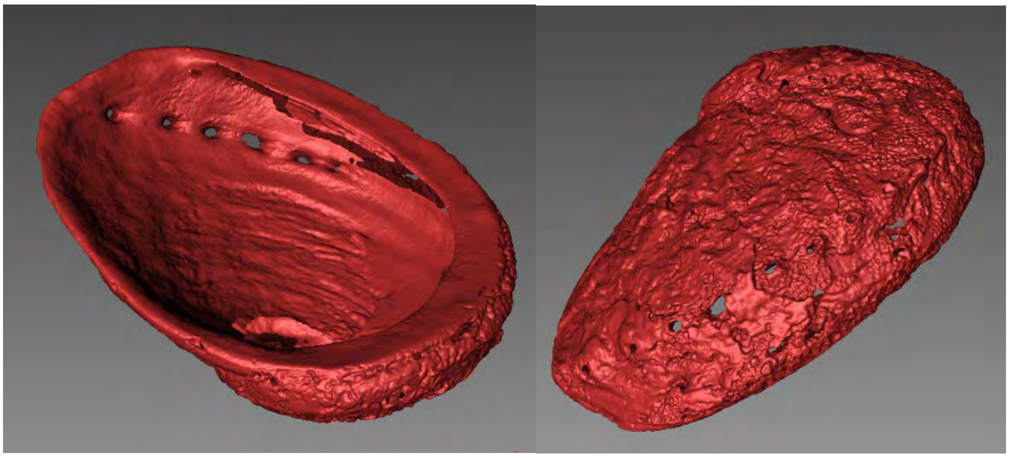
Could harvest from abalone stocks be increased through better management of the size limit/quota interaction?

Hugh Jones, David Tarbath, Caleb Gardner

Project No. 2009/746



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Contents

Non-Technical Summary

PROJECT NUMBER: 2009/746: Could harvest from abalone stocks be increased through better management of the size limit/quota interaction?

PRINCIPAL INVESTIGATOR: David Tarbath, ADDRESS: Institute for Marine and Antarctic Studies, Private Bag 49, Hobart, Tasmania, 7001

PROJECT OBJECTIVES:
1. Quantify density dependent effects on wild abalone growth and meat quality.
2. Develop a statistical tool for classification of shell age.
3. Use length-based models to test the adequacy of shell age performance measures.
4. Use length-based models to determine the sustainability and cost-effectiveness of a legal minimum length (LML) that optimises the proportion of ‘old’ shell within 5 mm of the LML.

ABSTRACT:

Tasmanian blacklip abalone (*Haliotis rubra*) populations exhibit spatial variability in biological characteristics, including meat quality, growth rates, size at maturity, and shell shape, which has important implications for the fishery. Blacklip abalone in the north-west Tasmanian fishery are characteristically smaller, slower growing and hence may recruit to the fishery at older ages than elsewhere. This has two consequences: firstly, older abalone have heavier shells and lower grade meat which reduces yield and saleability of product; secondly, slow growth rates make this part of the fishery less productive than other parts of the fishery. It was proposed that by increasing fishing mortality, population densities of older abalone would be reduced. As a result, recruits would grow faster through reduced intra-specific competition for food, and better quality, higher meat yields would be accessible by industry. A research program was established at Hunter Island, north-west Tasmania to test the proposal using three pairs of control-impact sites. Density reduction at the impact sites was achieved by unusually intensive fishing at a reduced size limit of 110 mm until catch rates fell to approx. 20 kg/hr. Growth rates, density and size at maturity were estimated before and after fishing at both control and impact sites. No evidence for density-dependent increase in growth was observed at impacted sites, nor was there evidence for improved meat quality and yield.

Abalone are believed to show predictable changes in shape and appearance at various stages in life. Newly emerged abalone are typically flat, oval in shape while older fully mature abalone are rounder and bowl-like. In the Tasmanian fishery, size limits are usually applied regionally to protect populations with average growth characteristics. In parts of these regions where blacklip are smaller with slower growth rates, size limits set to protect populations of average growth may be too high, preventing fishing of substantial quantities of abalone below the size limit and leading to underutilisation of the resource. It was proposed that qualitative visual assessment of shell shape and appearance to define shell age could be used as a tool for small-scale population management. It would be used to evaluate the suitability of current size limits and catch levels in slow-growth areas. A research program was established to determine whether morphometric measurements could reliably replicate a visual shell grading system. No suitable morphometric basis for the grading system could be identified and a simplified

grading system of shell shape was found to be applicable at spatial scales too small to be generally adopted as a management tool. Development of a morphometric model independent of shell grade (allometric shape model) highlighted differences in shape at size at maturity, limiting the applicability of morphometric models as alternative management tools for setting size limits. However, the allometric shape model was able to predict changes in shell shape should size limits be adjusted, and if a more comprehensive market-measuring monitoring program was established, could also provide a method for assessing changes in the size structure of the stock.

OUTCOMES ACHIEVED:

1. As a result of this study, the abalone industry of Tasmania are no longer considering a reduced size limit and thinned population density as a method for increasing abalone growth or quality at Hunter Island or other areas with similar biophysical attributes.
2. The visual assessment of shape and appearance as a method of defining abalone maturity and age is not a sufficiently precise measure to define a population’s status and as a result the abalone industry will not be considering it as a management tool.
3. The allometric morphometric analysis has potential as a processor-based method of collecting spatially defined abalone shell quality data, and should be considered for future market measure research. This has not yet translated to an outcome of better harvesting in the fishery but remains under consideration.

LIST OF OUTPUTS PRODUCED

1. Following the reduction of blacklip population densities at Hunter Island by intensive fishing, there was no evidence that productivity increased through increased growth rates or that abalone quality improved through increased meat recovery rates or higher meat grades.
2. It is likely that the density reduction strategy employed in this study will be ineffective in other parts of the blacklip fishery which share similar biophysical parameters to those found at Hunter Island, and consequently density reduction and reduced size limits should not be considered as a management tool to improve productivity in these areas.
3. Development of a morphometric statistical tool for the determination of shell grade, based on Tasmanian Seafood Pty Ltd (TSF) methods was achieved but was found unsuitable for management purposes. Improved accuracy in shell classification was achieved with a modified version of the TSF method (binomial model) but the improved model was found to be site dependent and not transferable between populations.
4. The economic modelling of sustainability using optimal proportions of ‘old’ grade shell at LML could not be achieved because no model using shell grades could be reliably applied.
5. An alternative statistical tool for shell shape (allometric shape model), independent of shell grade was built. Spatial variation in shell shape at size at maturity limits the application of shape models as alternatives to current methods of setting size limits but can provide a method for assessing shell quality at any given length within site.

6. The allometric shape model could be adopted within a factory environment with minimal additional equipment, and provide a factory-based method of collecting spatially defined shell-quality data, which could provide information about changes in fishery structure through time and space.

COMMUNICATION OUTPUTS

Fishing Today: Vol 26/2, April 2013: Hunter Island Shell Study
Presentation to Industry and Government: February 2013
Presentation to Tasmanian Seafoods Pty Ltd: September 2014
Presentation to Industry and Government: September 2014

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1. Introduction or Background

1.1 Format

This report summarises the findings of a project in north-west Tasmania that was developed to enhance yield from its fishery through improved understanding of the complex interactions between blacklip abalone growth, morphometrics, ecosystem functions and fishery responses.

Section 1 introduces the background and scope of each section of the report. It reviews current knowledge of abalone growth, density dependence, morphological variability and use of length-based models in fisheries management, and specifies the need for further research in these areas. The subsequent sections focus specifically on one of these areas (Fig. 1 Sections 2-4), which are then summarised in the conclusions (Fig. 1 Section 5) to provide an overall assessment of our findings and how they affect the management of the blacklip fishery in the region.

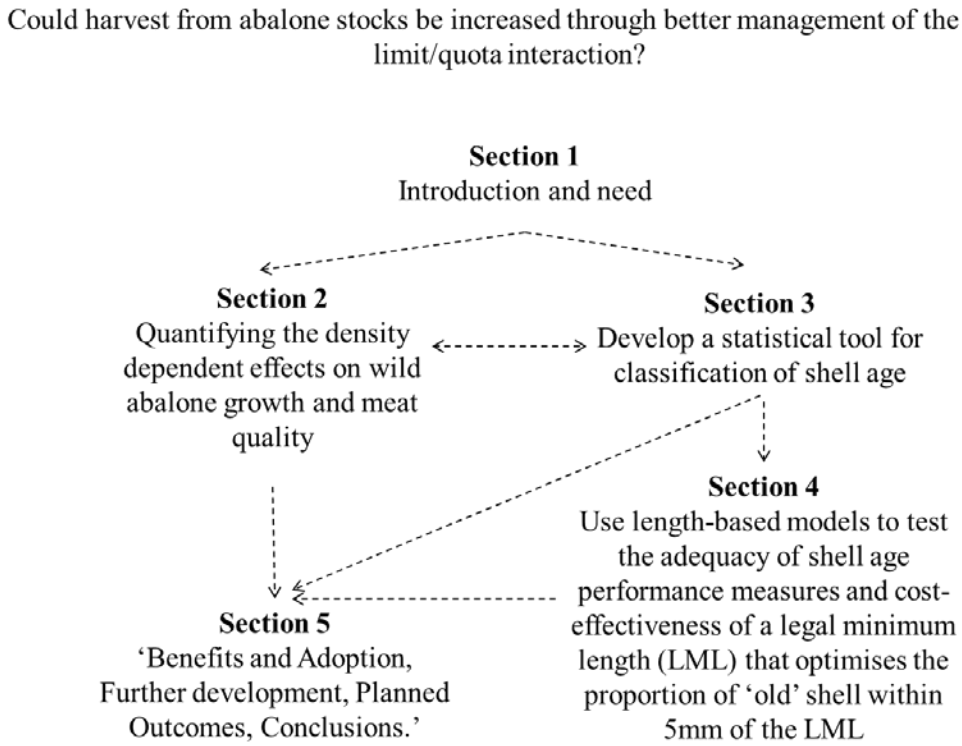

Fig. 1. Section map.

1.2 Introduction

A major challenge for the management of fisheries using length-based management practices is deciding practical spatial scales that allow for the spatial heterogeneity in population biology (Helidoniotis and Haddon, 2013). Abalone population structures are highly variable across both fine and large spatial scales (Mayfield and Saunders, 2008), and the resulting stocks often have different market values, depending on growth rates, appearance and meat recovery. In Tasmania, blacklip abalone (*Haliotis rubra*) from the south of the state are commercially preferred and are generally of higher value. Blacklip harvested from the north are generally of lower quality, are unsuitable for live markets and attract lower prices. However, within the north there are specific areas where blacklip are of higher quality, and these are fished preferentially to surrounding areas. The consequence of this is that fishing effort is at times regionally concentrated, risking serial depletion and localised collapse of preferred populations.

Throughout Australia, management of blacklip fisheries is generally broad-scale and covers many morphologically different populations at finer spatial scales (Saunders et al., 2009). In Tasmania, the abalone fishery is managed principally by adaptive response in catch to annual catch-rate trends. Differences in biological characteristics between stocks require management controls which rely on spatially-defined legal minimum lengths (LML), zone quotas and regional catch caps. These provide a mechanism to ensure stocks are harvested appropriately, according to their production (Day et al., 2005). Management policy in Tasmania specifies that LMLs are set by a rule of thumb allowing two year's spawning following onset of maturity (the 'two-year rule'), ostensibly to enable sufficient recruitment. In practise, LMLs are estimated using area-specific growth-rate and size-at-maturity information (Helidoniotis and Haddon, 2013). However, fine-scale growth-rate and size-at-maturity variation within management areas causes uncertainty about the use of broad-scale regional LMLs (Saunders et al., 2009), because over-estimation of LMLs may lead to underutilisation of the resource in slow growth areas, while under-estimation may lead to overfishing of faster-growing populations (Prince, 2005; Helidoniotis and Haddon, 2013). Despite extensive use of LMLs in abalone fisheries management, their performance in meeting management objectives is rarely assessed (Helidoniotis and Haddon, 2013), but remains a topic of interest throughout the fishing community, where increasingly finer scales of management down to scales appropriate to the component unit of stock (i.e. population level) have been promoted.

Essential to the development of finer-scale management is the formal analysis of the LML-TAC relationship, which is currently reliant on knowledge of growth rates and size at maturity at population scale. For Tasmania this is under investigation through a stock model (Haddon et al., 2014). Where growth rates are unavailable, the development of the model relies on theoretical estimations of growth rate from modelled areas where size at maturity and growth rate are known (Helidoniotis and Haddon, 2013). However, there is still uncertainty concerning the stability of growth rates and size at maturity over time, particularly with changes in fishing pressure. For example, experimental aquaculture and field studies in Australia have suggested that lower densities of abalone can lead to faster growth of post-larvae, juveniles and adults (Day et al., 2004; Dixon and Day, 2004).

1.3 Need

With estimates of more than 500 populations in the Tasmanian blacklip fishery, fine-scale LML settings are impractical from a management perspective (Helidoniotis and Haddon, 2013); yet if populations vary at fine scale there is a need to address population biology at the unit stock scale. This mismatch in scale between management and unit of stock has been highlighted as a cause of failure in abalone fisheries (Mayfield and Saunders, 2008), and therefore there is an urgent need to investigate alternative additional management strategies that may assist in the monitoring of stock structure and provide feed-back mechanisms for management. In the Tasmanian regions not covered by the stock model (Haddon et al., 2014), there is scope to design performance measures which could be used to evaluate the efficacy of the LML and be used to inform the stock model. For example, collecting abalone size- and shape-data from processing factories may be a cost-effective method of producing information for managers. Such performance measures would need to be quantitative and reliable, but if correctly applied would allow more timely and adaptive management responses, with increased profitability and reduced risk of recruitment overfishing. Ultimately this could stabilise catch levels, increase returns to the fishing industry through more consistent access to stocks, and deliver cost effective research.

The value of abalone at market is dependent upon attributes such as meat colour, meat yield, shell condition and survival in transit. Processors report that 'old shell' abalone yield lower meat weight than younger individuals of a similar size, have poorer survival while being transported, and are of lower market value. The shells of abalone graded old are typically thick, heavy, encrusted and dome-shaped, causing reduced meat yields. Variation in abalone morphology is important in terms of identifying management strategies that enable access to more marketable abalone without increased risk of over-harvesting. For example, in northern Tasmania, the proportion of slower growing, 'old' abalone at the LML is reported by processors to be greater than elsewhere. Maturity in blacklip is determined principally by age, rather than size, and size at maturity and maximum size vary widely over their geographical range (Prince, 2005b). This means that in areas where abalone growth is slow, the LML may overprotect stocks because the period between onset of maturity and recruiting is extended and consequently there may be a higher proportion of old individuals at the LML than in areas where growth is more rapid. Prince et al. (2008) argued that abalone showed predictable changes in shape and appearance at various stages in life from emergence through to full maturity, but it is not clear whether slower growing abalone have a characteristic shape throughout their size range (i.e. an inherent shape), or whether they are merely abalone with an altered shell shape due to natural ageing processes. It has been established that morphological plasticity exists between populations of variable growth rates (Mayfield and Saunders, 2008), and morphological markers have been identified as a method of defining population units (Saunders et al., 2009). However, how shape alters with age and size, and whether shape can be used as a measure of age to inform management models within a region remains unknown.

Slower growth rates among greenlip abalone (*Haliotus laevigata*) in dense populations has been attributed to limited food resources and growth- rate increases were observed as a result of stock thinning (Dixon and Day, 2004). Density-dependent growth responses have also been found in abalone aquaculture facilities (Huchette et al., 2003b), yet potential for growth (productivity) to increase as density is reduced by fishing remains unclear in wild blacklip populations. Slow growth rates and morphological differences between populations are may be due to environmental conditions (Prince, 2005; Appleyard et al., 2009; Saunders et al., 2009), which is supported by low genetic differentiation between adjacent areas with different growth rates (Temby et al., 2007). Wave stress environments can induce metabolic cost in abalone (Donovan and Taylor, 2008), which in turn may reduce growth rates and cause slow growth. Equally, the presence of shell parasites can reduce growth through the metabolic cost of shell repair (Lleonart et al. 2003). Consequently, density-dependent processes may potentially impact on yield, but there is no information to assess the likelihood or scale of density-dependent effects on production through harvesting, and therefore there is a need to address this question.

1.4 Objectives

Fundamentally, this project was designed to facilitate assessment and management of abalone fisheries through the following objectives:

1. Quantify density-dependent effects on wild blacklip abalone growth and its impact on meat quality.
2. Develop a statistical tool for the classification of shell age.
3. Use length-based models to test the adequacy of shell-age performance measures
4. Use length-based models to determine the sustainability and cost-effectiveness of an LML that optimises the proportion of 'old' shell within 5 mm of the LML.

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2. Quantifying density-dependent effects on wild blacklip abalone growth and its impact on meat quality.

2.1 Introduction

Of the many problems facing managers of Tasmania's blacklip abalone (*Haliotis rubra*) fishery, among the most difficult is the effect on fleet dynamics of regional variation in product quality within a management zone. For example, small differences in beach price between blacklip harvested from northern and southern regions of Tasmania's Western Zone fishery provide sufficient incentives for processors and/or quota owners to direct harvesters to focus effort in the higher value regions. If left unmanaged, this causes fishing effort to become regionally concentrated, risking serial depletion and the collapse of better quality populations.

Across the northern part of the Tasmanian fishery, the geographic scale over which such variations in value occur is much smaller, resulting in more localised variation in fishing intensity. Management of the fishery at the fine spatial scale required to prevent concentration of effort at local scales is challenging from a compliance perspective. Consequently, northern management regions continue to include populations of variable quality, with concomitant unequal distribution of fishing effort throughout the sector. It was proposed by a processor, Tasmanian Seafoods Pty Ltd (TSF) that managing the fishery to reduce population densities in areas with low-grade blacklip would improve blacklip quality and increase productivity from this part of the fishery.

Among abalone processors, blacklip quality is usually defined in terms of both meat-weight recovery and meat grade, and is believed to be closely correlated with growth rates. Abalone from populations with fast growth rates are typically younger at recruitment as existing Legal Minimum Length (LML) restrictions provide less protection for fast-growth areas. Tasmanian processors and handlers report that fast-growth areas provide higher meat-to-whole-weight recovery with higher grade meats and are hence more preferred than those from slower growing populations which require extensive processing before they are marketable.

