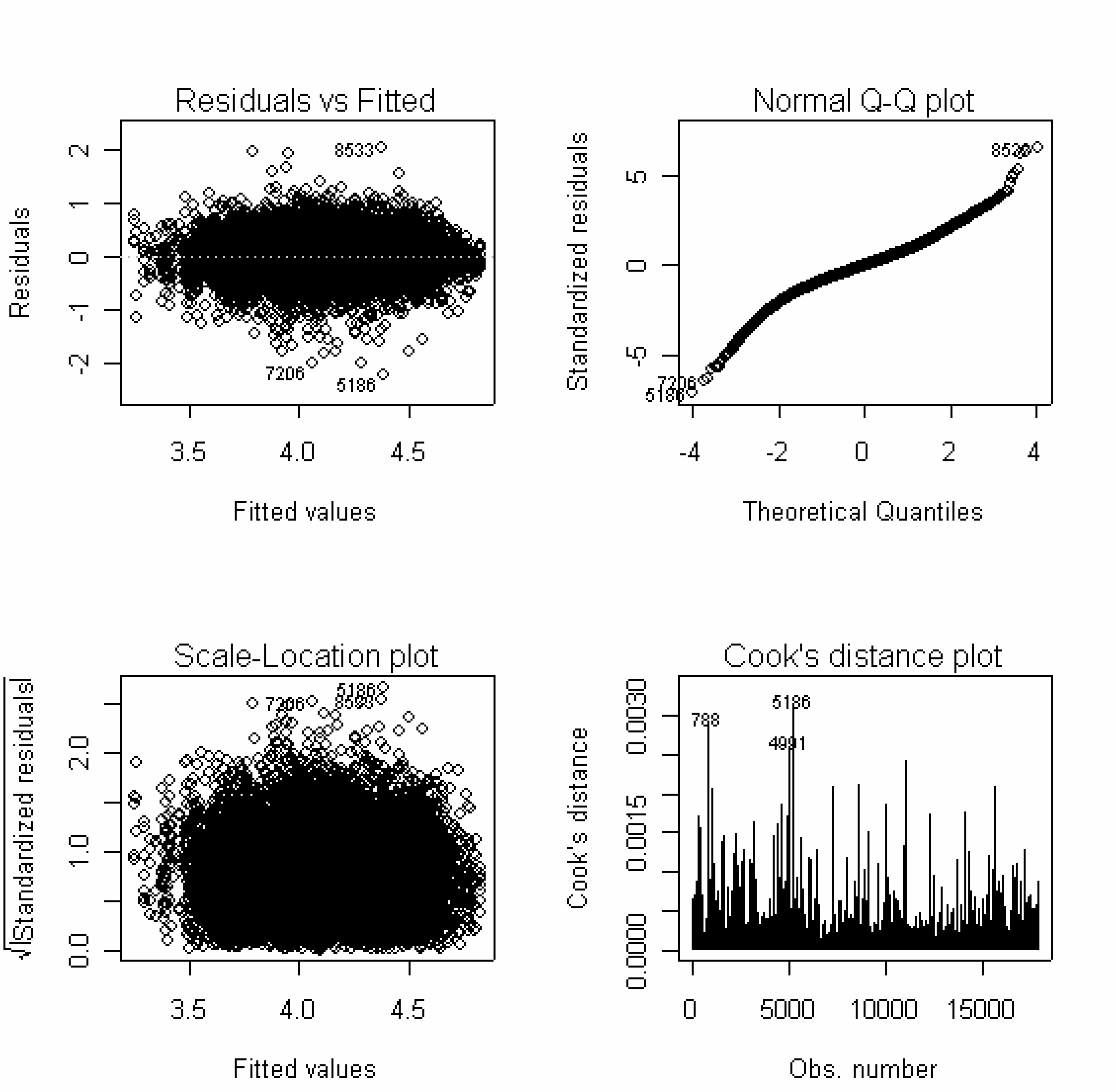

Figure 62. *Residual plots and Cook's distance plots for the optimal yearly CPUE model. The Residual vs Fitted and Scale-Location plots appear to be randomly distributed, which is good. The QQ plot shows that the model fits the observed data reasonably well and the Cook's distance plot would seem to suggest that none of the observed data is exerting a high degree of influence on the model.*