The slower growing abalone populations are often characterised by large numbers of small mature fish with a reduced size at maturity; often referred to as 'stunted populations' (Saunders et al., 2009). Slow growth rates in young abalone may be a density-dependent response through competition for preferred space (Huchette et al., 2003), or to food quantity or quality, and result in a perpetual occurrence of slow growing populations. Experimental aquaculture and field studies in Australia have suggested that lower densities can lead to faster growth of post-larvae, juveniles and adults (Day et al., 2004; Dixon and Day, 2004). Among wild populations of pinto abalone (*Haliotis kamtschatkana*), it was shown that stunted abalone transplanted from high-density populations to low-density populations grew faster, although it was not clear whether this was caused by the reduction in density or the change in habitat (Emmett and Jamieson, 1988). In stunted populations of greenlip abalone, growth rates increased when density was reduced (Dixon and Day, 2004). The effects of density on growth of blacklip abalone has only been established via controlled aquaculture experiments (e.g. Huchette et al., 2003; Wassnig et al., 2009) where it was demonstrated that growth can be accelerated by reducing stocking densities. The effect of density-dependence on growth rate has not previously been investigated in a wild blacklip abalone fishery.

One potential mechanism to achieve a density reduction is to selectively thin the larger blacklip from populations thereby releasing resources (food and space) for younger individuals, and quantify any resultant change in growth rate and product quality at market. Here we tested this hypothesis experimentally, by reducing the LML and increasing fishing mortality in selected areas of slow-growth abalone, and then quantifying the subsequent effect on growth and quality.

2.2 Method

To quantify density dependent effects on abalone growth and product quality in a wild fishery, we contrasted growth rates and abalone meat characteristics at control and impact sites following abalone density reduction by intensive fishing at the impact sites. A timeline of events affecting the project is shown below (Fig. 2).

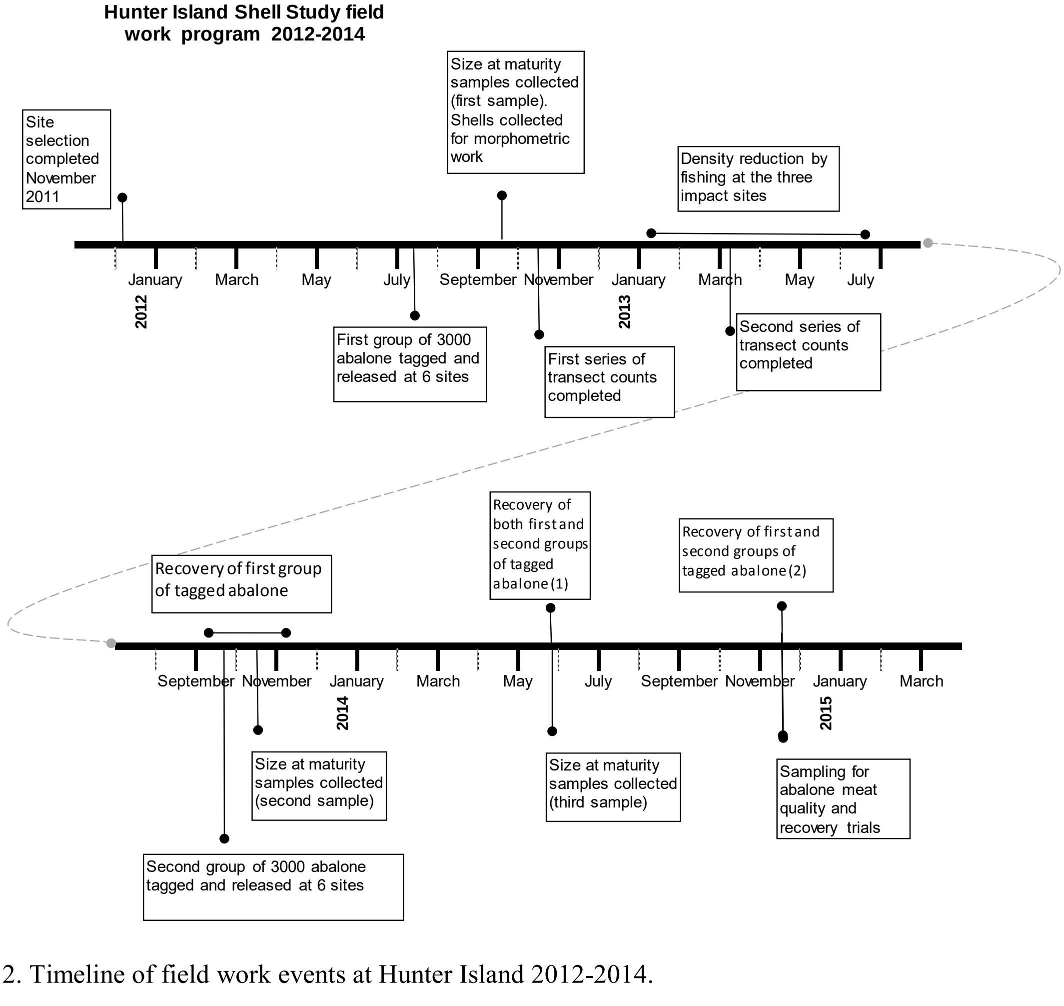

Fig. 2. Timeline of field work events at Hunter Island 2012-2014.

Our Industry partner, Tasmanian Seafoods Pty Ltd (TSF), requested that the work be conducted in the Tasmanian Northern Zone abalone fishery, where growth and product quality are regionally variable, and recommended Hunter Island, in the remote north-west of Tasmania. An initial survey of 15 sites along the 30 kilometre length of the western side of Hunter Island was undertaken with the help of a local abalone diver in

2011. From this survey, three pairs of adjacent control/impact sites were selected on the basis of their habitat similarity and close proximity to each other. Each site covered approximately 100-300 m of shoreline. The paired sites were chosen to minimize differences in reef characteristics (e.g. aspect, reef structure or algal growth) and therefore reduce the possibility of differential growth rates within pairings (Fig. 3).

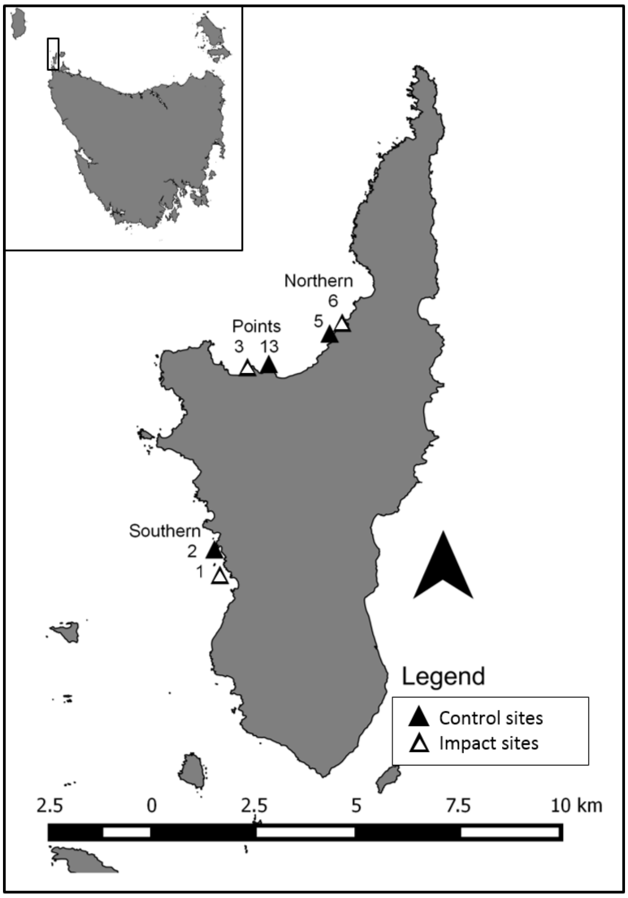

Fig. 3. Hunter Island Tasmania, showing the location of the sample sites.

In the southern part of Hunter Island, two sites were selected in the area known locally as Duck Bay. These were labelled Sites 1 (impact) and 2 (control), and collectively known as the 'Southern sites'. Further north, in Cuvier Bay, sites on two headlands separated by beach were selected. These were labelled Sites 3 (impact) and 13 (control), collectively known as the 'Points'. Further north again, the remaining two sites (the 'Northern sites'), labelled Sites 5 (control) and 6 (impact), were selected along a stretch of rocky shoreline.

The Points sites in Cuvier Bay sites were narrow fringe reefs at the base of the headlands extending between 10-50 m seaward to sand. At the Southern and Northern sites, reef extended seaward beyond diving depth, but abalone were present only in the shallows (generally <10 m) or other parts of the reef less than 100 m from shore. The restricted distribution of abalone and their low mobility meant that we were confident that density reduction would relatively unaffected by immigration of abalone from outside the study areas. More detailed habitat descriptions of each pair of sites is given in Appendix 3.

Independently, but coinciding with the start of the project in 2012, fishery managers implemented a series of measures to improve the productivity of the fishery around

Hunter Island These measures included reducing the LML by 5 mm to 120 mm and increasing the 2012 catch from the recent 10-year average of 65 t pa to 100 t. There was a substantial increase in fishing effort, and by mid-2012, the 100-t catch target had been met. We were concerned that the high levels of fishing mortality would reduce the contrast between control and impact sites and make it difficult to detect changes due to fishing, so we ensured that impact sites were fished more intensively until catch rates fell to approximately 20 kg/hr (compared with the prevailing 70-100 kg/hr) and under a reduced size limit (110 mm). Adjacent control sites remained available to commercial fishing at the normal LML of 120 mm.

A commercial abalone diver undertook the fishing, under the control of a permit issued by the Tasmanian Department of Primary Industry, Water, Parks and Environment (DPIPWE) under Section 12 of the Tasmanian Government's Living Marine Resources Management Act (1995). Fishing commenced in January 2013, and was substantially completed by May 2013, although the diver returned to the sites several times until July 2013 to ensure that catch rates had fallen to the required level.

The effectiveness of the density reduction was tested by surveys of abalone density both before and after fishing using the cross-drop fixed transect methods (Chick et al., 2012). The cross-drop method was preferred to continuous length transects because abalone distribution was frequently constrained by habitat to small areas, and the use of continuous length transects would place much of the survey area out of reef frequented by abalone. Length of all abalone were recorded by 10-mm size class.

In this study, the cross drop method featured four 10 m x 1 m transects (total area 40m^2) radiating in straight lines from a central point. The central point was marked with a steel post driven into the reef. The transects started 2 m from the centre to avoid overlap, and were usually laid at 90° to each other, normally to the cardinal points, but there were exceptions where habitat prevented this. Data were summarised in two size categories: permit legal-sized ($\geq$ 110 mm) and under-sized (<110 mm). There were three cross-drop samples at each of the six sites, and data from the three cross drop samples at each site were pooled. The effectiveness of density reduction was examined by Kruskal-Wallis analysis. Cross drop data were pooled by treatment (impact, control) and by size category (<110 mm, $\geq$110 mm), providing three replicates at each of six sites. Kruskal-Wallis was used in preference to parametric equivalents due to the low number of replicates and non-normally distributed data.

2.2.1 Comparison of biological parameters

It was proposed by the Industry partner that as a result of the reduced density, abalone would grow faster and to a larger size. Increased growth would occur through a reduction in interspecific competition, thus increasing food availability (Day and Fleming, 1992). To test this hypothesis, we used two methods: (a) a mark-recapture program to determine the effect of density on increases in shell-length through growth, and (b) through increased length at which abalone become sexually mature.

Growth rate

In August 2012, approximately 500 abalone were tagged and released at each site. Abalone were collected in small batches and fitted with tags on board the vessel, and their shell length (SL) was measured (± 1 mm). Abalone larger than approx. > 90 mm were tagged with sheep ear tags, while 'Floy' brand disc tags were used to mark smaller abalone (Appendix 4a). The abalone were kept moist with seawater at all times during processing, before being returned to the reef proximal to where they were taken.

In previous tagging studies, we have observed that marking abalone under these conditions produces negligible mortality.

Following an extension of the project, another 500 abalone were tagged and released at each site in September 2013, after the density reduction. Tagged abalone released in 2012 were recaptured in November 2013, measured for SL, and re-released. Tagged abalone released in 2013 were recaptured (and re-released) in May 2014, and in November, 2014.

We used the von Bertalanffy growth function to model growth. Growth increments from juvenile and large abalone were almost entirely absent from the samples, which prevented use of the preferred inverse logistic model (Helidoniotis et al., 2011). We used Grotag: Francis' derivation of the Von Bertalanffy growth model (Francis, 1988) to model growth because its increment-at-length parameters are more easily interpreted by a non-technical audience than the traditional von Bertalanffy parameters. Francis' derivation is

$$\Delta L = \left[\frac{y_2 g_1 - y_1 g_2}{g_1 - g_2}\right]\left[1 - \left(1 + \frac{g_1 - g_2}{y_1 - y_2}\right)^{\Delta T}\right] \qquad (1)$$

where y_1 (90mm) and y_2 (110mm) are two lengths that are adequately represented within the size range of the tagged sample. The parameters g_1 and g_2 are the mean annual size increments expected of animals of lengths y_1 and y_2. The more usual von Bertalanffy parameters K (growth rate) and L_∞ (asymptotic length or maximum average size) are derived from the parameters that describe growth at size:

$$L_\infty = \frac{y_2 g_1 - y_1 g_2}{g_1 - g_2} \text{ and } K = -Log\left(1 + \frac{g_1 - g_2}{y_1 - y_2}\right) \qquad (2)$$

Error (individual growth variability and measurement error) was estimated following the example of Francis (1995):

$$\Delta L_{observed} = \Delta L_{expected} \varepsilon_{growth} + \varepsilon_{measurement} \qquad (3)$$

where ε_{growth} and $\varepsilon_{measurement}$ describe growth and measurement error.

Residuals about expected increments appeared normally distributed, so we used a constant coefficient of variation approach to describe error i.e. standard deviation $\sigma = \nu\mu$, where μ the mean expected increment and ν describes the relationship between mean growth and growth variability. To improve the estimate of growth variability, a previously obtained estimate of measurement error was used (Tarbath, 2003a) which was obtained using measurements from a manual measuring board, whereas this study used an electronic measuring board. However, the measuring process was fundamentally unchanged, and it is assumed that the estimate of error was appropriate.

Two additional parameters, *u* and *w*, were included in the model to describe seasonal variation in growth, *u* describing variation from average annual growth (amplitude) and *w* describing the time of year with peak seasonal growth. These parameters potentially affected the period between release and recapture, and were included in the model by changing the ΔT term to:

$$(\Delta T + (\phi_r - \phi_m)) \quad (4)$$

where:

$$\phi_i = u(\sin(2\pi(t_i - w))/2\pi \quad (5)$$

for i = r (recapture date), m (release date), and ΔT is measured in years, the recapture and release dates in fractions of a year. In actuality, we had almost no intermediate-period recaptures, and while these parameters significantly reduced the negative log-likelihood, they were effectively meaningless. Consequently, we were unable to quantify seasonal effects on growth.

The model was fitted in stages, using Microsoft Excel's Solver routine. Initially the two growth-at-size parameters were fitted by least squares, establishing starting values for further development by minimising negative log-likelihoods. This approach was used because least-squares could fit the growth-at-size parameters accurately, whereas there were many possible likelihood solutions. Addition of further parameters was by minimising negative log-likelihoods. The growth variability parameter (ν) was added after establishing growth at size, followed by the pair of seasonal parameters u and w. Parameters were added in the sequence that produced greatest difference to the negative log-likelihood.

Ninety-five percent confidence intervals were produced from 1000 bootstrap samples for each data set. Because of the unequal distribution of increments by size-at-release, each data set was stratified in 10-mm increments, and bootstrap sampling was done within those strata.

We compared between-sample differences in growth rates using analysis of residual sum of squares (ARSS) for coincident growth curves to produce an F-statistic, with significance at $p = 0.01$.

Size at maturity

Age, rather than size is considered to determine when abalone become sexually mature (Prince et al., 1988; Shepherd et al., 1991; Nash, 1992); consequently if abalone grow faster, they should become sexually mature at a larger size, and differences in size at maturity at the control and impact sites, both before and after density reduction, should become apparent.

Size at maturity (SAM) was estimated from samples of abalone taken at each of the six sites, before density reduction in August 2012, after density reduction in November 2013, and at the tagged abalone recovery event in May 2014. Abalone (n≈ 200) were collected by haphazard collection from each site on each sample event. Sexual maturity was determined by visual examination of the gonad (Branden and Shepherd, 1983) and categorized into one of four groups: Stage 0, has no apparent development of gonad (immature). Stage 1, gonad development has started, such that it is possible to determine sex of animal, although the gonad at this stage is very slight, at its most developed form it is translucent so that the digestive gland is still visible underneath (immature). Stage 2, gonad is obvious at the extremities of the digestive gland, it is opaque but not yet fully formed. The eggs in females are visible at low magnification while males are viscous creamy yellow (mature). Stage 3, fully formed gonad (mature). Stages 1 to 3 can be grouped by sex but only stages 2 and 3 are considered mature as although in stage 1 sex may be determined, that individual is unlikely to be reproductive and so is categorised as immature male or female. The size-structure of each sample is shown in Appendix 1.

Size at maturity was estimated by non-linear regression of the maturation data (number mature, number sampled by size class, where size class is one millimetre) to the logistic equation:

$$p = \frac{e^{c+d.x}}{1+e^{c+d.x}} \tag{6}$$

where p is proportion mature, x is length, and c and d are parameters of the logistic function. The size at which 50% of the sample were sexually mature was estimated, and bootstrapped 95% confidence intervals were produced.

2.2.2 Abalone quality

Tasmanian Seafoods' Pty Ltd (TSF) assessed abalone quality using the percentage meat recovery of abalone following processing. There are two secondary methods associated with this; meat grade, and the proportion of 'old' grade shells in the catch.

The percentage meat recovery is the weight of shucked meat produced using TSF proprietary process, as a percentage of the landed weight. They also produce statistics about the percentage of canned weight relative to the landed weight. Meat grade is a statistic derived from a qualitative evaluation of the colour of the abalone foot following processing. The shucked weight percentage was the only indicator of abalone quality that was sufficiently precise for our purposes. We compared shucked meat recoveries between impact and control sites, before and after fishing.

2.3 Results

2.3.1 Density reduction

Approximately 9.8 t of permit legal-sized blacklip shell (≥110 mm) were removed from the three sites by commercial abalone divers: 3.8 t from Site 6, 0.8 t from Site 3 and 5.2 t from Site 1. Across the broader area of the sites most permit legal-sized abalone were removed by the end of May 2013, but at their peripheries, residual pockets remained until July 2013. At the end of the fish-down process, daily catch rates at impact sites were reported at ~20 kg/hr at 110 mm. In contrast, in the commercial fishery outside the research areas, catch rates at 120 mm LML were approximately 70-90 kg/hr.

Ongoing reduction of the number of legal-size abalone at the control sites was also apparent, which we attributed to heavy fishing mortality of abalone ≥120 mm by the commercial fleet. Between July 2012 and June 2014, 185 t was taken from around Hunter Island, including the study sites. As a measure of the depletion that this catch had on blacklip stocks, hourly catch rates in the region declined from approximately 90 kg/hr to 60 kg/hr over this period.

Differences in blacklip density by size class (<110 mm, ≥110 mm) were estimated at both impact and control sites, both before fishing in September 2012, and during the fishdown in March 2013. Median densities of permit legal-sized blacklip were reduced across the impact sites, from 0.88 abalone m^2, to 0.30 abalone m^2 (Fig. 4). Differences between median blacklip densities were significant ($\chi^2 = 3.79$, df=1, $p = 0.05$) at the impact sites among legal-sized abalone (≥110 mm), but not at the control sites ($\chi^2 = 0.2$, df=1, $p = 0.60$) , nor among sub-legal abalone (<110 mm) at either control or impact sites ($\chi^2 = 0.10$, df=1, $p = 0.76$, $\chi^2 = 0.00$, df=1, $p = 0.97$).

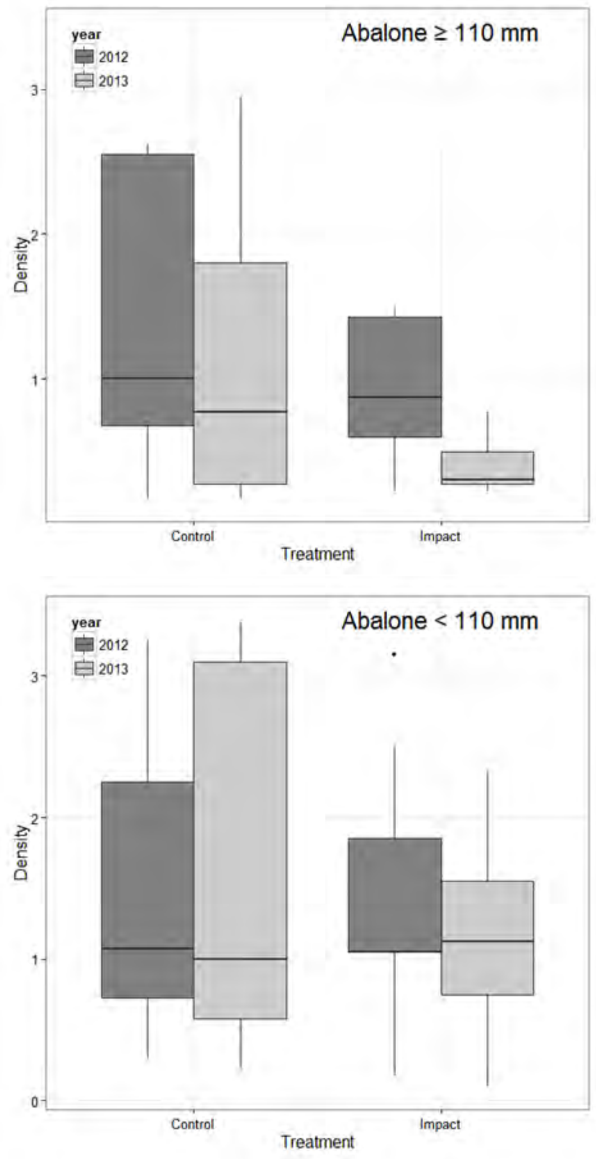

Fig. 4. Median densities of abalone (n/m^2) with first and third quartile densities, comparing pre-fish-down densities (2012) with post fish-down densities (2013) among permit legal sized abalone (≥110 mm) and sub-legal sized abalone (<110 mm) at control and impact sites at Hunter Island, Tasmania.

2.3.2 Comparison of growth rate parameters

Growth rate:

A total of 5,987 blacklip of shell length between 44-154 mm were tagged and released at the six sites, the majority of which were in the range 90-115 mm. Of the 3,000 abalone tagged and released in early August 2012, 362 were recaptured between September and November 2013 (average time released was 417 days). From the second group of 3,000 tagged abalone released between September and November 2013, 757 were recaptured in May 2014 (average time released was 247 days). In November 2014, a further 246 abalone from the second group were recaptured, after being released for an average of 416 days. Of the recaptures there were comparatively few recaptures of abalone less than 80 mm, or greater than 120 mm.

Initially we examined differences in growth rates among abalone released in 2012 prior to the density reduction, between paired (control and impact) sites (Fig. 5). If between-site differences were apparent prior to the density reduction, then any post-fishdown differences were not necessarily attributable to density reduction. We found significant differences in growth rates between control and impact sites at one of the pairs: the Points pair, Sites 3 and 13 ($F_{3,136}=18.69$, $p<0.001$). Abalone at Site 3 grew larger and faster, with estimated annual increments at 90 mm initial length: 6.49 (95% C.I. 5.47-8.66) mm, and at 110 mm initial length: 3.51 (95 % C.I. 2.98-3.98) mm, whereas the increments at the control site (Site 13) were much less: 3.46 (95 % C.I. 2.31-6.16) mm at 90 mm and 1.90 (95 % C.I. 1.35 -2.47) mm at 110 mm. At the Southern and Northern pairs, pre-fishdown differences between growth rates were not significant ($F_{3,77}=3.69$, $p=0.015$ and $F_{3,136}=3.69$, $p=0.014$).

We examined post-fishdown differences at the Northern and Southern pairs and at both locations, within-pair growth rates appeared similar (Southern: $F_{3,82}=1.65$, $p=0.183$, Northern: $F_{3,89}=0.23$, $p=0.872$) i.e. we were unable to detect changes in growth rates between the control and impact sites.

We then compared within-site changes in growth rate, between the first group of tagged abalone (i.e. tagged in 2012 prior to the fishdown, recaptured in 2013) with those from the second group (i.e. tagged in 2013, post-fishdown and recaptured in 2014) (Fig. 6). At both Sites 1 and 2, abalone tagged from the second group appeared to grow faster than those from the first group. Differences in growth rates were significant at the control Site 2 ($F_{3,83}=9.66$, $p<0.001$), but not at the impact Site 1 ($F_{3,74}=2.26$, $p= 0.088$). An examination of mean growth increments by size class shows several abalone of < 80 mm release length among the second group with increments of up to 27 mm (Fig. 7). The increased increments are most likely attributable to small sample sizes. No changes in growth rates were found at the remaining sites: impact Sites 3 ($F_{3,89}=1.02$, $p=0.388$) and 6 ($F_{3,101}=2.51$, $p=0.063$), and control Sites 13 ($F_{3,102}=0.22$, $p=0.882$) and 5 ($F_{3,122}=0.20$, $p=0.982$). A summary of growth parameters by year and by site is shown in Appendix 4b.

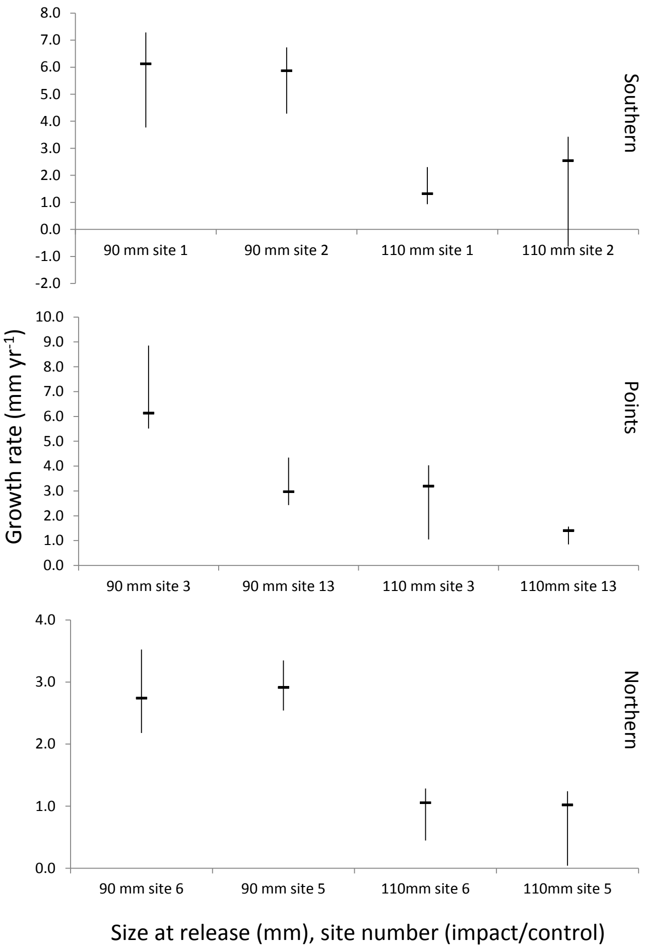

Fig. 5. Comparison of post-fishing growth increments between paired impact and control sites, showing estimated annual growth increments of blacklip abalone released after the fishdown operation for the period September 2013-November 2014, with bootstrapped 95% CI at 90-mm and 110-mm release lengths. Impact sites (Sites 1, 3, 6) are shown on LHS of each pair at the same release length, control sites (2, 13, 5) are shown RHS. Differences in growth rates between control and impact sites were significant prior to the fishdown at the Points sites (Sites 13 and 3).

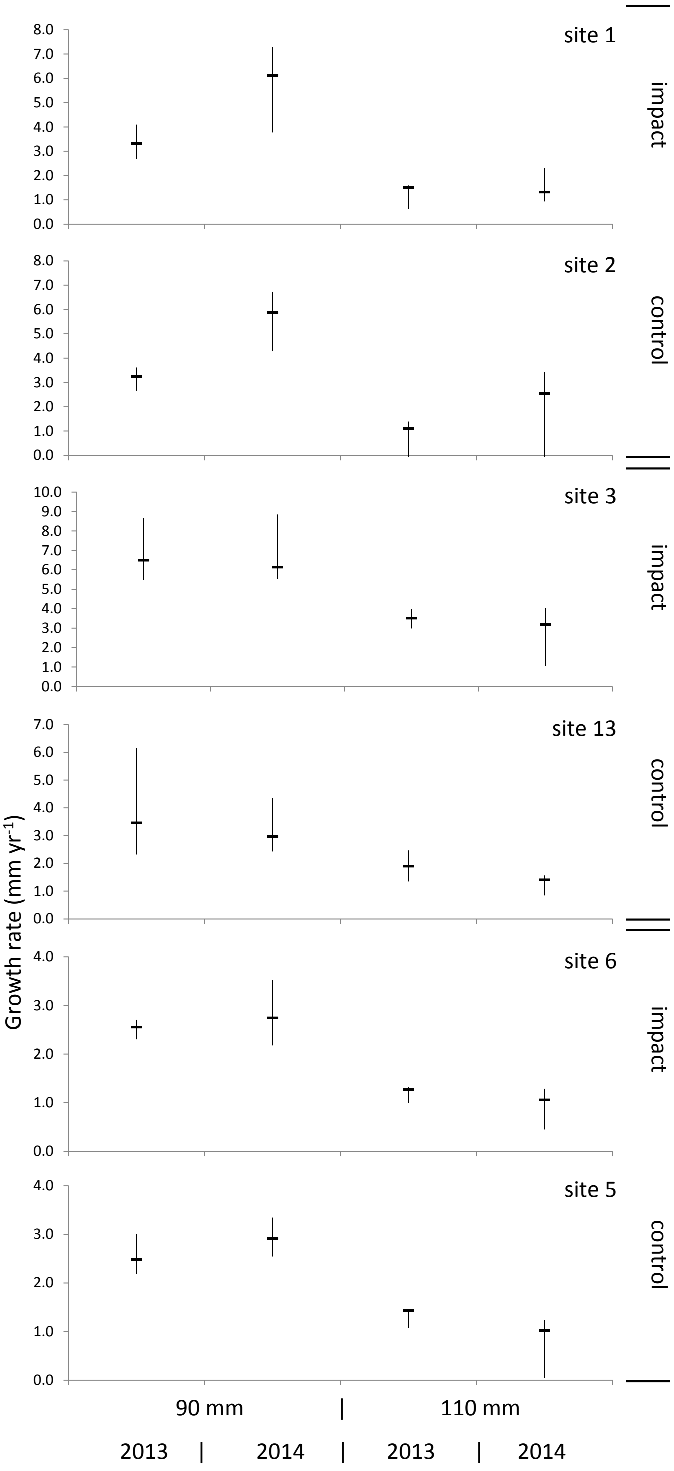

Fig. 6. Comparison of growth increments between years, by site, showing estimated annual growth increments of blacklip abalone released before (2013) and after (2014) the fishdown at impact sites, with bootstrapped 95% CI at 90-mm and 110-mm release lengths. Sites are grouped in control/impact pairs.

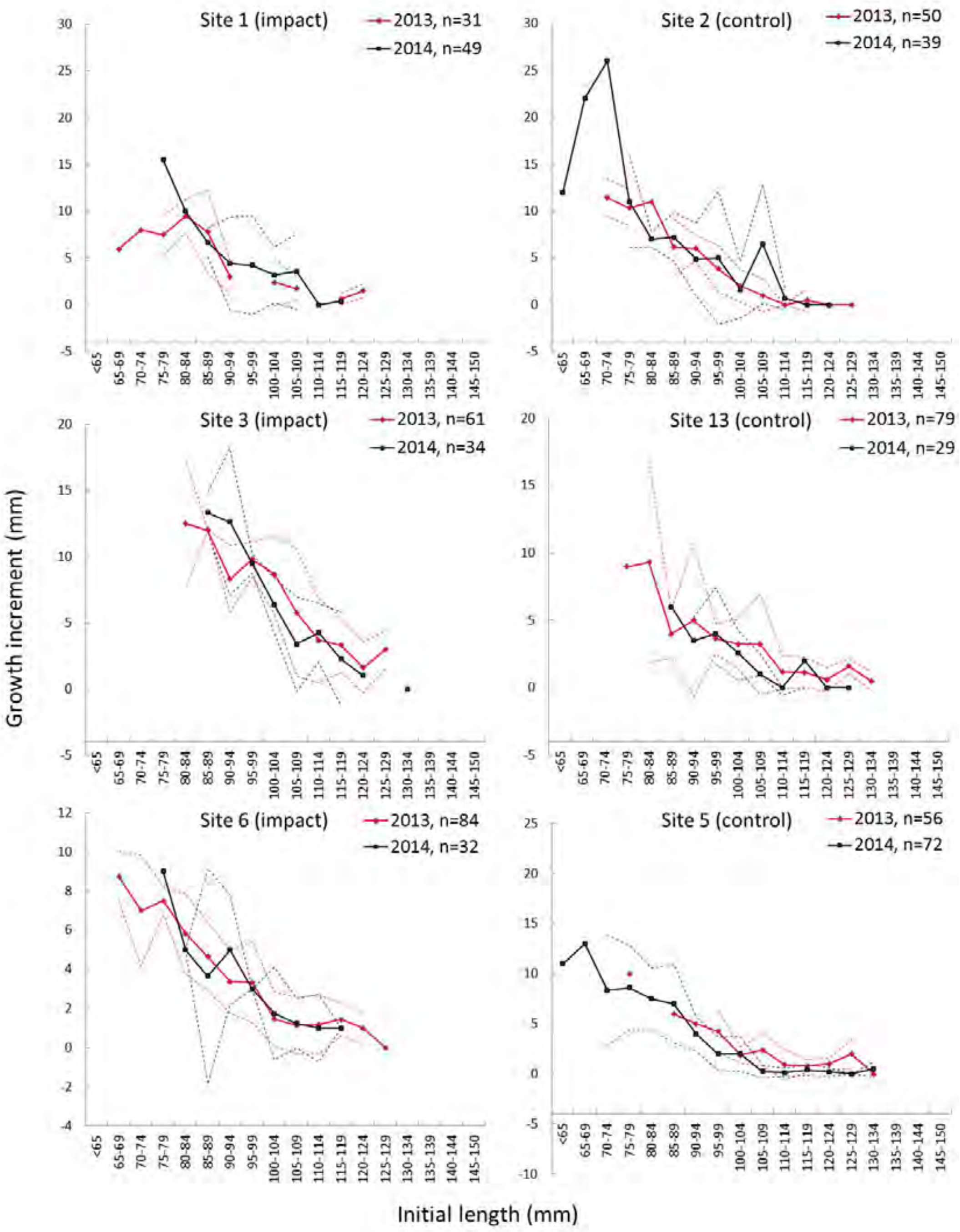

Fig. 7. Mean growth increments with standard deviations, by 5-mm size-class of abalone tagged in 2012 and recaptured in 2013, compared with abalone tagged in 2013 and recaptured in 2014, for control and impact sites. Impact sites were fished at a reduced LML (110 mm) compared with the control site (120 mm). The average release period for the first group was 416 days, and for the second group, 417 days.

Size at maturity:

Size at maturity samples were collected in September 2012, November 2013 and May 2014. In the Southern pair of sites (Sites 1 and 2), the mean size at maturity over the sampling period was 81.6 mm, while further north at the Points in Cuvier Bay (Sites 3 and 13) it was 85.8 mm, and was smallest in the Northern sites (Sites 5 and 6) at 78.4 mm (Fig. 8). There were no differences in size at maturity within the control and impact pairs that could be considered consistent with increased growth rates at the impact sites following density reduction, and the differences observed appeared to be due more too random variation associated with sampling bias. The size-structure of each size at maturity sample is shown in Appendix 5.