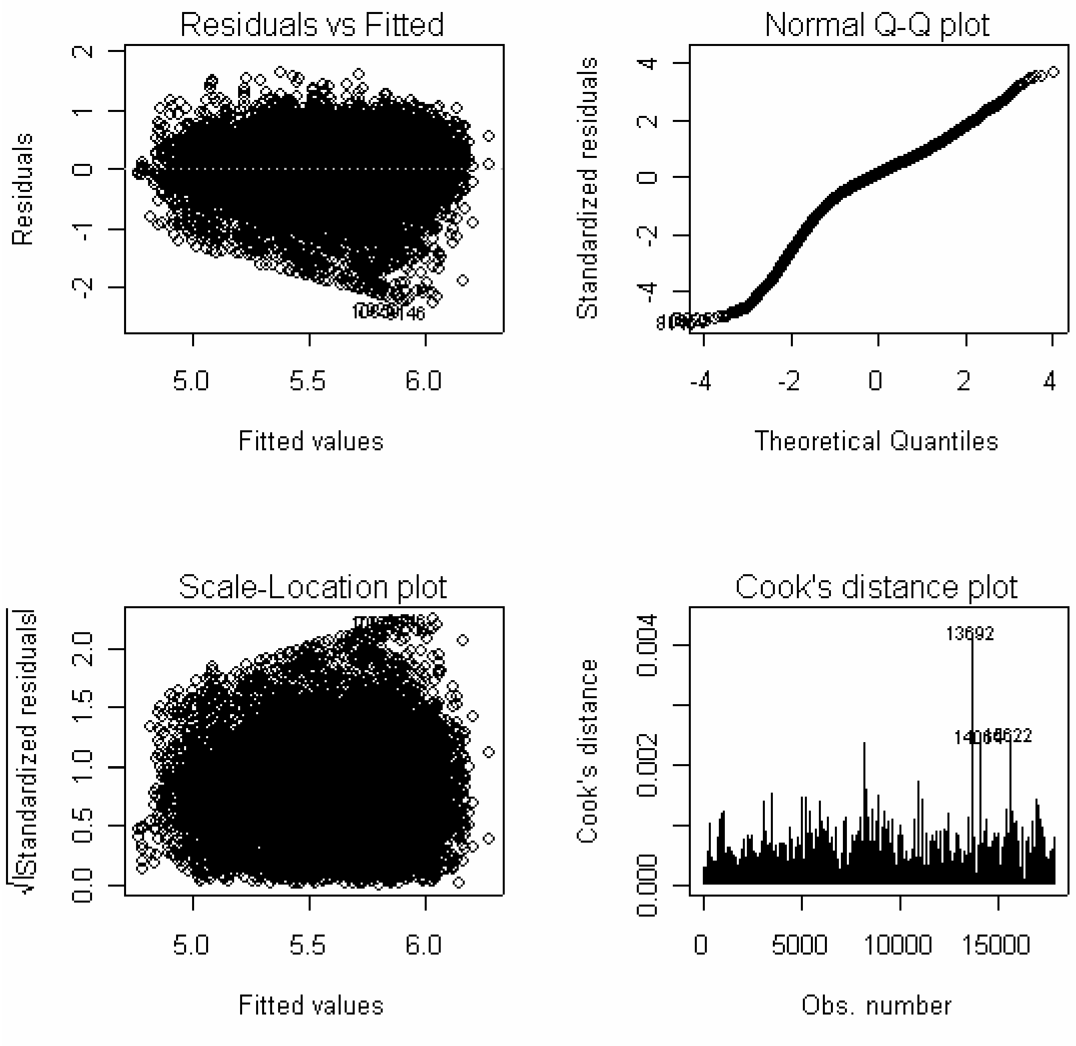

Figure 63. *Residual plots and Cook's distance plots for the optimal yearly catch per day model. The Residual vs Fitted and Scale-Location plots appear to be randomly distributed, which is good. The QQ plot shows that the models fit to the observed data is not ideal, however it is not unreasonably bad. The Cook's distance plot would seem to suggest that none of the observed data is exerting a high degree of influence on the model.Point 13692 may appear high bu tin absolute terms a Cook's distance of 0.004 is insignificant.*

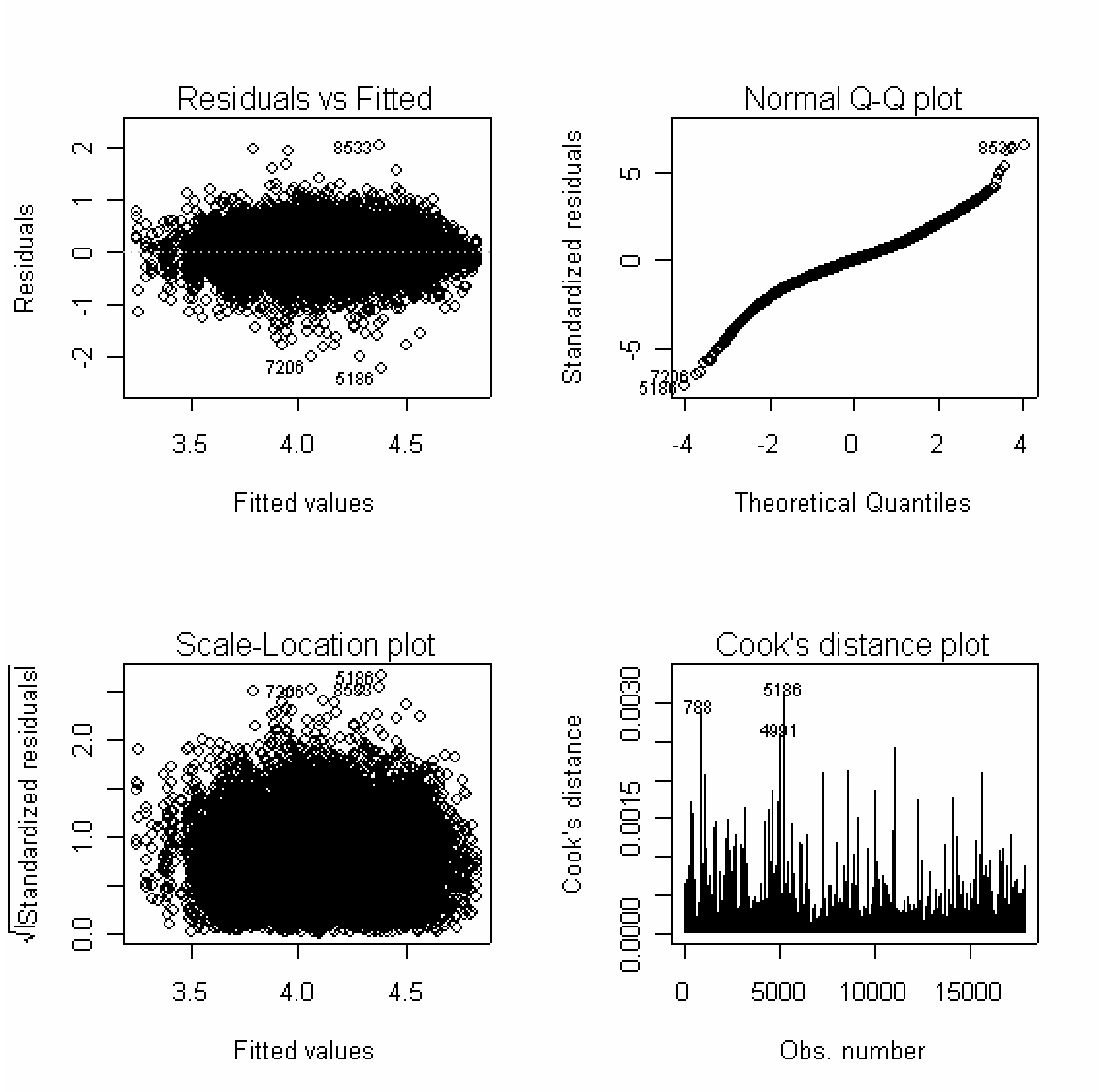

Figure 64. *Residual plots and Cook's distance plots for the optimal seasonal CPUE model. The Residual vs Fitted and Scale-Location plots appear to be randomly distributed, which is good. The QQ plot shows that the model fits the observed data reasonably well and the Cook's distance plot would seem to suggest that none of the observed data is exerting a high degree of influence on the model.*

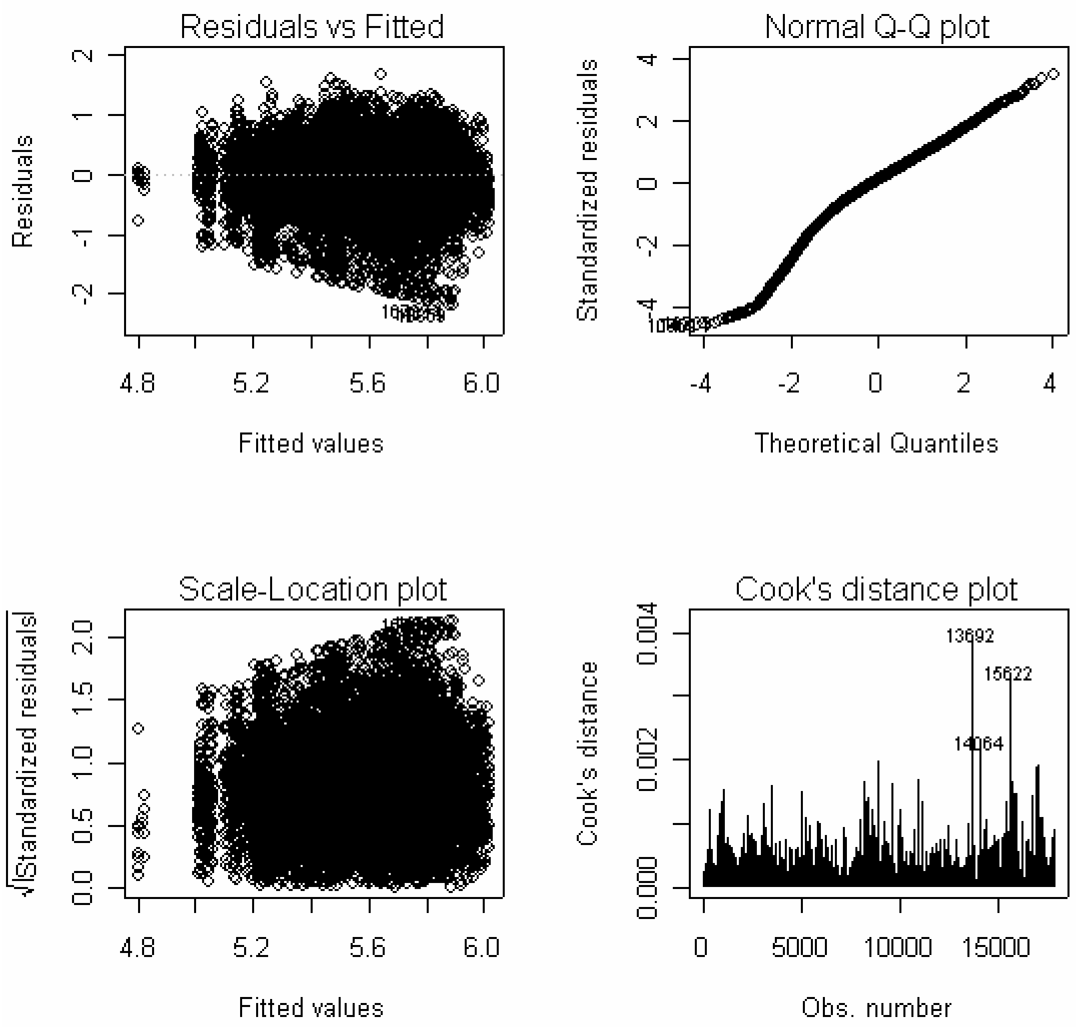

Figure 65. *Residual plots and Cook's distance plots for the optimal seasonal catch per day model. The Residual vs Fitted and Scale-Location plots appear to be randomly distributed, which is good. The QQ plot shows that the model fits the observed data reasonably well and the Cook's distance plot would seem to suggest that none of the observed data is exerting a high degree of influence on the model.*

12.Linking Fishery-Independent and -Dependent Data Sources

12.1.Practicality of onboard observer programs

A key component of the research involving onboard observers was to integrate data (depth, diver path, effort) from the DiveTracker® system with catch (Section 4.3.1). The DiveTracker® system was never operable during the course of this project. Had it functioned as intended the data obtained would have been of limited value because of the restricted coverage of the hydrophones. We also received mixed views with respect to having an observer on board Tasmanian abalone diver vessels. As the majority of fishing is undertaken from small runabouts (5m – 6m in length) as a general rule there is little room for an additional person to function as an observer. This is particularly problematic at the end of the day's fishing when the boat is loaded with abalone, diver, deckhand, and diving and safety equipment. Those divers that would allow research observers onboard are also the divers that freely provide information to TAFI, and are reliable and responsible in the reporting of their catches. In many respects, placing observers onboard these vessels is an inefficient use of resources as we already obtain valuable information from these divers. Among the remaining divers, there is considerably hesitancy in having a research observer present, and we are certain that diver behaviour and practices would be modified by the presence of an observer.