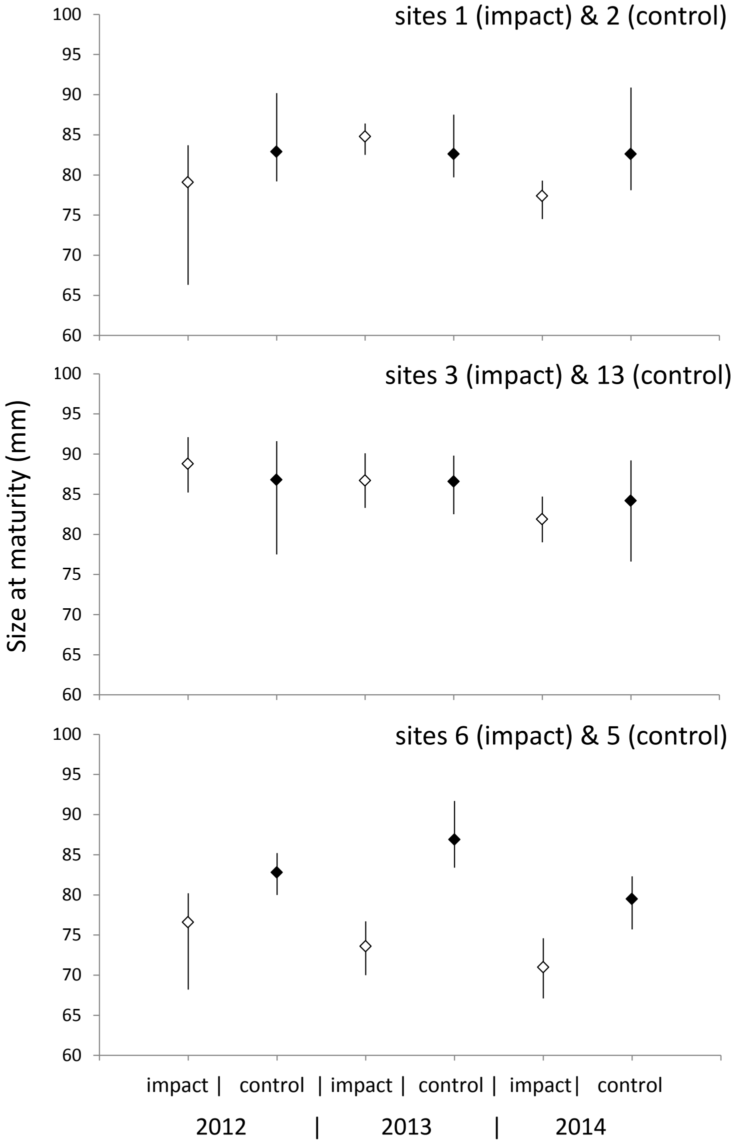

Fig. 8. Size at maturity from samples collected at impact sites (white marker) and control sites (black marker) in 2012, 2013 and 2014. Vertical bars indicate bootstrapped 95% confidence intervals.

2.3.3 Abalone Quality

Blacklip abalone from Hunter Island are generally of lower grade than from other parts of Tasmania (A. Hansen, pers. comm.), and for many years when caught at larger LMLs, have produced recovery rates of approx. 35% processed shucked weight to landed weight.

Recovery rates from abalone caught during fishdown (June 2013) at the 110-mm permit LML ranged between 33.9% (Site 6) and 35.9% (Site 3) (Table 1). Meat grades were not recorded. Post-fishdown (May and November 2014) recovery rates ranged between 36.0 and 36.9%. Although marginally greater than the fishdown rates, they are not regarded as significant by TSF, who ascribed the differences to a combination of effects such as seasonal variation and minor differences in processing procedures, and regarded them as within the range normally encountered with product from this part of the State.

In November 2014, two samples, one from each of the impact sites (combined) and the control sites (combined) yielded almost identical recovery rates and meat grades. Despite the similar grades, TSF considered that the meat quality from the control sites was superior to that of the impact sites. Shells from all the catches were described as very thick and scarred.

Table 1. % processed shucked recovery and % meat grade (% A grade, % B grade) from blacklip abalone caught at the study sites during the fishdown process (June 2013) and after the fishdown (May 2014, November 2014). All abalone were caught at the 110-mm permit LML.

Period	Site	Treatment	Kg	% shucked recovery	% A grade	% B grade
Jun-13	1	impact	5,205	35.3	-	-
Jun-13	3	impact	754	35.9	-	-
Jun-13	6	impact	3,984	33.9	-	-
May-14	2	control	144	36.9	84.4	15.6
Nov-14	1, 3, 6	impact	517	36.4	92.0	8.0
Nov-14	2, 13, 5	control	443	36.0	91.0	9.0

2.4 Discussion

The study failed to detect any increase in growth rates, size of maturity or improvements to fish quality following density reduction of abalone stocks on Hunter Island reefs, suggesting that these biological attributes are not dependent on the density reduction of large mature animals. This contrasts with the expectations of Tasmanian Seafoods Pty Ltd (the project proponents) who had anecdotal evidence of density-dependent responses among blacklip abalone in the region, and with a study of emergent wild greenlip abalone in South Australia where thinning a population caused the remaining abalone to grow faster (Dixon and Day, 2005). It also contrasts with the results of a survey of blacklip in the Hogan and Kent Groups (Tasmanian Bass Strait fishery), where size at maturity appeared increased followed high levels of fishing mortality and reported density reduction (Tarbath, 1999). The results are however similar to those of McShane and Naylor (1995a), who were unable to detect any differences in growth rate of *H. iris* between high-density and low-density aggregations.

The abalone densities at Hunter Island were elevated compared with those found in other productive parts of the fishery (Mundy et al., 2006) and overall abalone were smaller. The growth rates presented in this work are among the lowest recorded for blacklip in Tasmania (Helidoniotis and Haddon, 2013). During the fishdown process, the number of abalone ≥ 110 mm at the impact sites was reduced by approximately two thirds, to approximately one abalone every three square metres, while density of abalone < 110 mm remained at approximately $1/m^2$. This suggests that the experimental fishing process employed by this study was successful in reducing stock density above the permit legal size without impacting sublegal densities. Further commercial fishing at 120 mm followed our population counts around the study sites, thus the final effect of the density reduction of legal sized abalone is likely greater than presented here, but not defined. This experiment was conducted to meet the expectations of wild fishery management and was therefore constrained to maintain levels of spawning biomass and by practical limitations such as fishing costs and a time frame of three years. If the level of density reduction and time frame effected at Hunter Island in this study was insufficient to significantly increase growth and quality, then on a broader scale, as a fisheries management tool the method would not be a viable option.

It must be considered that factors other than density, and including shell parasites and food quality may limit abalone growth and quality at Hunter Island. It was noted that the shells from Hunter Island, particularly those from emergent abalone, were thick and brittle, and in parts riddled with small holes. In 1995, an investigation by the Tasmanian Department of Primary Industry and Fisheries found that blacklip abalone from the north-west region of Tasmania, including Hunter Island, had disproportionally high loadings of parasitic spionid polychaetes (polydorids) compared with those from other parts of the fishery (M. Lleonart, pers.comm.). These parasites bore holes and live within the shell matrix (Shepherd and Huchette, 1997), which can result in infested abalone growing more slowly, as they devote more energy to shell repair (Shepherd and Breen, 1992). As a result of this shell repair, shell thickness increases compared with un-bored shells (Marshall and Day, 2001) and heavily infested abalone had lower meat weights (i.e. lower meat recovery) than lesser infested abalone (Kojima and Imajima, 1982; McDiarmid et al., 2004). Consequently, polydorid shell parasites maybe a key driver limiting growth rates in this region but was untested within this project.

In addition, growth rates in this part of the fishery may be affected by food quality. Differences between algal communities at the Hunter Island locations and sites with comparable exposure in other parts of Tasmania where faster blacklip growth rates were observed and qualitatively noted. In particular, the shallow reefs at the Hunter Island study sites were frequently covered in sediment, with brown turfing algae and *Cystophora* spp. dominant (Appendix 3). In food trials involving a range of brown algae, *Cystophora* spp. were least preferred (Shepherd and Steinberg, 1992). In contrast, at faster-growing blacklip reefs elsewhere in Tasmania, we have observed that *Phyllospora comosa* with a red algae understorey is most common. Red algae have been associated with faster growth rates among blacklip (Cropp, 1989; Hone et al., 1997), although brown algae (particularly *P. comosa* and *Durvillea potatorum*) may form a greater part of their diet (Guest et al., 2008). Consequently, it is possible that abalone growth rates at Hunter Island may be supressed because of reduced nutrition, and that improving access to greater quantities of food by lowering population densities was not an appropriate means of increasing growth rates there.

Finally, it may take longer for density-dependent effects to appear than anticipated. The period between the fishdown and the final collection of samples in November 2014 may have been too short for improved growth and quality to become apparent. The slow growth rates observed in Hunter Island blacklip may mean that an extended period of time is required for these abalone to grow through and show a response to density reduction. It is however noted though that this is inconsistent with thinned populations of stunted greenlip which showed improved growth after six months (Dixon and Day, 2005), and translocated pinto abalone (*H. kamtschatkana*), which responded after eight months (Emmett and Jamieson, 1988). In addition, there are anecdotal reports involving translocated blacklip in other parts of Tasmania that have shown changes in growth rate during periods of less than one year, and increased growth in transplanted South Australian blacklip after 6 months (Saunders et al., 2009b). Notwithstanding this the Tasmanian Abalone Industry have requested that low-level sampling at Hunter Island be maintained for the next few years, so if there is a density-dependent response, it should become apparent in time.

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3. Developing a statistical tool for the determination of shell grade

3.1 Introduction

The maximum size and shell shape of blacklip abalone (*Haliotis rubra*) varies across a range of geographic scales, and is considered to reflect the suitability of environmental conditions for somatic growth (Saunders et al. 2009b). Isolated populations or larger areas with sub-optimal conditions show different shell characteristics, and commonly reach a smaller maximum size and have lower growth rates. The legal-sized abalone in these areas frequently have a higher profile shape, characterised by higher, wider and thicker shells. These populations are often referred to as ‘stunted’ populations by fishers. Typically, the inference is that the Legal Minimum Length (LML) in place for these slow growth populations is too high, preventing fishing of substantial quantities of abalone below the LML and leading to underutilisation of the resource (Day et al., 2005). In Tasmania, most of these populations are in the Northern and Bass Strait blacklip fishing zones and the northern parts of the Eastern and Central Western fishing zones. The biological and environmental processes that control and possibly limit growth are not fully understood, and it is not clear whether stunted abalone have a characteristic shape throughout their size range (i.e. an inherent shape), or whether stunted abalone are merely abalone with an altered shell shape due to natural ageing processes (i.e. the LML restricts access to a window of older age classes than faster growth areas).

Quantitative definition of chronological age has only been achieved in abalone by the use of stable oxygen isotopes (Gurney et al., 2005; Naylor et al., 2007) but this technique is significantly limited by procedural costs and shell quality requirements prevents application to older animals and populations with degraded shells. The need for establishment of guideline ages in abalone is essential as maturity and subsequent spawning potential is principally determined by age, not length (Prince et al., 2008). Prince et al., (2008) argued that abalone showed predictable changes in shape and appearance at various stages in life from emergence through to full maturity. Newly emerged abalone were flat, oval in shape and relatively free from epibenthic growth, while older fully mature abalone are rounder and bowl-like in response to a decrease in length increase and an expansion in volume of the shell to incorporate reproductive organs (Prince et al., 2008; Saunders et al., 2009a). Experimental evidence for a relationship between abalone shell shape and growth rate is rare. However, a recent study (Mayfield and Saunders, 2008) explored the biology and ecology of adjacent fast and slow populations on mainland Australia and found significant variation in shell length (SL) to height ratios (SH) associated with fast and slow growth rates. They developed a diagnostic tool which categorised stunted abalone populations as having a mean SL:SH < 3.25 while non-stunted populations were >3.25. The use of SL:SH removes some of the effects of shell size on defining shape, however ratios are still subject to size-dependent changes in shape because shape changes with size as the animal grows, i.e. changes allometrically (Lleonart et al., 2000). Abalone maturity is principally determined by age, not size, so any diagnostic tool should be independent of shell size. The effects of allometric growth can be removed by the use of standardisation techniques which then allow comparison of individuals and populations shape independent of size (Lleonart et al., 2000).

Prince et al., (2008) used a qualitative visual assessment of shell shape and appearance to define shell age as a basis for small-scale population management. Although this technique did not provide chronological abalone age, the authors argued that this rapid assessment of shell age provided a cost-effective means of assessing large numbers of abalone at population scales, and assisted in developing small-scale management processes. A similar technique of grading abalone shells is also used by Tasmanian Seafoods Ply Ltd (TSF) in Smithton, Tasmania to assist in determining abalone quality and they have promoted this method as a tool for evaluating the appropriateness of current size limits and catch levels in slow-growth areas.

This project investigates the proposed use by TSF of phenotypic variation in shell morphology as a fishery performance measure with dual use as an indicator of appropriate LML and TACC. Currently morphology and shell grade assessment is subjective in nature and there is a need to develop a quantitative diagnostic tool to assess shell grade based on external features. To develop an effective method of defining shell grade we started by testing the repeatability of the TSF shell-grading technique. We then examined a series of abalone shells for evidence of allometric growth. From this initial analysis we developed and tested a range morphometric models using shell ratios and standardised shell dimensions to validate the TSF shell grade method. Finally, after evaluating the best performing shape models against the TSF model we used the results to develop a quantitative model for assessing how shell shape varies with shell length.

3.2 Method

3.2.1 Field operations

This work was conducted in the north-western coastal waters of Tasmania, Australia at Hunter Island (40^0 31’39E, 144^0 45’16S) (Fig. 9). Three pairs of sites were selected on the west coast of Hunter Island. Sites 1 and 2 were collectively termed the ‘Southern’ region of Hunter Island, Sites 3 and 13 the ‘Points’ region and Sites 5 and 6 the ‘Northern’ region. Abalone (*n*=1190, ≈ 200 per site) were collected as part of the 2012 size at maturity sample outlined in the previous chapter (Section 2.2.1).

3.2.2 Tasmanian Seafoods grade classification

All shells were sent to TSF for classification into three shell grades (NEW, MODERATE or OLD). Allocation of category by TSF was based on the following criteria:

1. Appearance of the outside of the shell e.g. amount of growth of epiphytes and epifauna (low, moderate, high).
2. Thickness of the leading edge of the shell (thin, moderate, thick).
3. The extent of the shell scar (circumference) and depth against new shell layers (small scar, medium scar, large scar).
4. Internal appearance of the shell outside of the scar area, including colour of the shell (bright, moderate, dull), evidence of ridging (waviness in young shells), over-growth by new layers on the underside of the shell, presence of dark blotches.
5. Extent of shell doming (flat, moderate, domed).

Following classification the shells were soaked in a weak solution of swimming pool chlorine for one month to remove epifaunal and epifloral growth.

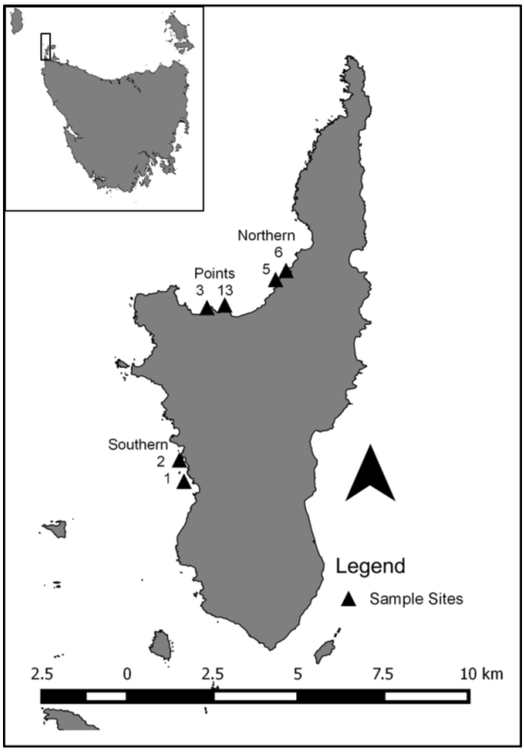


Fig. 9. Blacklip abalone sites around Hunter Island (Tasmania) used within this study. Sites are paired by region (Sites 1 and 2 =Southern region, Sites 3 and 13 = Points region, Sites 5 and 6 = Northern region).

3.2.3 Measurement of shell dimensions and allometric growth

To examine differences in shell morphology across nominal age grades (NEW, MODERATE and OLD), approximately 35 shells from each grade were randomly selected from each site for detailed analysis. The selected shells ($n \approx 105$ per site) were scanned by a high definition 3D scanner (LMI Technologies, Canada). Shells were mounted on an automated rotary board and scanned 12 times through 360° on the ventral and then dorsal surfaces. The subsequent 24 dorsal and ventral scans were combined and saved as .ply files (FlexScan3D software, LMI Technologies, Canada). Prior to each scanning session the 3D scanner was calibrated against a 10-mm calibration grid. Sequential scans were performed until the calibration range coverage exceeded 75 % and a re-projection error of < 24 µm obtained. Verification of scanned shell measurements was achieved by taking a sub-sample of shells from each site (n=60) and measuring each shell axis by hand using digital vernier callipers, tape measures and digital measuring boards (SciElex, Tasmania).

Data analysis of .ply files was performed using the R statistical package (version 3.0, 2013). Measurements of shell parameters were obtained by automating measurements of the 3D shell images in R using packages gdata (Warnes et al., 2004), reshape (Wickham, 2014), MASS (Ripley et al., 2002) and ordinal (Christensen, 2013) and custom functions. The digitally obtained dimensions were shell length (SL), shell width (SW), shell height (SH), and shell thickness (STh) with additional hand-measured variables of curved length (CL) and curve width (CW) (Fig. 10). To calculate SL, SW and SH the shell must be consistently oriented. When measured conventionally by hand, the shell is placed on a flat surface and its natural resting position defines one axis (SH), and the remaining axes are defined by the shortest length perpendicular to SH (SW) with the remaining axis perpendicular to both of these (SL). This process cannot be easily reproduced from a 3D scan as the resting position of a shell depends in part on its weight distribution. This also highlights a potentially undesirable aspect of conventional measurements where slight protrusions on the shell edge and growth (hence weight) on the side of the shell can fundamentally alter the definition of the measurements. The 3D scans were systematically aligned using principal components analysis (PCA). This aligned the first axis with the direction of greatest variation in the data (SL), the next axis perpendicular to this with as much variation as possible (SW) and the remaining axis perpendicular to both of these (SH) (Fig. 10). The dimensions SL, SW and SH were calculated as the maximum difference between points on each axis after removing the most extreme 0.1% of points at either end (to remove outlying points due to the scanning process). A two dimensional grid of 1 mm x 1 mm resolution was then created in the dimensions defined by SL and SW (to which SH is perpendicular/normal). The 'heights' (i.e. position in the perpendicular axis) of each 3D point were then allocated to the cells in this grid. In each grid cell the difference between the highest and lowest points was taken as a measurement of the shell thickness at that point. After removing outliers (thicknesses exceeding 10 mm) the median thickness over all grid cells containing data was used as a measure of the shells overall thickness (STh). CL and CW were measured as the curved distances on the dorsal shell surface from along the same axis as SL and SW respectfully (Fig. 10). A paired T-test was used to test for differences between 3D scan-generated measurements and hand-measured variables for SL, SW and SH.