A key issue in Tasmania is that there are insufficient human resources to undertake an observer program to provide sufficient coverage of the fishery to be useful. At the scale of the fishery in Tasmania where there were more than 110 divers operating in 2003, establishing an annual or biannual observer program is beyond the scope of TAFI and DPIWE resources. It is doubtful then that the small amount of observer data we could collect will provide a robust dataset to undertake standardisation of CPUE data, or improve the capacity to link fishery-dependent and fishery-independent data.

Several alternatives to an onboard observer program were considered. The first involved options for divers to record more detailed information concerning fishing activities, and the second option centred on catch reporting at a finer scale.

12.1.1. Recording of additional research information on catch returns

Discussions were held with Tasmanian Abalone Council representatives with respect to obtaining better data related to fishing activities in the absence of a viable Observer Program. Consideration of additional research data to be provided by industry divers included reporting of depth in three categories (0 10, 10 - 20, > 20), the number of drops/day, GPS locations of diving activities, reporting of catch within smaller spatial units (5km x 5km grids), and fishing conditions. Manual reporting of catch, and provisions of GPS coordinates were not considered acceptable by the commercial divers during these discussions (but see section 12.1.2). In hindsight, this related to the practicalities of divers and/or deckhands recording this additional data on research logbooks, rather than a rejection of the concept of reporting of catch at a fine scale. The divers did however agree to report depth in three categories, record the number of drops/day and fishing conditions, and were incorporated into the catch docket system from 2004.

The number of drops will assist us with identifying diver behaviour e.g. diver working an unfamiliar section of coast will tend to make several drops before locating fishable reef, and in the case of a declining resource, more drops to achieve the same daily catch. Concerns about shifting patterns in relation to the depth divers work and that a single figure to indicate the average depth worked prompted a change in recording of depth. For example a trend of increasing time spent at depth for a part of the fishery indicates a change in diver behaviour in relation to changes in availability of abalone. Fishing conditions for that day attempts to identify outliers, e.g. extraordinary good or bad conditions associated with very high or very poor catch rates.

12.1.2. Reporting of catch at fine scale

Following rejection of manual reporting of catch at a fine scale by divers and that an onboard observer program was unsuitable for the Tasmanian abalone fishery we continued searching for an alternate method for obtaining fine-scale catch data. Any new approach must be able to be implemented across the entire Tasmanian Abalone Fishery.

Discussion among stakeholders in Tasmania of how best to link fishery-dependent and fishery-independent data sources while obtaining more detailed data on fishing activity included the potential application of VMS technology on all abalone boats. However, it is difficult to power and install VMS units on small (4m – 5 m) aluminium boats, and the VMS concept is optimally designed for larger vessels that are engaged in trawl activity. In many respects VMS is expensive, imprecise and not particularly useful when applied to small fishing vessels such as those used in the most Australian abalone fisheries.

As a consequence of these discussions, however, it was identified that the vessel path information obtained from VMS would be very useful in terms of mapping fishing effort at a finer scale, and that the information was not required in real time. Industry indicated strong concern that our sites were not located near or on key areas of the fishery, and questioned the relevance of our data should this be the case. Additionally, towards the end of the field program for development of fishery-independent sampling methods we became concerned that estimates of stock abundance obtained by annual field surveys would be subject to additional variability in the form of catch taken prior to the survey and time since each site was last fished. Consequently, we investigated the use of GPS technology to obtain fine scale catch data as an alternative to the “satellite polling” based VMS system. Several commercial products are available that could be adapted to track abalone fishing vessel paths, particularly those that are designed to track positions of moored or free floating buoys.

In response to the above discussions and consideration of GPS, the PI (CM) developed a concept utilising a small weather proof GPS receiver and a data-logger capable of storing standard NMEA output from the GPS receiver at 10 sec intervals continuously for 30 days. The description of this unit, its potential for use in abalone fisheries research and assessment, and the tracks from a pilot study with two commercial abalone divers are provided in the Variations to Project section below (14.1).

12.2. Selecting sites for research

Linking fishery-independent data with fishery-dependent data has proved to be less than straight forward however. A strong criticism that has emerged from the industry members is that if our sites are not within fished areas, then the data will have no relevance to the performance of the fishery. Sites at which fishery-independent radial transects have been completed were chosen on the basis of discussion with divers, and in several instances, by having divers accompany us on trips to identify areas to locate survey sites. Despite the hands-on approach in terms of industry advice on site location, many of the sites investigated had extremely low numbers of abalone (often with zero abalone recorded on ten replicate transects). The second major problem with linking fishery-dependent and fishery-independent data is that the scale at which the commercial catch is reported is too large to be able to relate catch-effort data to abalone density data on our surveys in any meaningful way.

13. Benefits and Adoption

The development of new sampling protocols for radial transect surveys will benefit researchers in all abalone producing states were habitat is amenable to radial transect sampling. However, where traditional survey techniqueshave been in place for many years (e.g. Victoria), the implications of changing sampling protocols must be carefully considered. The value of a long time series using a constant method may outweigh the negative consequences identified in this study. Testing and development of full circular and semicircular options of radial transect configuration expands the potential number of sites where radial transects can be implemented. This will assure that researchers can target a greater number of sites relevant to the fishery. The development of a practical protocol for parallel placement of strip transects provides additional benefits for surveys in reef systems that are narrow or constrained by depth.

Adoption of the modified radial transect method is simplified by the development of a spreadsheet based macro that enables bearings and start distances to be generated for a large number of sites prior to the commencement of the field trip. Macros have been developed for both radial and parallel transect configurations.

The recognition that the results of an annual survey of abundance may be substantially influenced by the timing and amount of recent fishing activity at the site is an important consideration for all sampling programs, regardless of sampling method used. For those studies that are already in place, weighting of fishery-independent survey data by indices that accounts for effort and timing of effort should be explored as a high priority.

The development of GPS technology to capture fishing effort at a smaller spatial scale will benefit all demersal, inshore fisheries where stocks of the target species are spatially structured. The GPS approach may also be the primary source of data to derive weighting indices identified in the paragraph above.

14. Further Development

14.1. Use of GPS data-loggers for fisheries research and assessment

14.1.1. Background

Abalone are not distributed uniformly on temperate rocky reefs, and are patchy at several spatial scales from metres, 10s and 100s metres, to kilometres. A consequence of this is that fishing effort is also patchy. However, because the scale at which fishing is reported is relatively large (10s of kilometres at best) the actual distribution of fishing effort along a coast is not known. A major consequence of the large scale of reporting is that serial depletion, considered to be the primary cause of the collapse of abalone stocks around the world, cannot be detected until well after it is too late to generate useful management responses.

Manual reporting of fishing effort at a smaller scale by divers is difficult due to the nature of the fishing activity, which is often cold, windy and very wet, with divers operating from small dinghies. Consequently, it is mostly impractical for divers and deckhands to manually record fishing effort at a smaller scale than currently practised. A practical solution to achieving smaller scale reporting of fishing effort is to use a GPS receiver/data-logger to automatically record the position of the dinghy at regular intervals.

The GPS receiver used in this pilot study is a Haicom HI-204S capable of tracking up to 12 satellites, and has a 2D accuracy of 25m depending on satellite access. The data logger stores output data from the GPS receiver in a standard NMEA format. The trial unit has a single button that when pushed, inserts a new record into data stream and is identified by a single letter code. This button can be used to identify for example the start and end points/time of diving, or the location at which the deckhand hauls each bag of abalone. The cost of this unit was less than $800, an order of magnitude less than a VMS unit.

14.1.2. Evaluation of GPS data logger for obtaining fine-scale data on fishing location

To determine whether the GPS reciever/data-logger approach was feasible, and could provide data at a scale that was considered desirable (20m – 50m), two abalone divers agreed to take the GPS data logger unit onboard their vessels. The unit was operated by the deckhand, and researchers were not onboard at the time of data collection. Data retrieved from the two abalone divers were processed and summarised using ArcView (Environmental Research Systems Institute – ESRI). The data recorded in the pilot study were time, position, speed and bearing, at ten second intervals for the duration of the fishing activity for that day. A button was pushed by the deckhand to record the time/position at which a bag of abalone was retrieved.

The information obtained by the GPS data-logger unit provided excellent data at a spatial scale smaller than was initially hoped for. The activity of the diver can be diagnosed using vessel speed, and the use of the button on the GPS data-logger unit to indicate location of bag lifts could also prove to be highly valuable (Figure 66). Preliminary analysis of speed data suggests that vessel speed while the diver is in the water (almost all divers work live -- i.e. not at anchor), is usually less than three knots, and that travel between sites, boat ramps or mother vessels is usually at speeds greater than three knots. While speed information can reliably indicate travel between fishing locations, it cannot be assumed that all segments of the vessel path at speeds lower than three knots indicates fishing activity, as the vessel may slow for several reasons that do not involve diving. To accurately identify the area fished by the diver, a mechanism for identifying the start and end of each dive must be considered.