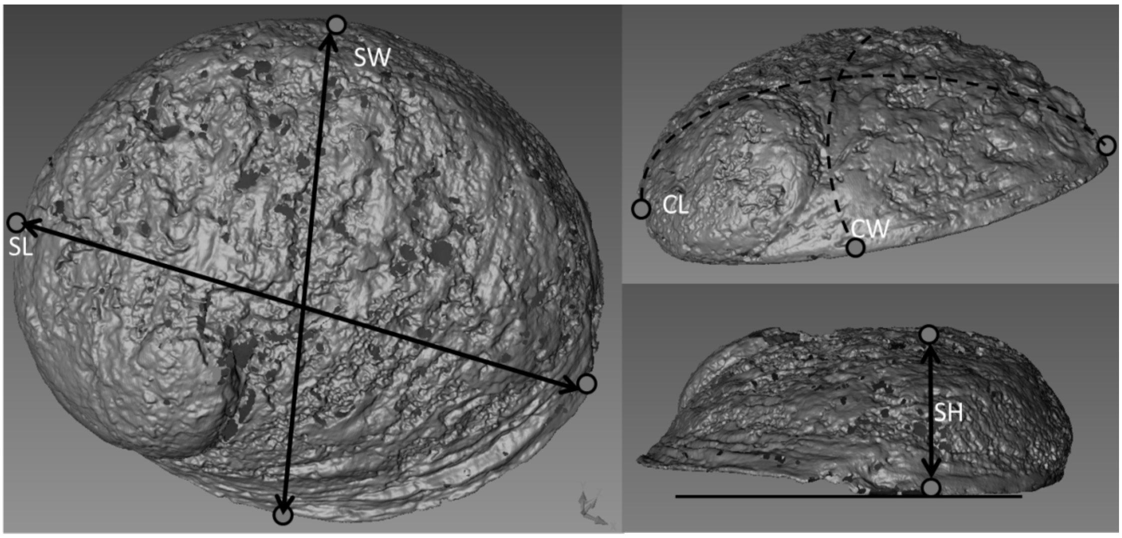


Fig. 10. Shell dimensions of blacklip abalone used within this study. SL = shell length, SW = shell width, CL = curve length, CW = curve width, SH = curve height. Shell thickness (STh) (not shown) is the median thickness of shell calculated as the difference between minimum and maximum values on the Y-axis at each digitised point across the shell.

Presence of allometric growth was assessed by testing for significant differences between shape vectors of SL, SW and SH scaled to a shell size (log 10 geometric mean of SL) (Claude, 2008).

$$Z = 1/g(X) \text{ x } \varepsilon \qquad (1)$$

Where; Z is the shape vector of one of the three shape dimensions, X is the vector of distance measurements, and $g(X)$ is the size function (Claude, 2008). A one way analysis of variance (ANOVA) of size variation explained by the log-shape vectors provides a test for isometry (Claude, 2008).

3.2.4 Testing TSF shell grade

Consistent classification (repeatability) of shells via the qualitative shell-grade classification process is an essential requirement if it is to be used as a fishery performance measure. Repeatability of the visual shell-grade classification (NEW, MODERATE, OLD) using the TSF method was assessed by comparing the classification results of two shell graders. Within-grader agreement was determined by single blind grading of the same set of shell twice, with percentage agreement assessed. Between-grader agreement was determined by providing two TSF staff with the same set of shells. The two graders were TSF staff who had been responsible for grading shells at TSF for many years. Neither of the graders had any knowledge of the other graders results i.e. they operated independently. Both between-grader and within-grader precision were examined by percentage agreement.

3.2.5 Transformation of shell dimensions to remove scaling effects

Due to the influence of size (shell length) on shape, transformations of shell dimensions were used to remove scaling effects. The first transformation used ratios of shell dimensions (SL:SH, SL:CL, SW:CW). In the second transformation, shell dimensions were normalised to SL using the formulae provided in Lleonart et al., (2000).

$$Y_i{}^* = Y_i\,[X_o/X_i]^b \qquad (2)$$

where; $Y_i{}^*$= normalised variable, Y = variable of interest for each shell (e.g. shell height), X = body size (e.g. SL of each shell), $X_0 = \bar{x}$ of SL for that region, X^b = is the slope of the linear regression of SL against the variable of interest:

$$\ln Y = \ln a + b \ln X + \varepsilon. \qquad (3)$$

Each normalised dimension was assigned the prefix Y; i.e. normalised shell height = YSH, shell width = YSW, shell thickness = YSTh, shell curve length =YCL, shell curve width =YCW.

3.2.6 Quantification of TSF shell grade by shell dimensions

The predictability of TSF shell grading was analysed against shell ratios (SL:SH, SL:CL, SW:CW) and normalised shell dimensions (YSH, YSW, YCW, YCL, YSTh, SL:YSH) using discriminate function analysis (DFA). DFA provides a prediction of categorical dependent variables (TSF shell grade NEW, MODERATE, OLD) based on a series of independent variables (e.g. shell ratios and normalised shell dimensions). DFA was applied by using a cross-validation procedure where the dataset was divided into two sub-samples (one site from each of the three regions), with one sub-sample used as a statistical predictor and the other sub-sample use to test predictive performance. For this purpose the control sites from each pair of Hunter Island sites (sites 2, 13, 5) were used as the statistical predictor to build a training set of ratios and normalised shell dimensions for each shell grade (NEW, MODERATE, OLD). The training values for each shell dimension or ratio for the three shell grades (NEW, MODERATE, OLD) was then applied to the experimental site in the pair (sites 1, 3, 6) to test predictive performance. The percentage of correct shell grade recorded in the experimental sites along with overall percentage accuracy was then used as a gauge of model performance. Stepwise regression of independent variables was then applied across all combinations of variables to find the optimum performance measure for defining TSF shell grade.

Proportional contribution of shell grade at SL was determined by regression of binomial proportions (NEW/OLD) by 1-mm size class using a logistic regression fit with Ld_{50} (50 % OLD shell) described by bootstrapped (1000 iterations) function. Lower (2.5%) and upper (97.5%) confidence intervals for the midpoints (Ld_{50}) were estimated by bootstrap resampling the original data 200 times. SL at 75 %, 90 % and 99 % OLD shell were also calculated. One way analysis of variance (ANOVA) was used to detect differences in shell dimensions between regions. Linear regression of shell dimensions against SL was used to assess change in shell shape with size and assess differences in slope and intercept between locations.

3.3 Results

3.3.1 Measurement of shell dimensions, ratios and allometric growth

Comparison of hand measured dimensions and digital derived dimensions generated from the .ply files returned significant differences in paired T-test for SL (t_{333}= 4.48, p = <0.001), SW (t_{333} = 4.78, p = <0.001) and SH (t_{333} = 4.34, p = <0.001). Mean difference between methods for each dimension was <0.3 mm (SL = 0.26 mm ±0.12, SW = 0.23 mm ±0.10, SH = 0.12 ±0.05) suggesting that although the measurements differ significantly between methods, the scale of the difference was negligible. Furthermore, there appeared to be no inherent bias in the methods and the significant paired T-test is a function of high levels of replication (n = 334). All further morphometric analysis was therefore based on digitally derived dimensions. Mean SL:SH ratio of shells > 110 mm was 3.23 but significant variation was evident between the three locations (ANOVA =$f_{2,233}$= 19.44, p<0.001) with Northern = 3.04 ±0.03, Southern = 3.13 ±0.03, Points = 3.27 ± 0.03. Scaled shape vectors of SL, SH, SW significantly varied with shell size (ANOVA =$f_{2,547}$= 172.12, p=<0.001), indicating significant allometric growth in blacklip abalone.

3.3.2 Testing of TSF shell grade

The TSF methodology for shell grading indicated a strong ability to identify NEW shells (between reader agreement 98 %), but agreement levels decreased for MODERATE (55 %) and OLD shells (10 %) (Table 2).

Table 2. Percentage of agreement between reader categorization of blacklip abalone from Hunter Island (*n=100)* using grades defined by Tasmanian Seafood's (TSF). Standard deviation in parentheses. Graders 1 and 2 were TSF employees.

Grading	Grader1	Grader 2	% agreement
New	41	40	97.6
Moderate	56	31	55.4
Old	3	29	10.3
Mean (s.d)	-	-	54.4 (43.6)

Overall there was only 54 % agreement between the two graders on shell grades per batch. Within reader treatment, where a single grader graded the same set of shells (*n*=110) found a mean agreement of 71.4 % with the lowest agreement level in the OLD category (50 %) (Table 3).

Table 3. Percentage of agreement of within-reader categorization of blacklip abalone from Hunter Island using grades defined by TSF. Standard deviation in parentheses.

Grading	Grading 1	Grading 2	% agreement
New	19	16	78.9
Moderate	75	54	85.3
Old	15	30	50
Mean (s.d)	-	-	71.4 (18.8)

3.3.3 Quantification of TSF shell grade by shell dimensions.

Discriminant Function Analysis (DFA) was applied to shells from the three control sites (Sites 2, 13, 5) as a training model (n= 253) to predict shell grade in the paired experimental sites (Sites 1, 3, 6, n= 234). Stepwise regression of variables suggested that the best representation of TSF grade was found in model YSH + YSW + YSTh where predictability of TSF grade class was 59.8 % (Table 4).

Table 4. Predictability of Tasmanian Seafood shell grade using discriminant function analysis (DFA) of blacklip abalone from Hunter Island using shell ratios and normalised measurements. Variables modelled: shell length: shell height (SL:SH) shell length: curve length (SL:CL), shell width: curve width (SW:CW), normalised measures of shell height (YSH), shell width (YSW), curve width (YCW), curve length (YCL), shell thickness (YSTh). Normalisation of shell dimensions was achieved using the formula given in Lleonart et al., (2000).

DFA	% correct
Shell ratios	
SL:SH	47.1
SL:CL	37.1
SW:CW	44.8
SL:SH + SW:CW	47.4
Normalised measurements	
YSH + YSW	51.2
YSH + YSW + YSTh	59.8

Within the YSH + YSW + YSTh model, predictability of NEW and OLD shells was similar (67.7 % and 66.6 % respectively), but predictability of MODERATE shells was lower (53 %) (Table 5). The second best model removed the YSTh argument leaving YSH and YSW with overall predictability of shell grade reduced to 51.2 % (Table 4). Model characterisation of OLD shells in this second best model was similar to that of the primary model of YSH + YSW + YSTh, but characterisation of MODERATE and NEW shell grades was significantly less (NEW 44.4 %, MODERATE 43.1 %) (Table 5). No model that contained raw shell-ratio data (e.g. does not account for allometry) provided a predictability of shell grade >50 % (Table 4).

Table 5. Success of discriminant function analysis (DFA) of blacklip abalone from Hunter Island separated by Tasmanian Seafood shell grade. Control shell sites (C.New, C.Moderate, C.Old) values (Sites 2, 13, 5 *n*= 253) were used as a training group to predict shell grade allocation in experimental site shells (F.New, F.Moderate, F.Old) (Sites 1, 3, 6 *n*= 234) with percentage agreement in parentheses. Variables modelled = normalised shell height (YSH), normalised shell width (YSW) and normalised shell thickness (YSTh). Normalisation of shell dimensions was achieved using the formula given in Lleonart et al., (2000).

Model	C.New	C.Moderate	C.Old
YSH + YSW + YSTh model			
F.New	42 (67.7 %)	17 (14.8 %)	0 (0 %)
F.Moderate	15 (24.2 %)	61 (53.0 %)	26 (33.3 %)
F.Old	5 (8.1 %)	37 (32.2 %)	52 (66.6 %)
YSH + YSW model			
F.New	28 (44.4 %)	14 (13.7%)	5 (7.2 %)
F.Moderate	32 (50.8 %)	44 (43.1%)	16 (23.2 %)
F.Old	3 (4.8 %)	44 (43.1 %)	48 (69.6 %)

3.3.4 Binomial model of shell grade

Models using YSH, YSW and YSTh were found to be the best shell dimensions for separating between NEW, OLD shells and MODERATE shells (Fig. 11). However, with predictability of allocating shell grade based on these variables below 60 % accuracy, alternative methods for the development of a statistical tool for shell grade were sought.

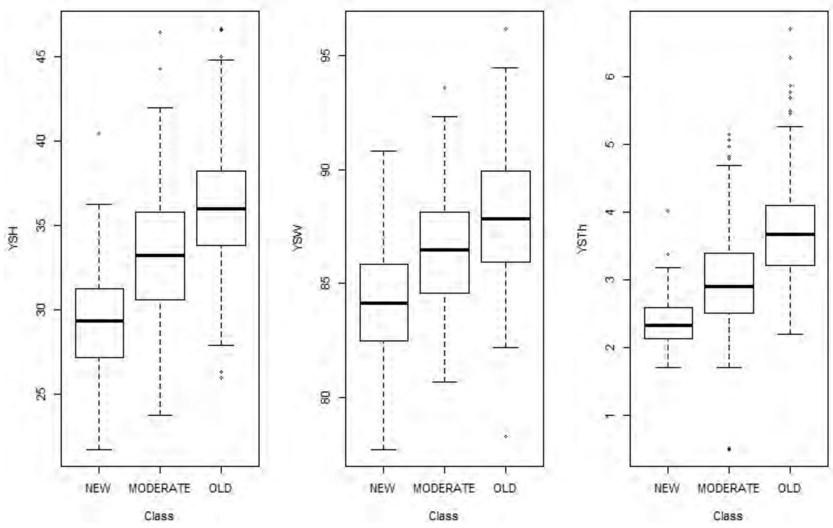


Fig. 11. Tasmanian Seafood Pty Ltd (TSF) shell grade (NEW, MODERATE, OLD) examined by shell dimensions (median, interquartile range, 2nd and 98th percentile and outliers) normalised by shell length using the method outlined in Lleonart et al., (2000). YSH = normalised shell height, YSW normalised shell width, YSTh = normalised shell thickness.

YSH +YSW +YSTh and YSH +YSW models were re-run with MODERATE grade shells omitted, in order to assess shell grade membership without the middle shell-grade category. In these model runs control sites (Sites 2, 13, 5, *n*= 152) were again used to train the model and tested against the experimental sites (Sites 1, 3, 6, *n*=142). Allocation of shell grade in the test sites was correct for 87 % of the shells (NEW =

80.8 % and OLD =90.5 %) in the YSH +YSW +YSTh model and 83 % of the shells in the YSH +YSW model (NEW = 72.3 % and OLD =88.4 %). This was significantly higher for both models than when MODERATE grade class was included. Both models were then trained on NEW and OLD shells (*n*=294) from all sites in order to reclassify TSF graded MODERATE shells (*n*= 193) as modelled NEW or OLD shells. Predicted group membership in the training dataset containing all NEW and OLD shells overall was 88.4 % for the YSH + YSW +YSTh model and 85.7 % for the YSH + YSW model (Table 6).

Table 6. Group membership of observed and expected values for blacklip abalone from Hunter Island based on discriminant function analysis (DFA). Observed grade class allocation was determined by TSF O.New and O.Old. Expected grade class allocation (E.New, E.Old) were modelled from shell dimensions. Shell dimensions modelled were normalised shell height (YSH), normalised shell width (YSW) and normalised shell thickness (YSTh). Normalisation of shell dimensions was achieved using the formula given in Lleonart et al., (2000).

Model	E.New	E.Old
YSH + YSW + YSTh model		
O.New	91 (82.0 %)	14 (7.7 %)
O.Old	20 (18.0 %)	169 (92.3 %)
YSH + YSW model		
O.New	82 (81.2 %)	23(11.9 %)
O.Old	19 (18.8 %)	170 (88.1 %)

Reclassification of TSF MODERATE shells to model NEW and OLD shell grades was dependent on the model used (Table 7). With the YSH + YSW + YSTh model 56 % of TSF MODERATE shells were reclassified as OLD while in the YSH + YSW model 65 % were reclassified as OLD (Table 7). In both models mean values for YSH and YSW for NEW and OLD shells were similar (Table 8).

Table 7. Allocation of group membership of Tasmanian Seafood moderate abalone (*H. rubra*) shells to NEW and OLD shell grades based on discriminant function analysis (DFA) modelled from shell dimensions. Shell dimensions modelled = normalised shell height (YSH), normalised shell width (YSW) and normalised shell thickness (YSTh). Normalisation of shell dimensions was achieved using the formula given in Lleonart et al., (2000).

Model	Model New	Model Old
YSH + YSW + YSTh model		
Moderate	84 (43.5 %)	109 (56.5%)
YSH + YSW model		
Moderate	67 (34.7 %)	126 (65.3 %)

Binomial regression of NEW and OLD shells by SL suggested that at Hunter Island 50% OLD shells are present at 101.6 mm (confidence intervals (99.8 – 103.1), 75% at 108.9 mm and 90% at 116.2 mm (Fig. 12). The interquartile distance (25% - 75%) spanned 14.4 mm (94.5 mm - 108.9mm), indicating a short SL transition from NEW to OLD shell.

Table 8. Mean values for NEW and OLD shell grades based on discriminant function analysis (DFA) modelled from shell dimensions, standard deviations given in parenthesis. Shell dimensions modelled were normalised shell height (YSH), normalised shell width (YSW) and normalised shell thickness (YSTh). Normalisation of shell dimensions was achieved using the formula given in Lleonart et al., (2000). * denotes significant difference at *p*=0.05.

Model	Shell dimension	NEW(sd)	OLD(sd)
YSH + YSW + YSTh	YSH	30.0 *(2.9)	36.0 *(3.4)
	YSW	84.5 *(2.5)	87.7 *(2.6)
	YSTh	2.4 *(0.4)	3.6 *(0.7)
YSH + YSW	YSH	29.6 *(2.8)	35.9 *(3.3)
	YSW	84.3 *(2.5)	87.7 *(2.5)

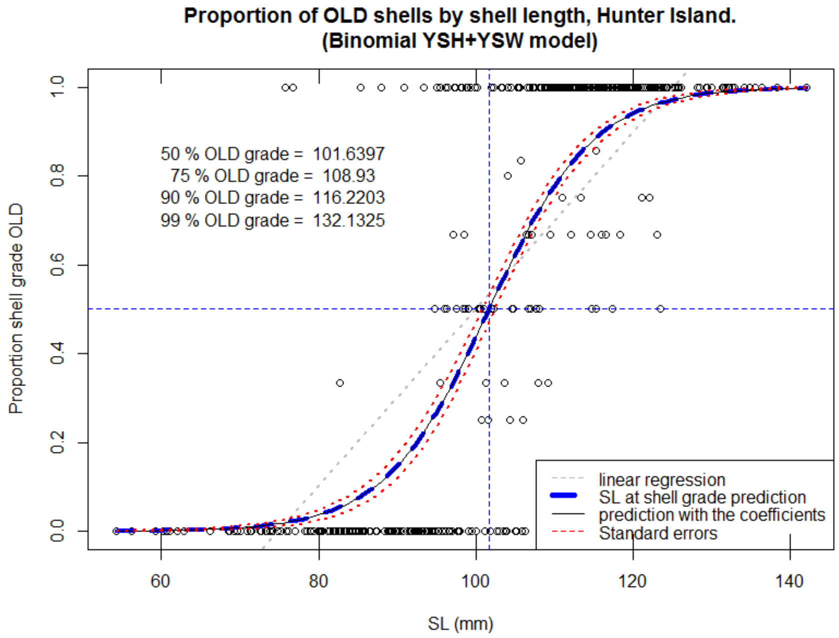


Fig. 12. Binomial regression of shell grade in blacklip abalone from Hunter Island in 2012, (n=550). Shell grade allocation determined from YSH + YSW model.