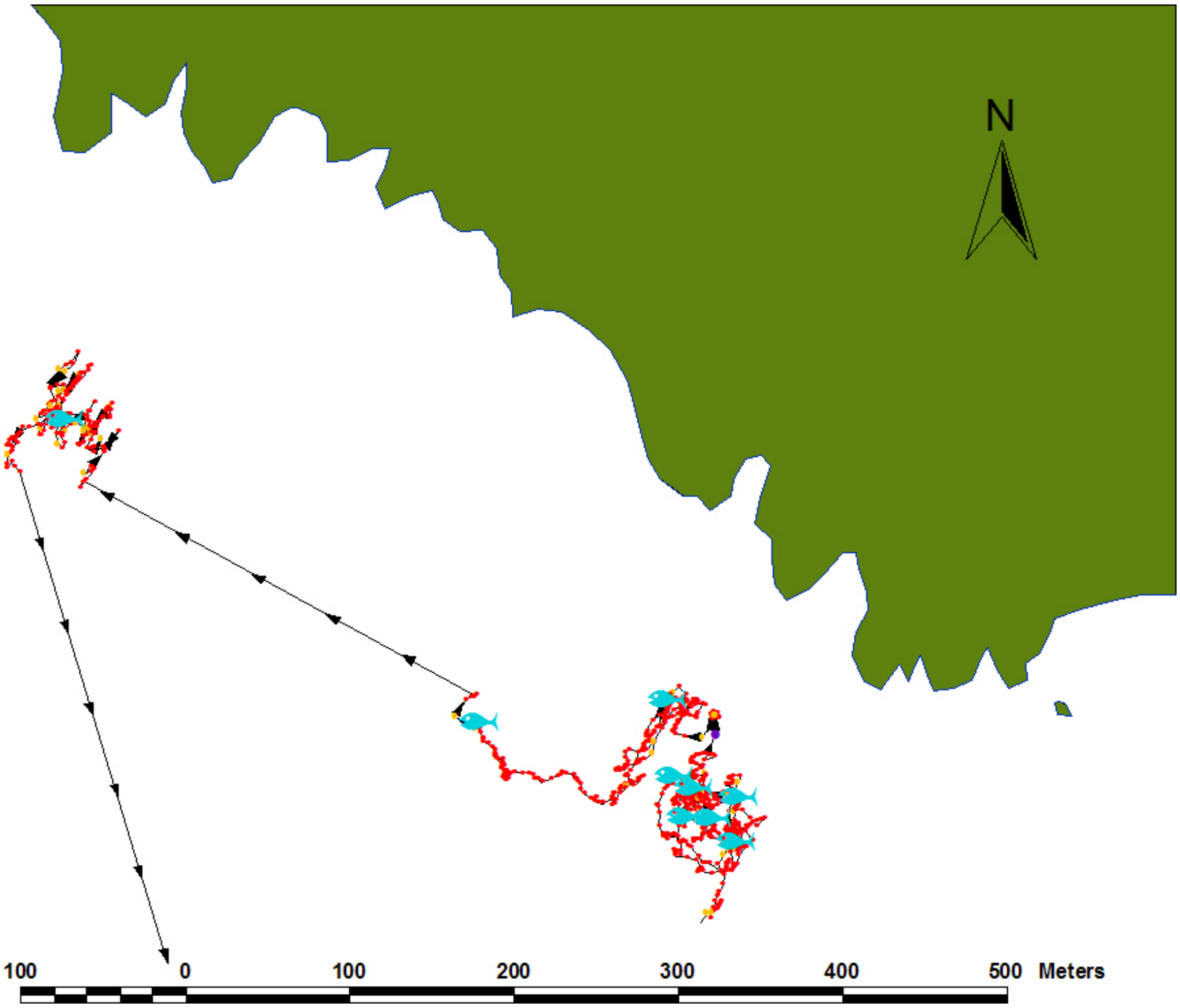

Figure 66. *Vessel path showing location of bag lifts, and direction of travel. Red dots indicate diver in water. Black line with arrows indicate direction of travel. Fish symbols indicate points where the deckhand retrieved a bag of abalone from the diver.*

In addition to gaining a more accurate understanding of the location of fishing events, information about the sub-tidal habitat (e.g. habitat maps) can be overlayed with vessel path data. This could provide a better understanding of the types of habitat that support commercial fishing activity can be obtained. Habitat mapping data provided by SEAMAP Tasmania (based at TAFI) was overlaid with the vessel path of the diver (Figure 67). This analysis clearly shows that most of the time the diver was fishing (indicated by red dots on vessel path, and location of bag lifts), the diver was on medium profile reef.

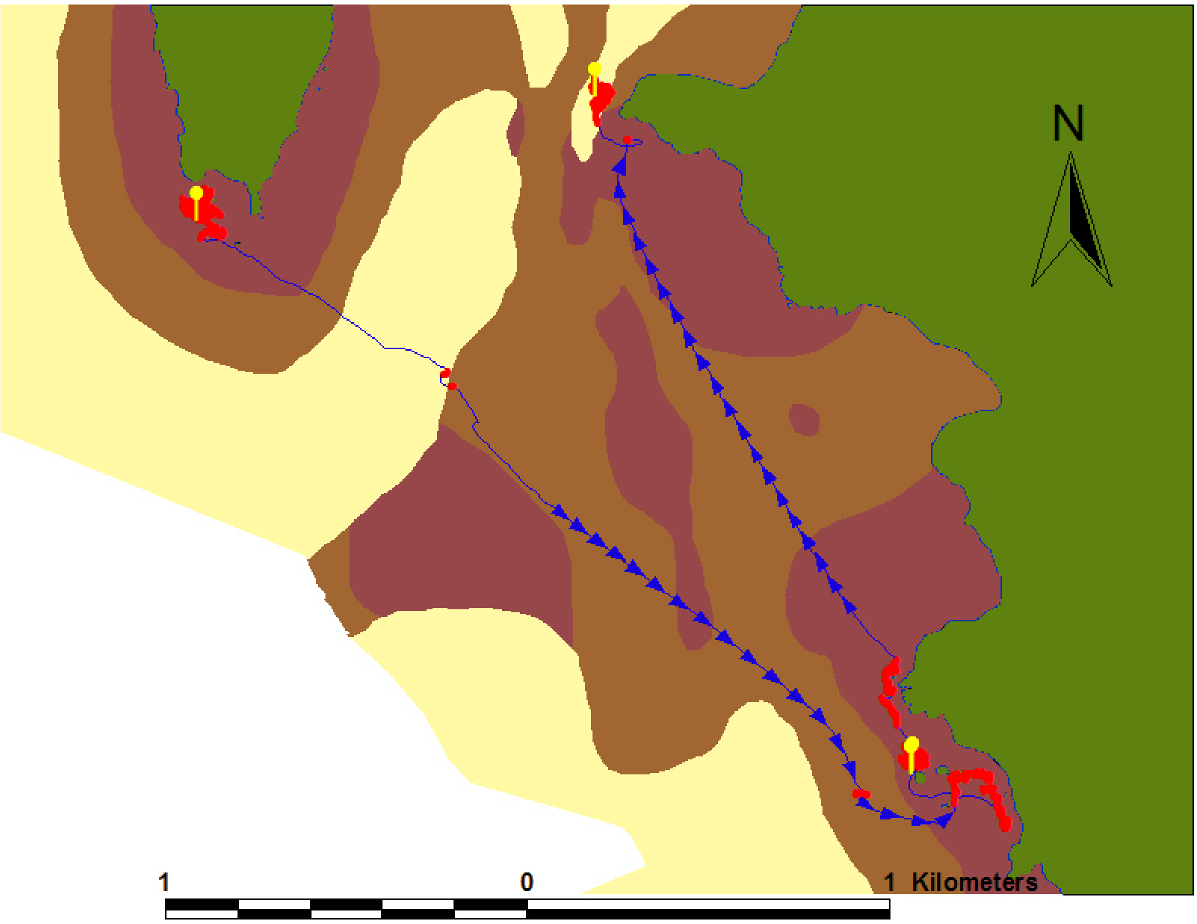

Figure 67. *Vessel path showing location of bag lifts, and direction of travel, overlaid on SEAMAP Tasmania habitat mapping data. Boat speed indicated by red dot when less than two knots. Blue line and arrows indicate direction of travel. Yellow sticks indicate location of bag lifts. (N.b. scale different to Figure 66).*

14.1.3. Future application of GPS technology in the Tasmanian abalone fishery.

The success of the pilot study has led to the development of a new TAFI project (funded internally in 2005) to conduct a larger scale study, involving 20 divers. The GPS data-loggers for this study are being developed in conjunction with a local electronics company, SciElex (formerly Cfish). The new units have three buttons that are designed to store the time/location of the commencement of fishing, completion of fishing and the location of each bag of abalone retrieved while fishing. The units are capable of storing data at ten second intervals continuously for 120 days. A postgraduate student will commence research on diver behaviour and fleet dynamics in relation to this project in July 2005.

Data obtained on vessel path with the GPS data-loggers has the potential to make major improvements in the management and assessment of abalone fisheries (and other small vessel based fisheries). Importantly, the data will, for the first time, allow us to undertake an accurate investigation of serial depletion in abalone fisheries. While serial depletion (or the failure to recognise serial depletion) has been identified as the cause of collapse in several abalone fisheries around the world, this has been primarily assumed rather than determined empirically, largely because catch-effort has never been recorded or reported at a sufficiently small scale to understand the nature of the collapse.

Several research areas have already been identified for further research using data obtained from the GPS data-loggers;

1. Synchronising collection of fishery-independent data with fishery-dependent data.

   Currently, researchers choose sites for collection of fishery-independent data based on advice from commercial abalone divers. This advice is often in the form of " … between this point and that point ..", and provides a low to moderate level of accuracy given the patchy distribution of abalone. The GPS data-logger information will clearly identify areas that are important to the fishery, and allow researchers to target these sites with a high degree of accuracy, ensuring that fishery-dependent and independent data are obtained from the same section of reef.

2. Weighting of fishery-independent estimates of abalone abundance by time since fishing, and frequency of fishing, at surveyed sites.

   A major problem associated with annual monitoring of abalone density at sites within the Tasmanian (and other) abalone fishery, is that the pattern of fishing effort at a site can have a substantial effect on the accuracy of abundance estimates. The amount of catch taken from a site and the time period between the last fishing trip and the independent survey may vary among years. This will increase the variability in the data set, and potentially mask any real change (increase/decline) in abalone density. This is an issue faced, but not addressed, by all abalone monitoring programs that operate within an active fishery.

   One solution to this is to use GPS data-logger records of fishing effort to determine the extent of fishing activity at a survey site, and, to determine the last time a site was visited by an abalone diver. The estimates of abalone density obtained during the research survey, can then be weighted or adjusted accordingly.

3. Optimising catch-effort figures by identifying sequential depletion of reefs.

   Anecdotal evidence and observations from commercial divers working in the productive Acteons region suggest as many as three or four divers fish the same area in a single day.

If GPS data-logger information was available, catch-effort data could be matched with the degree of overlap and the timing of visits by different divers, and adjusted or weighted to reflect depletion of the stock at that site.

4. Fleet dynamics – diver behaviour.

Hypotheses concerning diver behaviour could be tested, for example; do divers in smaller boats travel shorter distances from boat ramps to fishing grounds; and do new or less experienced divers spend more time looking for abalone than experienced divers? Such information would also assist in the interpretation and standardisation of commercial catch-effort information.

5. Development of catch/area statistics.

Abalone fishing data are almost always expressed as catch (weight) per unit effort (time). Preliminary analyses of vessel track data using Home Range Analysis techniques such as Minimum Convex Polygons (MCP), Kernel Analysis, or Buffer Analyis allow the calculation of the area of reef fished. Because all vessel track data can be linked to the daily catch data of that diver, this allows the calculation of catch (weight) per unit area figures. Additionally a more accurate estimate of the time spent in the water can be obtained, since the time interval between start and finish of a dive can be calculated easily from the GPS data. The combination of catch-effort and catch/area data could prove to be a far more reliable mechanism for assessing fishery performance. From a stock assessment perspective this should provide greater insight into the variability in catchability of abalone among areas.

6. Documenting changes in the area fished/unfished through time.

There have been numerous suggestions from Tasmanian abalone divers that many reefs, which supported commercial catches of abalone in the past, are no longer productive. The ability to map the literal area fished using GPS data-loggers means that if we can establish a baseline of area fished now, we can assess temporal change in reef areas fished. Increases or decreases in area fished may be an important indicator of a change in the health of the fishery.

7. Linking with habitat maps to better understand reef systems capable of supporting commercial fisheries.

The ability to link habitat maps produced by SEAMAP Tasmania will allow us to gain insights into the types of reefs that support commercial abalone fishing (see Figure 67).

8. Affordable alternatives to collection of fishery-independent abalone density data.

Collection of fishery-independent data on abalone density is proving to be time consuming and expensive. For example, to provide robust data on abalone density at 200 sites within the Tasmanian abalone fishery will cost in excess of A$250000. As there are more than 150 sub-block reporting units with the fishery, and as several sub-blocks produce annual catches in excess of 50 tonnes, the fishery cannot be adequately monitored with only 200 sites. The conclusion that detailed and high quality fishery-dependent data may alleviate the need for a large expensive abundance monitoring program that helped inspire the development of the GPS system described above.

If GPS datalogger derived catch/area data prove to be a practical source of reliable high quality fishery-dependent information, perhaps fishery-independent data collection programs could then focus on the collection of size frequency data, which is more efficient to collect than density data, and is a core requirement of any based assessment.

15. Planned Outcomes

The planned outcomes of this project were partially met. The planned outcomes identified in the project proposal assumed that the research done would validate existing practices with respect to data collection and provision for stock assessments. In reality this research has identified several significant issues that must be addressed in relation to the collection of fishery-independent survey data. The concept of collecting fishery-independent data to provide an unbiased perspective on stock abundance is advisable and prudent given that many socio-economic and weather factors influence fishery-dependent catch data. However, in practice the collection of robust fishery-independent data is difficult and expensive, and does not always achieve the desired aim.