3.3.5 Allometric shape model

The binomial model (NEW/OLD) of shell grade provides an improvement over the multinomial TSF shell-grade models that include the MODERATE shell-grade classification. However, regardless of the statistical improvement achieved, the classification is still limited by its initial reliance on visually assessed shell categories to generate the training model and group allocation. We showed that reader agreement for TSF OLD shell categorization was low (Tables 2 and 3) and therefore any statistical model developed on the basis of this categorisation is weakened due to inadequate repeatability. In order to develop a quantitative model of shell grade categorization, a model independent of TSF grade classification was developed using the ratio of shell dimensions YSW and YSH. YSW:YSH ratio provides a size-independent method of assessing changes in shell shape. YSW:YSH showed no significant difference between locations ($F_{547,2}$ = 0.87, *p*=0.42) (Fig. 13) with a mean value of 2.64 (s.d. 0.36). YSW:YSH however, showed significant deviation with shell size ($F_{548,1}$ = 803.82, *p*=

<0.001) with the ratio decreasing with increasing SL ($R^2 = 0.59$) indicating a definable allometric change in shell shape with size (Fig. 14).

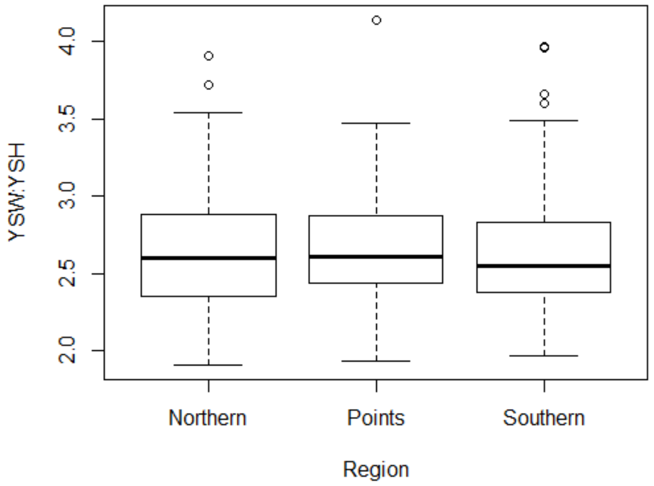


Fig. 13. YSW:YSH shell dimensions (median, interquartile range, 2nd and 98th percentile, and outliers) for blacklip abalone from Hunter Island. YSH refers to normalised shell height, YSW to normalised shell width. Normalised values were calculated using the method outlined in Lleonart et al., (2000).

Separation of Hunter Island data into locations and analysis of the YSW:YSH against SL revealed a statistical difference in shape between the Points region and the Northern and Southern regions ($F_{546,2} = 40.63$ p=<0.001). There is evidence of a common intercept between all regions which gradually diverges with increased SL with abalone from the Points region showing lower levels of decrease in YSW:YSH than the other two regions (Fig. 15).

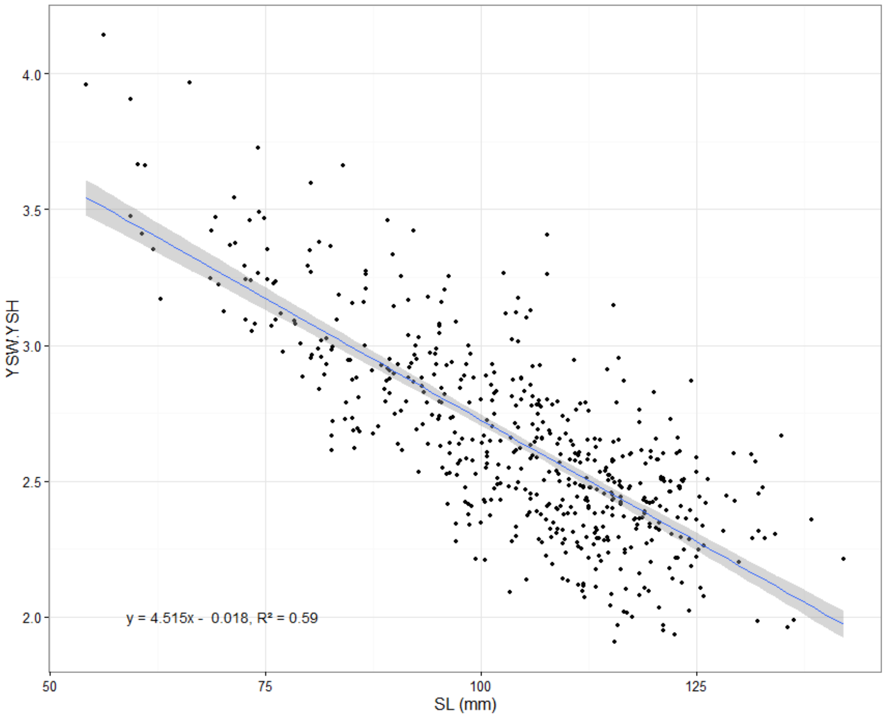


Fig. 14. Allometric variation in abalone shell shape with shell length (SL) for blacklip abalone from Hunter Island. YSW:YSH is the ratio of normalised shell width: normalised shell height. Normalised values were calculated using the method outlined in Lleonart et al., (2000). Grey banding represents standard error.

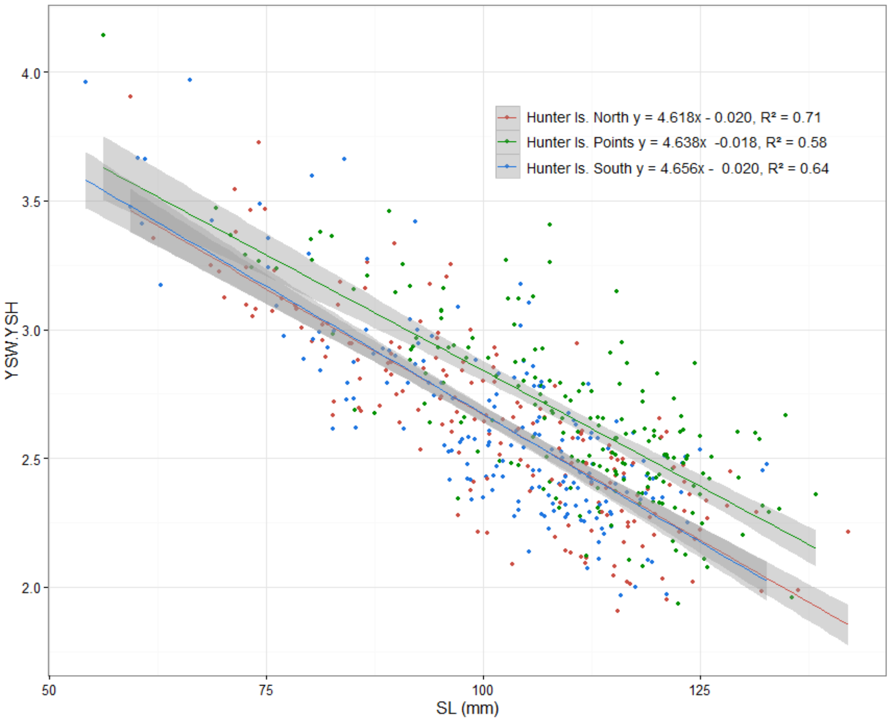


Fig. 15. Allometric changes in abalone shell shape with shell length (SL) for blacklip abalone from the three Hunter island regions. YSW:YSH is the ratio normalised shell width: normalised shell height. Normalised values were calculated using the method outlined in Lleonart et al., (2000). Grey banding represent standard error.

3.4 Discussion

This is the first study to use 3D scanning technology in the development and validation of morphometric based fishery performance measures. We found that automated, digital measurement of images derived from 3D scanning to be suitably matched to those measurements obtained by classic methods. As well as provision of accurate empirical measurements of shell shape, the 3D scan approach opens up further possibilities for shape assessment such as geometric landmark analysis, as well as the capacity to archive digital images rather than the storage of bulky physical specimens.

The Hunter Island region represents the lower end of the observed growth regimes present in Tasmania (Helidoniotis and Haddon, 2013). At two of the Hunter Island locations the SL:SH ratios were below the 3.25 ratio (Northern = 3.05, Southern = 3.13) threshold that separates slow and fast growth sites in South Australia (i.e. the Northern and Southern Hunter Island locations would be classified as ‘stunted’) (Mayfield and Saunders, 2008). The Points location of Hunter Island had a mean SL:SH of 3.27 (±0.03),classifying this area as having intermediate growth (Mayfield and Saunders (2009), intermediate growth SL:SH ratio =3.25 +1 s.e.). This is despite the relatively close proximity of the Points location to the Northern location (<2 Km), and being geographically intermediate between the Northern and Southern locations. As found in South Australia, substantial phenotypic variation has been identified among proximal locations, confirming fine-scale morphological variation can be found within geographically distinct regions (McShane et al., 1994; Mayfield and Saunders, 2008).

The substantial variation found in the grading of shells using the TSF method highlights problems associated with the subjective visual evaluation of shell quality, reducing its efficacy as a fishery performance measure for assessing an existing LML. The TSF method was acceptable for identifying NEW shells, but the interpretation of the boundaries between MODERATE and OLD shells was insufficiently defined and the principal cause of large discrepancies in shell class allocation. Stepwise regressions suggested models which contained standardised measurements of shell dimensions as the most reliable predictors of TSF shell grade. Of the models examined against the TSF shell grading, the best model incorporated standardised measures of shell height (YSH), shell width (YSW), and shell thickness (YSTh). The second best model fit dropped the YSTh term containing only YSW and YSH measurements.

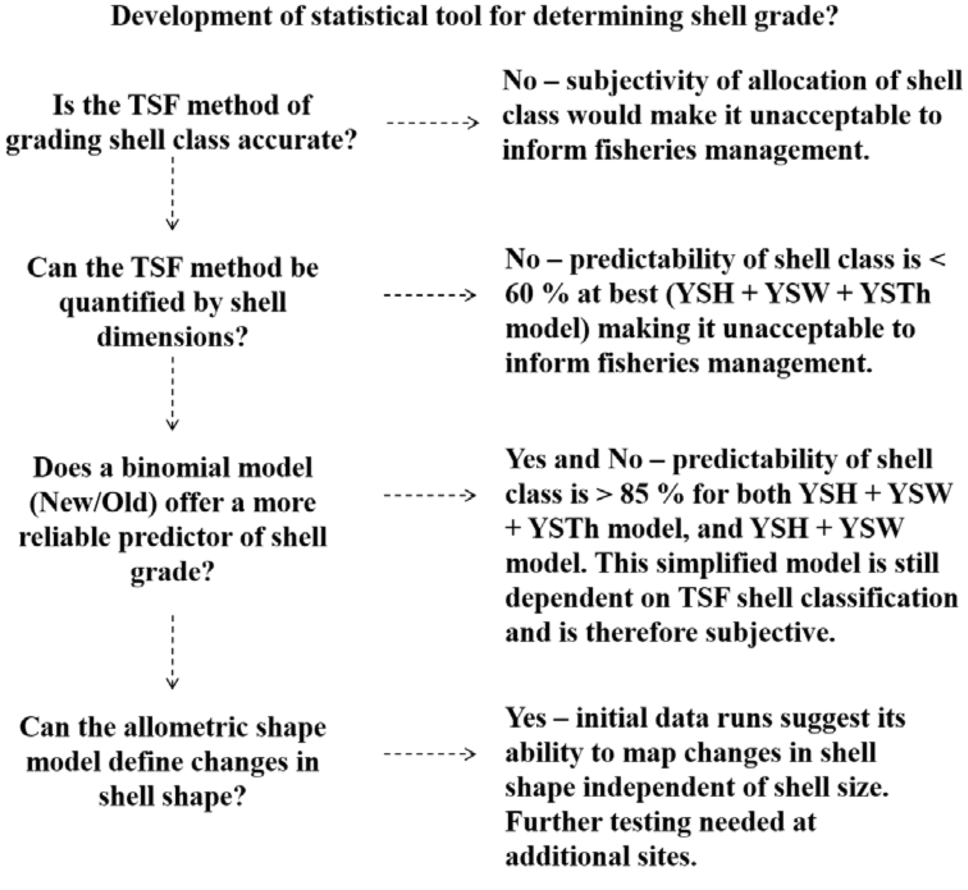
Shell ratio (SL:YSH) has previously used to define shape variation in blacklip abalone (Mayfield and Saunders, 2008) but this did not perform as well as other models where shell dimensions were standardised by SL. The YSH + YSW + YSTh achieved a level of predictability < 60 % for the three TSF shell grades. Given that the qualitative TSF within-reader agreement for shell grade was 72 % and between-reader agreement was 54 %, this highlights the model performance as providing a similar level of accuracy in distinguishing shell grade to the readers, and models could not be expected to perform any better given the TSF allocation limitations. The model analysis suggests that the subjective allocation of shell grade using the TSF visual grading approach restricts the fit of morphometric models of shell age. We conclude that TSF grade classification is insufficiently defined for fisheries management purposes, as are morphometric models based upon it.

While the YSH + YSW model did not perform as well as the YSH + YSW + YSTh model, developing a shell-grade based model using YSH + YSW would have significant advantages in field and factory applications over the YSH + YSW + YSTh model. The YSTh term in the primary model can only be produced from shucked abalone (which precludes its use where live abalone are required to be assessed). A key driver in the development of a diagnostic shell grade tool lies in its potential ability to offer a rapid method of measuring catch at abalone processing factories. Collection of this information needs to be quick, simple and cost –effective, but sufficiently robust to form a basis for management decisions. The YSH +YSW model has the capacity to be used in factories as it only requires three measurements (shell length, shell width and shell height), whereas median thickness (YSTh) used in the YSW+ YSH+YSTh model requires 3D shell scanning technology.

The binomial models of shell grade provided an improved fit to the TSF three-grade models because they use a defined numerical boundary between NEW and OLD shells. Distinct morphological variation in YSH, YSW and YSTh was evident between NEW and OLD shells and although the two models showed slight differences in predictability (YSH + YSW + YSTh > YSH + YSW) both were able to allocate NEW and OLD shells with predictability > 80 %. Using the YSH + YSW model, a binomial regression was fitted to assess percentage contribution of shell grade at 1-mm SL intervals. For example, the YSW+YSH binomial model applied to all Hunter Island sites indicated 50 % of abalone were graded OLD at 102 mm, while 99 % were OLD at 132 mm. However, the binomial model approach is still inherently limited by its conceptual roots reliant on the subjective allocation of shells to either NEW or OLD categories under the TSF classification system. The model is dependent on TSF shell categories to generate the training model and therefore unless the TSF system of classification can produce repeatable, objective results, the binomial model will remain subjective and its reliability questionable.

As an alternative to a visual grading system, a quantitative morphometric approach has considerable benefits including objectivity and a defendable scientific basis. In order to provide a quantitative model it was necessary to look at shell grade independent of the TSF methods. Prince et al., (2008) indicated that abalone showed predictable changes in shape and appearance from emergence through to full maturity. Newly emerged abalone are typically flat and oval in shape, while older fully mature abalone are rounder and bowl like (Prince et al., 2008; Saunders et al., 2009b). This shape change can be explained by erosion of shell margins when growth slows, and layering of nacre to repair/protect internal organs in the absence of linear extension of the shell. Prince et al (2008) also suggest that shell shape could be used as a marker of maturity and the evidence of allometric growth present in the shells of this study highlighted size-independent shape change. As YSW and YSH were considered the principal shape determinants in the models examined so far, a ratio of these two measurements was taken (YSW:YSH) to produce a model which defined shell shape into a single numerical value independent of SL. This is a similar approach to that of Mayfield and Saunders (2008) with their SL:SH ratio model, but offers an improved measure of shape by using a full allometric scale that is not compromised by shell length. The allometric shape model (YSW:YSH) represents high narrow shells with low values, while flatter and wider shells have higher values. The allometric shape model displayed a linear decrease with increasing SL signifying a change in shell shape from flat wide shells to higher narrower shapes with increasing size. These attributes have previously been observed (Prince et al., 2008), but never quantified until this study, and represent a linear incremental shift in shape.

The allometric shape model was able to separate abalone from the Hunter Island Points location from the other locations because of a slight lower rate of decline of YSW:YSH with increasing SL. That the model was able to detect this at such fine scale suggests a potential value in assessing abalone stocks. The common intercept of the regressions from the three Hunter Island regions suggests a common shape at an early age (SL > 50mm) (Fig 15). Common shape in early juvenile stages is probable as these populations are unlikely to be genetically isolated given their close proximity (Temby et al., 2007). It also proposes that the phenotypic divergence that appears between the Hunter Island locations is due to environmental conditions affecting growth (Temby et al., 2007; Saunders et al., 2009b). The linear path of YSW:YSH change in the model suggests shape is being determined at a very early stage of development (i.e. smaller than at onset of maturity) and therefore changing fishing practices at the high end of SL, i.e. by density reduction through a ‘fishdown’ are unlikely to elicit any changes in shell shape.



Development of statistical tool for determining shell grade?

Is the TSF method of grading shell class accurate? → **No – subjectivity of allocation of shell class would make it unacceptable to inform fisheries management.**

Can the TSF method be quantified by shell dimensions? → **No – predictability of shell class is < 60 % at best (YSH + YSW + YSTh model) making it unacceptable to inform fisheries management.**

Does a binomial model (New/Old) offer a more reliable predictor of shell grade? → **Yes and No – predictability of shell class is > 85 % for both YSH + YSW + YSTh model, and YSH + YSW model. This simplified model is still dependent on TSF shell classification and is therefore subjective.**

Can the allometric shape model define changes in shell shape? → **Yes – initial data runs suggest its ability to map changes in shell shape independent of shell size. Further testing needed at additional sites.**

Fig. 16. Model development process to generate a statistical tool for the determination of shell grade in blacklip abalone.

The linear shape change with increasing shell length (proxy for age) found in the allometric shape model highlights the issue of compartmentalising a linear variable such as shell shape into discriminant grades. By separating shells into grades that may include a large number of year classes, categorical models such as the TSF model and the binomial model reduce the ability to detect variation present within datasets, e.g. the variation in shape between Hunter Island locations observed in the allometric shape model. By removing the ability to detect small variances between populations, categorical models are unlikely to prove useful as a management tool (Fig. 16). In contrast, the allometric shape model offers a range of possible uses to understand how shape may change in response to either environmental factors, or in response to change in population density. For example, does the intercept, slope, or linearity change when LML is reduced or population density changes. It can also be used in the opposite manner: if a particular shell shape is desirable e.g. because of meat weight recovery, or appearance, this approach can identify the range in shell length that matches the desired criteria. The method for calculating YSW:YSH values is relatively simple because it requires only two measurements in addition to SL, and therefore requires little specialised equipment to allow processors and researchers to assess mean population shape at any given SL. The next stage in the development of the allometric shape model is to use it in comparisons between regions which exhibit different growth rates, which will provide evidence of how shell shape changes regionally, and how altered growth rates affect shell shape.

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4. The use of length-based models to test the adequacy of shell age performance measures

4.1 Introduction

Local-scale variation in key abalone population parameters (abundance, growth, recruitment) (McShane, 1995; Saunders et al., 2009b; Helidoniotis and Haddon, 2013), combined with high levels of self-recruitment (Miller et al., 2009) requires alternative approaches to broad scale fishery management. Local dynamics means application of classic stock assessment models to entire abalone fisheries requires assumptions and generalisations that are impossible to justify. Empirical fine-scale approaches to fishery management offer an opportunity to tailor management actions (size limits, spatial management) to break points along gradients of change across the scale of the fishery. To address the high heterogeneity among abalone populations, Day et al. (2005) suggest there is a need to manage stocks at reef-size scales to better utilise wild abalone stocks, provide protection for faster growth stocks and allow access to slow growth areas. While acknowledging the logic in this approach, inappropriate or ineffective scaling of management can lead to decreased protection for the most productive and valuable populations in the fishery which will be no better than broad-scale management. Key to the strategy of fine-scale management is understanding the productivity of stocks at individual reef scales, to determine the trade-offs between cost of fine-scale management and the realised economic benefit (catch rates, yield). If reef-scale management is to be considered, it requires collaborative efforts between management, research and industry (Mayfield and Saunders, 2008).

Diagnostic tools for the assessment of shell shape as methods of fine-scale population management have been proposed as possible options to assist classification of populations into groups with similar growth parameters (see Chapter 3 and Mayfield and Saunders (2008)). The key to such a tool lies in its potential ability to offer a rapid cost-effective method of sample collection which can be implemented through abalone processing factories, provided that the catch can be assigned to an individual location. This regular collection of data could then be used by researchers to assess fine-scale differences in the fishery and it may assist advisory councils to develop fast response management strategies. Development of methods of assessing abalone stocks within the processing factory setting may also prove to be more cost-effective than a strategic research program to collect information at local scales. Ultimately this may assist in increasing returns to the fishing industry, through collection of fine-scale data and more cost-effective research not available at current zonal/regional scales of management. From a yield perspective, a mis-match between regional legal minimum length (LML) and locally appropriate LML in slow-growth regions can lead to reduced meat weight recovery compared to faster growing regions due to increased shell weight. In many of these areas the larger abalone have heavy encrusted shells which are generally unsaleable in ‘live’ markets, and therefore attract a lower beach price. There is a need to find a LML that balances maintaining fecundity on reefs sufficient for future populations yet provides access to abalone with peak marketability.

The development of a doming index by Prince et al., (2008) and the proposed shell grade index (NEW, MODERATE, OLD) by Tasmanian Seafoods Pty Ltd (TSF) both seek to provide a rapid-assessment tool to produce such information. The binomial model developed from the original TSF concept and the allometric shape model (Chapter 3) offers a more quantifiable method of measuring morphology which may be suitable for fine-scale assessment of stock class. However, these models require testing outside the Hunter Island study area to determine their applicability to the wider fishery. Both the binomial regression model and allometric shape model have the ability to estimate shell shape or class at a given shell length and therefore may provide insight how shape or class will alter with changes in LML. Tasmanian size limits for blacklip are currently based on the two-year rule, where any population should have a minimum of two years post-onset of maturity before harvest (Tarbath et al., 2001). The current method of determining size limits requires growth-rate and size-at-maturity data which is resource intensive and costly (Tarbath, 2003b; Helidoniotis and Haddon, 2013), and financial and time constraints limit the ability to collect sufficient representative samples to determine the extent of variation across a fishery management area (Proudfoot et al., 2008). There is a database of size-at-maturity data available for the Tasmanian fishery, and theoretical estimations of LML from size-at-maturity data (i.e. that avoid the requirement for growth data) have been modelled (Helidoniotis and Haddon, 2013). If the allometric shape model is capable of defining a common shape at size at maturity and a linear shape change with SL, it could be used in combination with theoretical growth estimates to assess the suitability of current LMLs. This would also allow researchers to compare the shape difference between the current LML and theoretical LML, and subsequently provide information on the marketability of abalone should changes in LML be implemented.

Here we use the binomial and allometric shape models to assess co-variation in morphometry and population parameters at local and state-wide scales. Four approaches were used; a) the binomial model was applied at the two spatial scales to test its ability to correctly identify shell grade and suggest proportional contribution of shell grades by shell length; b) the same spatial scales were then used to assess the allometric shape model and determine whether measureable differences in morphometric characteristics are detectable at size at maturity and LML; c) differences in LML were explored that may affect the mean shape of abalone from each location; and d) shape at LML within a location was contrasted with shape at a theoretical model of LML based on size at maturity.

4.2 Method

4.2.1 Site selection

The initial development of the shape models focused on three reef locations of Hunter Island in the Northern Tasmanian blacklip fishing zone (statistical reporting block 49B) (Fig. 17). These primary locations comprised two pooled sites; Sites 1 and 2 from the ‘Southern’ location, Sites 3 and 13 the ‘Points’ location and Sites 5 and 6 the ‘Northern’ location. In addition to these three primary locations, seven secondary locations with a range of growth parameters were selected from elsewhere in the Tasmanian abalone fishery. Two of these secondary locations were in close proximity to the primary study area; Wallaby Pt (Hunter Island, 40.5065S, 144.7045E, stat. block 49B) and West Point (40.9451S, 144.6122E, stat. block 5C) (Figs 17, 18). While the remainder provided contrast between the primary locales and more distant locations within Tasmania; Northern Zone: (Swan Island, 40.7335S, 148.1270E, stat. block 31B), Western Zone: Black Island (42.9672S, 145.4938E, stat. block 10D), Louisa Bay (43.5231S, 146.3410E, stat. block 12D), and Eastern Zone: Actaeon Island (43.5339S, 146.9962E, stat. block 13E), The Nuggets (42.11547S, 148.3476E, stat. block 27D) (Fig 18). The Northern Zone locations of Hunter Island, West Pt and Swan Island are generally considered slower growth areas, while all other regions from the Eastern and Western zones are considered faster growing.

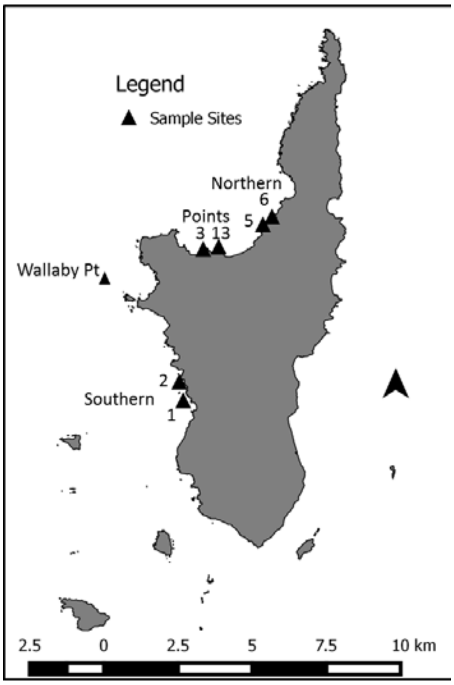

Fig. 17. Hunter Island sample sites.

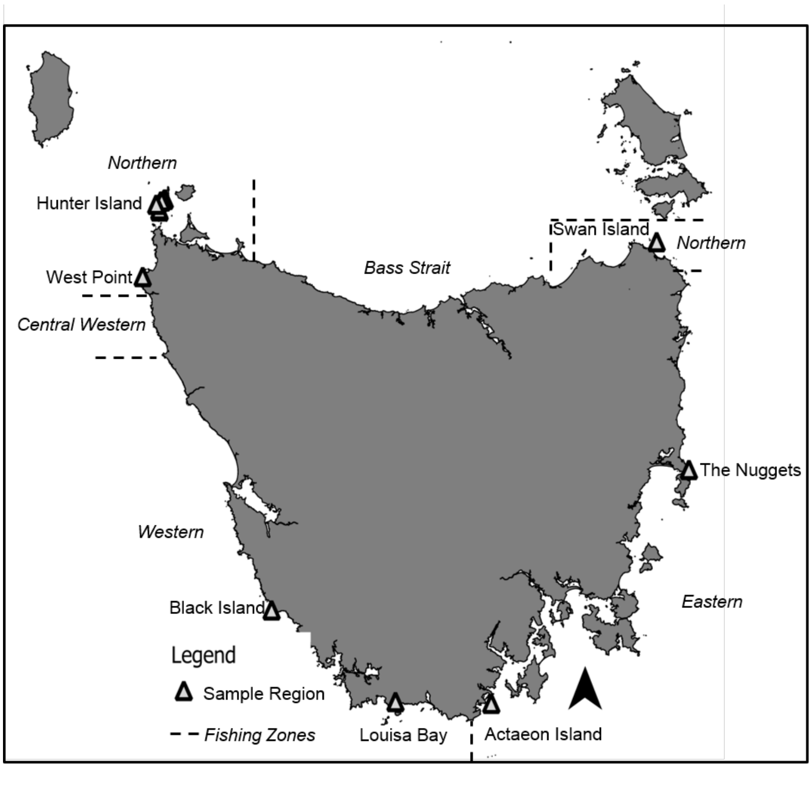

Fig 18. Location of the broad scale sites and the Tasmanian blacklip fishing zone boundaries.

Samples ($n \approx 200$) were collected from primary locations in 2012, while samples from secondary sites were taken from archive collections obtained between 2000 and 2003. The empty shells were cleaned by immersion in a weak solution of swimming pool chlorine for four weeks to remove some of the larger epifauna and traces of pedal muscle tissue. The cleaned shells were then measured for shell length (SL), shell height (SH) and shell width (SW) either by hand or using the 3D shell scanner (method in Chapter 3) (n =1781).

4.2.2 Statistical analysis

Data analysis was conducted in R (R Development Core Team 2013) using the packages MASS, (Venables and Ripley, 2002), ggplot2 (Wickham, 2009), car (R Core Team, 2014) and custom functions.

4.2.3 Size at maturity

Size at maturity in a population was defined as the size at which 50% (Ld50) of a representative sample showed mature gonad development i.e. where they were capable of reproducing and contributing to the population. Size at maturity was determined by regression of binomial proportions (immature/mature) by 1-mm size class using a logistic regression (Haddon, 2001). Lower (2.5%) and upper (97.5%) confidence intervals around the midpoints (Ld50) were estimated by bootstrap resampling the original data 1000 times. The method is described in full in Chapter 2.2 and in earlier reports (Officer, 1999; Tarbath, 1999; Tarbath and Officer, 2001). Distribution of data around size at maturity was examined by frequency histograms. Size at maturity is considered a response to growth rate in abalone (Day and Fleming 1992) and was used in this study to separate fast- and slow-growth regions. Regional differences in size at maturity were assessed through the comparison of overlap in 95% confidence intervals.

4.2.4 Transformation of shell dimensions to remove scaling effects.

SW and SH were normalised to SL using the formulae provided in Lleonart et al., (2000).

$$Y_i{}^* = Y_i\,[X_o/X_i]^b \qquad (1)$$

Where; Y_i is the normalised variable, Y is the variable of interest for each shell (e.g. shell height), X is the body size (e.g. SL of each shell), X_0 is the $\bar{x}$ of SL for all regions within the analysis (120.1 mm), b is the is the slope from the linear regression of SL against the variable of interest for the data within region:

$$\ln Y = \ln a + b \ln X + \varepsilon. \qquad (2)$$

Each normalised dimension was assigned the prefix Y, and therefore normalised shell height = YSH, shell width = YSW, and the ratio of YSW to YSH was calculated for each shell from these values.

4.2.5 Variation in shell shape with size and location – Binomial model

Discriminant function analysis (DFA) (Chapter 3.2.6) was used to predict SL at which contributions of OLD grade shell comprised 50%, 75%, 90% and 99% of the sample. Modelled variables for the determination of shell grade were YSH and YSW. The training data set from Hunter Island (n = 550) (Chapter 3.2.6) was used to allocate shell grade at each of the secondary locations. Proportional contribution of shell grade at SL was determined by regression of binomial proportions (NEW/OLD) by 1-mm size class using a logistic regression fit with Ld50 providing a SL at which 50% of the sample is OLD shell). SL at 75%, 90% and 99% OLD shell were also calculated in a similar manner.

4.2.6 Variation in shell shape with size and location – Allometric shape model

To assess variation in shape (YSW:YSH) between locations, data were analysed using one-way ANOVA, with locations as treatments (fixed effect). Data were transformed to meet assumptions of normality using BoxCox power transformation (YSW:YSH^1.4). When significant differences were identified, Tukey honest significant differences (Tukey HSD) were used to distinguish which locations were different from each other. To explore the relationship between shell length (SL) and shell shape YSW:YSH values were regressed against SL. Change in shell shape with SL was examined by linear regression and to assess homogeneity between slopes and intercepts between locations, type 2 sums of squares analysis of co-variance (ANCOVA) with locations as treatments (fixed effect) and SL (covariate) was applied.

Shape at size at maturity (SAMy) was calculated using the linear regression equation for that region

$$\text{SAMy} = \ln a + b \ln X + \varepsilon. \qquad (3)$$

where: a is the intercept, b is the slope, X is the size of maturity for that region, ε is the error term. 95% confidence intervals of size of maturity were used as X to estimate the confidence intervals around SAMy. Similarity between regions for SAMy was assessed by overlap between these confidence intervals.

Shape at LML (LMLy), was calculated in the same manner as SAMy with the LMLy term set at the LML prevailing at each site. LMLy ± 5 mm was also calculated for each site to assess change in shape around the LML. Mean LMLy (±s.e.) for the fast-growth regions (i.e. those from the Eastern and Western Zones) was calculated and used as a base value to calculate the SL at which slow-growth regions would have a similar shape. Location-specific linear regressions of YSW:YSH against SL (equation 3) were rearranged to calculate the SL required to achieve shape in the slow-growth regions similar to the mean LMLy of the fast-growth regions:

$$X = \ln(Y-b)/a \qquad (4)$$

where: X is the theoretical SL defined by shape (SL_{ty}), Y is the mean LMLy from the fast growth areas, a and b are the site specific intercept and slope from Equation 3.

4.2.7 Theoretical growth rate estimates and LML_{ct}

Growth rate estimates and corrected theoretical LML (LML_{ct}) were calculated from size-at-maturity data from each region using the method described by Helidoniotis and Haddon (2013). In brief, inverse logistic growth parameters for the estimation of LML_{ct} were derived from the following equations:

$$\text{L50}_T = 1.1539 * \text{Ld50} - 15.335 \qquad (5)$$

where L50_T is the is the initial length at 0.5 times the difference between maximum growth increment (MaxΔL) and lowest length increment. Ld50 is the size at maturity.

$L95_T = 1.0862 * Ld50 - 32.461$ (6)

where $L95_T$ is the initial length at 0.95 times the difference between maximum growth increment (MaxΔL) and lowest length increment. Ld50 is the size at maturity.

$Max\Delta L_T = 0.46095 * L95_T - 0.46856 * L50_T + 5.58943$ (7)

where $Max\Delta L_t$ is the theoretical maximum growth increment and $L50_T$ and $L95_T$ are calculated from Equations 5 and 6.

LML_{ct} for each sample required the calculation of expected length increment using the parameters $L50_T$, $L95_T$, and $Max\Delta L_T$, and the inverse logistic growth model:

$\Delta L_i = Max\Delta L_T/1 + \exp(Ln(19)((Ld50_i - L50_T)/(L95_T - L50_T))) + \varepsilon$ (8)

where ΔL is the expected length increment, Ld50 is the initial length (in this case size at maturity) and $L50_T$, $L95_T$ and $Max\Delta L_t$, are the values calculated from Equations 5, 6 and 7 and ε is an independent additive normal random error term. ΔL_1 provides an estimated SL increase from size at maturity plus one year's growth. To calculate LML_{ct} with two years growth from size at maturity, ΔL is added to Ld50 to create a new initial length (Ld50) after one year and Equation 8 is rerun to calculate a second year growth increment (ΔL). Finally, LML_{ct} is calculated by adding the second ΔL to the Ld50 after one year and applying the following correction factor:

$LML_{ct} = ((Ld50^b + \Delta L) - 16.8868)/0.8946.$ (9)

A full account of this method and the need for the correction factor is given in Helidoniotis and Haddon (2013). Lower and upper confidence intervals for LML_{ct} and growth increments were calculated from the size at maturity 95 % confidence intervals using the same Equations 5-9.

4.3 Results

4.3.1 Size at maturity

The smallest size at maturity was found in the Northern (80.6 mm) and Southern (81.5 mm) locations of Hunter Island (Table 9). Among Hunter Island locations, significant differences were evident between the Points and the Northern and Southern locations, and the Points and Wallaby Pt, but there was no difference evident between the Northern and Southern locations (Table 9). Across primary and secondary locations size at maturity varied, being largest in the Western Zone sites of Black Island (128.3 mm) and Louisa Bay (127.9 mm) (Table 9). Size at maturity from Northern Zone sites was significantly smaller than Western and Eastern Zone sites, with the exception of The Nuggets which was similar to Swan Island and Wallaby Point (Table 9). Binomial regression figures and histograms of size distributions for each region are given in Appendix 6.

Table 9. Size at maturity (SAM) and 95 % confidence intervals (C.I.) in blacklip abalone taken from 10 locations within the Tasmanian fishery between 2000-2012.