The outcomes that were achieved are the improved radial transect theory and validation of a new protocol for obtaining fishery-independent estimates of abalone abundance in Tasmania. A new procedure for linking fishery-dependent and fishery-independent data sources using GPS technology has far reaching implications and is likely to reshape the method of collecting fishery-dependent data. The outcome of improved quality of data capture and spatial resolution of effort will lead to significant advances in the assessment of abalone fisheries, and broadening of research questions that can be addressed.

16. Conclusion

The modified radial transect procedure performed well, and was an efficient and practical technique in all regions and habitats visited. Distribution and aggregation patterns of abalone in certain reef habitats (e.g. granite slabs) are likely to result in greater variance than areas with comparable abalone densities in the South-East. Higher levels of replication may be required in these areas. The modified method can be implemented in both fully circular sites, and those comprising one or more sectors (e.g. a semicircular site configuration). This provides a greater degree of flexibility in choice of sites than can be achieved by the current Victorian radial transect method.

The major restriction of the modified radial transect technique is that survey locations need to be at least 40m x 80m in area. An alternate parallel transect design was adopted (with macros) to enable sampling in areas where the reef is too narrow to accommodate radial transects. While the parallel technique is less efficient than radial techniques in general, it provides abundance estimates at the same level of precision as the radial technique, and will enable sampling of abalone populations that couldn’t otherwise be sampled.

While the modified radial transect technique has proven to be an effective and efficient method for obtaining robust estimates of abalone density, there are two key issues that must be addressed prior to implementation of a strategic fishery-independent survey program; 1) limitations on diving in remote areas imposed by the Australian Scientific Dive Code, and 2) the potential confounding of fishing effort history and survey based estimates of abalone abundance. These two issues are discussed in detail below.

16.1. Remote area restrictions in scientific diving: implications for survey programs

An important issue in the application of the radial transect technique in the Tasmanian abalone fishery relates to regulations for Scientific Diving, particularly in remote locations. This will be a significant challenge for the establishment of a long term fishery-independent monitoring program in Tasmania. For the large part of the South and West Coasts of Tasmania, the bulk of the catch comes from depths below 10m, and in many other more accessible areas a significant part of the catch is also taken from depths below 9m. Additionally, due to typical weather conditions there are limited days when surveys can be conducted in the 5m to 9m depth range. Thus, to implement a fishery-independent monitoring program on the South, West and other remote coasts requires a solution to the limitations imposed by the Australian Scientific Dive Code (Standards Australia 2002). This solution must allow access to depths of up to 15m, without compromising the safety of divers.

A possible solution is the use of mixed gases such as Nitrox which will enable surveys to be undertaken in deeper water, at depths more relevant to the fishery (10m – 15m). Nitrox is not regulated under the Australian Scientific Dive Code, and can be used for research activities providing guidelines are prepared and accepted by the institution conducting the research. However, the cost of establishing a Nitrox diving program in remote areas will be in excess of $50,000. If Nitrox diving is incorporated into the addition Australian Scientific Dive Code, there is a risk that remote area restrictions with the use of Nitrox may again significantly limit the research that can e undertaken in remote areas (>2 hours from a chamber)

16.2. Accounting for the effect of commercial fishing activity at independent monitoring sites

A major problem associated with independent monitoring of abalone density within the Tasmanian (and other) abalone fishery, is that the history of fishing effort at a site can have a substantial effect on abundance estimates. This may result in incorrect conclusions that stocks have significantly improved, or significantly declined. In Tasmania, fishing takes place all year around although there is some seasonality on both the East and West Coasts. A consequence of fleet dynamics is that fishing effort applied at particular sites or regions is likely to vary from year to year. Consider the following example of commercial activity at and around an independent monitoring site, with the same total catch removed in both years;

Year 1.

Abalone divers fish a site heavily in June, but do not visit that site again before research divers survey the site in October and obtain an estimate (X) of abalone density. Three months have elapsed between fishing and survey, allowing re-aggregation and emergence of abalone, recruitment and/or immigration of new individuals.

Year 2.

Abalone divers fish a site variably during the year, with an abalone diver fishing the site two days prior to research divers undertaking a survey, which returns an estimate (Y) of abalone density.

Inter-annual variation in fishing effort of the nature of X and Y above (catch taken and the timing of fishing) relative to the timing of surveys may mask any real change (increase/decline) in abalone density. This is an important issue relevant to all abalone monitoring programs, and is independent of survey method used. This issue is also relevant to the collection of research size structure data.

The reality of this issue was experienced first hand while an experienced abalone diver was assisting the field team with site selection. The diver accompanied the research team in the site selection trip to ensure the correct location was identified and marked with GPS. At one particular site, the diver had taken a large catch, at high catch rates the previous month. When the research team returned the following week, abalone abundance was substantially lower than most other sites surveyed.

A potential solution is to record fishing effort at a very small spatial scale, to enable researchers to determine the extent and timing of fishing activity at a survey site. Estimates of abalone density obtained during research surveys, could then be weighted or adjusted accordingly. In practice this may be difficult, as the intensity of fishing effort over the survey site will be difficult to quantify. The alternative to fine-scale data collection of fishing effort, is to survey every site several times per year. This would enable some estimate of the change in density, but would significantly decrease the number of sites that could be surveyed annually. This approach is not a suitable solution in the Tasmanian fishery for reasons of cost and boating and human resources.

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Appendix 1: Intellectual Property

There are no intellectual property issues relating to this project.

Appendix 2: Staff

All staff on this project were employed by the Tasmanian Aquaculture and Fisheries Institute, University of Tasmania.

Dr Craig Mundy – Principal Investigator
Mr Tim Karlov – Research Officer
Assoc. Prof. Malcolm Haddon – Co-investigator
Ms Kate Stark – Research Assistant
Mr Stewart Dickson – Research Assistant
Ms Leigh Gurney – Research Assistant
Mr Tim Hyndes – Research Assistant
Mr Chris Jarvis – Research Assistant
Mr Dane Jones – Research Assistant
Mr Mike Porteus – Research Assistant