Zone	Location	Year	SAM	C.I. lower	C.I. upper
NORTHERN	HI Northern	2012	80.6	78.2	82.4
NORTHERN	Hi Southern	2012	81.5	77.3	84.3
NORTHERN	HI Points	2012	88.2	85.5	90.8
NORTHERN	HI Wallaby Point	2001	98.2	95.7	101.9
NORTHERN	West Point	2012	89.3	87.7	94.3
NORTHERN	Swan Island	2001	98.0	95.7	99.8
EASTERN	Actaeon Island	2001	119.6	116.0	123.3
EASTERN	The Nuggets	2000	101.3	96.6	105.5
WESTERN	Black Island	2003	128.3	124.4	131.5
WESTERN	Louisa Bay	2001	127.9	125.0	130.0

4.3.2 Variation in shell shape with size and location – Binomial model

Shell length at which 50% OLD grade shell was evident varied at both fine and broad spatial scales (Table 10). Within the original three Hunter Island locations (South, North, and Points), 50% OLD shell grade occurred at 99.7 mm, 103.3 mm, and 109.4 mm respectively, or 18.5 mm, 22.7 mm and 21.2 mm *larger* than size at maturity. At Wallaby Point, the 50% OLD grade shell was 90.9 mm, or 7.3 mm *below* size at maturity.

Table 10. Percentage of OLD grade shell at shell length (SL) (mm) of blacklip abalone from 10 Tasmanian sites. SAM = size at maturity, LML = legal minimum length, % OLD 5 mm LML = the percentage of OLD grade shell within 5 mm of the current LML. OLD grade shell was modelled using a discriminant function analysis (DFA), from shells from the three Hunter Island study locations (Southern, Northern, Points) based on standardised measures of shell width and shell height. The dotted line separates fine-scale and broad-scale regions. West Pt data is unavailable due to lack of binomial model fit.

Zone	Location	SAM	% OLD grade shell at SL (mm)				LML	% OLD 5 mm LML
			50 %	75 %	90 %	99 %		
NZ	HI Southern	81.5	99.7	105.7	111.7	124.8	120	>90
NZ	HI Northern	80.6	103.3	108.5	113.8	125.2	120	>90
NZ	HI Points	88.2	109.4	117.8	126.1	144.3	120	>75
NZ	HI Wallaby Pt.	98.2	90.9	94.9	98.9	107.7	120	>99
NZ	West Point.	89.3	-	-	-	-	127	-
NZ	Swan Island	98.0	90.7	95.6	100.5	111.2	127	>99
WZ	Black Island	128.3	101.7	108.2	114.7	128.9	140	>99
WZ	Louisa Bay	127.9	104.6	108.1	111.7	119.4	140	>99
EZ	Actaeon Island	119.6	110.9	116.1	121.2	132.4	138	>99
EZ	The Nuggets	101.3	108.6	113.0	117.4	127.1	138	>99

A similar trend of 50% OLD shell being below size at maturity was found in all other samples except The Nuggets (Table 10). In the Actaeon Island and Swan Island samples, size at maturity occurred at the 90% level of OLD grade shell. At Black Island, size at maturity occurred at 99% of OLD grade shell and at Louisa Bay at >99% OLD shell. West Point was not included in this analysis because the binomial model classified only four shells as NEW preventing fitting of the model. The percentage of OLD shell at the LML was found to be greater than 75% in all samples apart from the Hunter Island locations on which the model was based. Binomial regression figures of proportion NEW and OLD shell grades for each sample are given in Appendix 7.

Table 11. Significant variation in shape (YSW:YSH) between samples ($f_{9,1771} = 29.13$, p=<0.001) from Fig. 19. Tukey honest significant test difference values.

Location	Actaeon Island	Black Island	HI Northern	HI Points	HI Southern	HI Wallaby Point	Louisa Bay	Swan Island	The Nuggets
Black Island	<0.01	-	-	-	-	-	-	-	-
HI Northern	0.06	<0.01	-	-	-	-	-	-	-
HI Points	0.96	<0.01	0.75	-	-	-	-	-	-
HI Southern	0.28	<0.01	1.00	0.98	-	-	-	-	-
HI Wallaby Pt.	0.95	<0.01	<0.01	0.34	0.02	-	-	-	-
Louisa Bay	<0.01	0.68	<0.01	<0.01	<0.01	<0.01	-	-	-
Swan Island	0.14	<0.01	<0.01	0.01	<0.01	0.87	<0.01	-	-
The Nuggets	1.00	<0.01	0.01	0.72	0.08	1.00	<0.01	0.38	-
West Point	0.95	<0.01	1.00	1.00	1.00	0.52	0.01	0.05	0.81

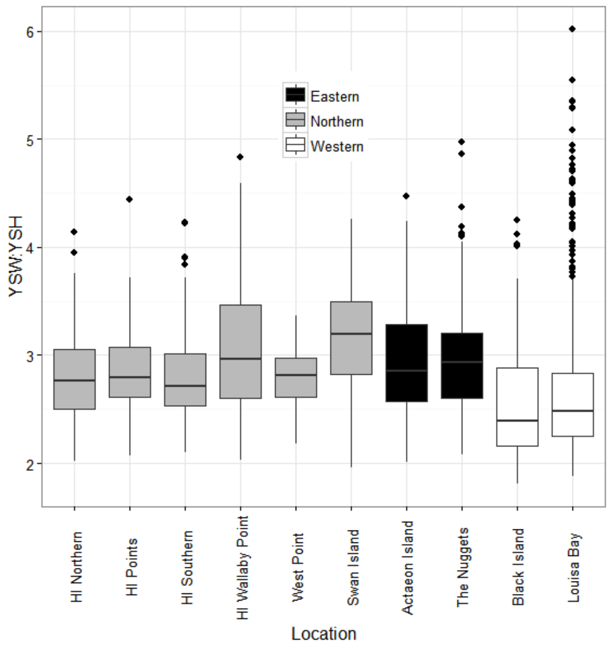

Fig. 19. Comparison of shape (YSW:YSH) between blacklip abalone shells from ten sites in Tasmania. YSW:YSH is the ratio of shell width (SW) and shell height (SH) standardised by shell length (SL). Each sample's data is represented by a central horizontal line which is the median value, a box which is the interquartile range, vertical lines which are the 2.5th and 97.5th percentiles, and black dots which are outliers.

YSW:YSH shell shape varied between samples ($f_{9,1771} = 29.13$, p=<0.001) (Fig. 19). At the finer spatial scale Wallaby Point varied significantly in shape from Hunter Island Northern and Southern locations while West Point was similar to all other samples in the Hunter Island region (Table 11). The Western Zone samples from Black Island and Louisa Bay were dissimilar to all other samples examined (Fig. 19, Table 11). There were no significant differences in shape between the Eastern Zone locations of Actaeon Island and The Nuggets, and these samples showed similarities with all the Northern Zone samples except between The Nuggets and Hunter Island Northern (Fig. 19 and Table 11). Swan Island was dissimilar to all other Northern Zone locales (Table 11).

4.3.3 Variation in shell shape with size and location – allometric shape model

In all samples, YSW:YSH significantly decreased with increasing SL (ANCOVA $f_{19,1761}$= 320.5 p =<0.0001, R^2=0.78). There was no evidence of difference in intercept between samples, but significantly differences in slope were found (Table 12). The Nuggets (p=0.06), Hunter Island Points (p=0.44), West Point (p=0.61) and Black Island (p=0.67) had similar slopes to Actaeon Island, while Hunter Island North (p=0.01), South (p=0.05) Wallaby Point (p=0.001), Louisa Bay (p=0.05), and Swan Island (p=0.01) all showed a larger decrease in YSH:YSW with increasing SL (Table 12, Fig. 20).

Shape at size of maturity (SAMy) varied significantly between locations (Fig. 21). Within the Hunter Island group Northern, Southern and Points locations were similar but Wallaby Point was only similar to the Southern area. Black Island and Louisa Bay showed sufficient overlap in confidence intervals to suggest that they are similar to each other; while SAMy at Actaeon Island and Swan Island were also comparable (Fig. 21). The Nuggets had the highest SAMy followed by the Hunter Island locations with Black Island and Louisa Bay in the Western Zone having the lowest and second lowest SAMy scores respectfully (Fig. 21).

Table 12. ANCOVA analysis of standardised shell width: standardised shell height (YSW:YSH) as a factor of shell length (SL) and sample site for blacklip abalone from ten Tasmanian locations. Asterisk denotes significance at $p<0.05$.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)
Actaeon Island	1.83	0.03	55.43	< 2e-16*
The Nuggets	0.09	0.05	1.57	0.12
HI Northern	-0.07	0.05	-1.32	0.19
HI. Points	-0.08	0.06	-1.30	0.19
HI. Southern	-0.08	0.06	-1.51	0.13
HI. Wallaby Point	0.02	0.05	0.52	0.60
West Point	-0.02	0.13	-1.566	0.12
Swan Island	0.02	0.06	0.25	0.81
Louisa Bay	0.03	0.04	0.88	0.38
Black Island	-0.04	0.05	-0.87	0.38
SL	-0.0060	0.0003	-23.26	< 2e-16*
The Nuggets:SL	-0.0008	0.0004	-1.84	0.06
HI Northern:SL	-0.0012	0.0005	-2.54	0.01*
HI Points:SL	-0.0004	0.0005	-0.78	0.43
HI Southern:SL	-0.0010	0.0005	-2.01	0.04*
HI Wallaby Point:SL	-0.0014	0.0004	-3.46	0.001*
West Point:SL	0.0006	0.0012	0.50	0.61
Swan Island:SL	-0.0016	0.0006	-2.62	0.01*
Black Island:SL	-0.0002	0.0004	-0.43	0.67
Louisa Bay:SL	-0.0006	0.0003	-1.98	0.04*

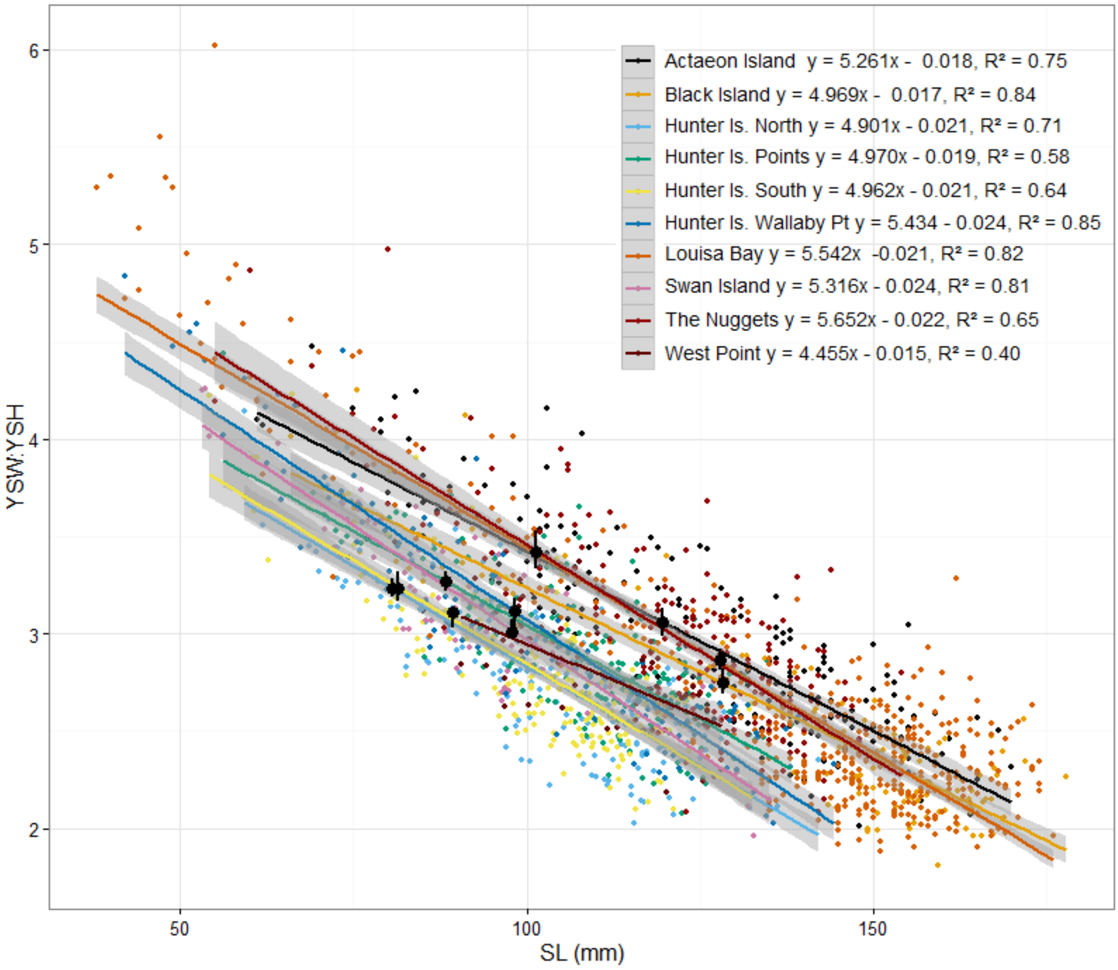

Fig. 20. Shape (YSW:YSH) change of blacklip abalone shells from ten sites around Tasmania with shell length (SL). YSW:YSH is the ratio of shell width (SW) and shell height (SH) standardised by SL. For each sample the size at maturity and 95 % confident intervals are highlighted by a black circle and error bars. Size at maturity is calculated from a binomial logistic regression of each sample using the proportion mature/immature by SL (mm).

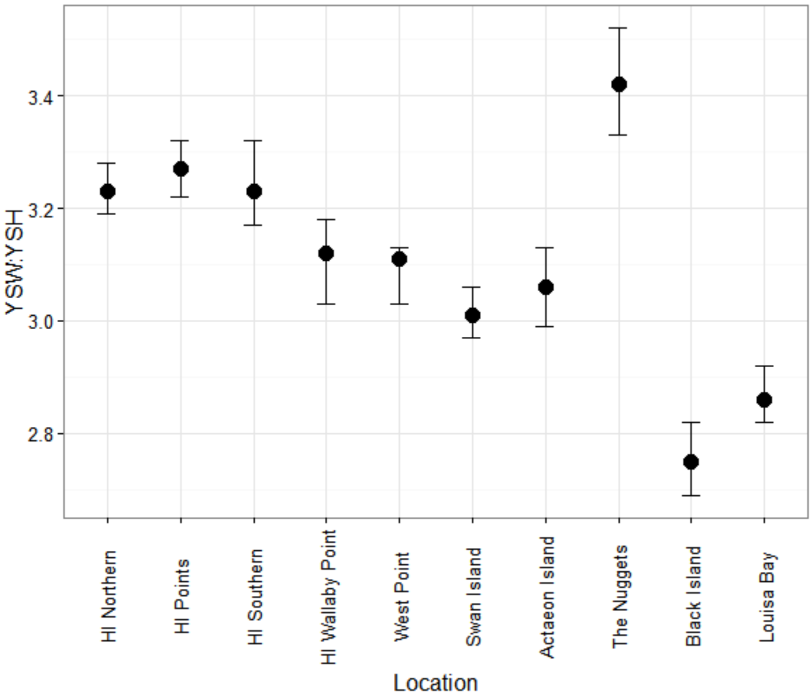

Fig. 21. Shape at maturity (SAMy) from ten sites in Tasmania. SAMy is the ratio of the standardised shell width to standardised shell height (YSW:YSH) of blacklip abalone shells at size at maturity, calculated from the linear regression equation of YSW:YSH against shell length (SL) within site. YSW:YSH is the ratio of shell width (SW) and shell height (SH) standardised by SL. Size at maturity is calculated from a binomial logistic regression at each region using the proportion mature to immature abalone by SL (mm). Size at maturity is the SL at which 50% of individuals were mature. Error bars are confidence intervals derived from the size at maturity bootstrapped 95% confidence intervals. Overlap between error bars indicates lack of significant difference between sites.

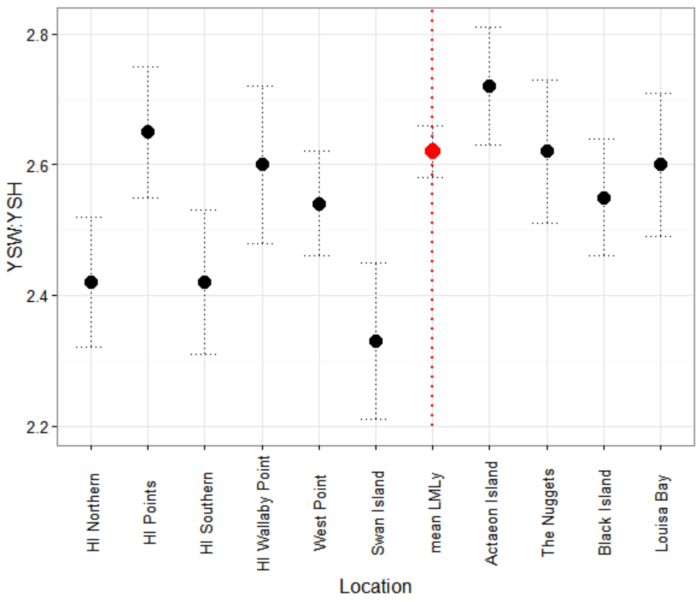

Fig. 22. Shape at legal minimum length (LMLy) for ten sites in Tasmania. LMLy is calculated from the standardised shell width: standardised shell height (YSW:YSH) of blacklip abalone shells at legal minimum length (LML). YSW:YSH is the ratio of shell width (SW) and shell height (SH) standardised by shell length (SL). LML represents the current (2014) legal minimum length of commercially caught blacklip within the Tasmanian zones: Eastern Zone (Actaeon Island and The Nuggets) 138 mm, Northern Zone (Swan Island) 127 mm, Western Zone (Black Island, Louisa Bay) 140 mm, Hunter Island (Northern Zone) 120 mm. Error bars show predicted change in mean shell shape (YSW:YSH) with a LML decrease and increase of 5 mm. Red dotted line shows the division between sites considered fast growing (right side) slow growing (left side). 'mean LMLy' is the mean LMLy (± standard error) of the four fast growing sites (right side).

Shape at legal minimum length (LMLy) also varied between locales, with Swan Island representing the lowest LMLy and Actaeon Island the highest (Fig. 22). At Hunter Island, there were distinct differences in LMLy between both the Points and Wallaby Point and the Southern and Northern sites, with LML shells from Hunter Island Points and Wallaby Point similar to the mean LMLy from the fast growth regions (Fig. 22). Hunter Island Points shells showed a higher LMLy than all other Northern Zone abalone. Due to the significant negative regression between SL and shape a 5-mm decrease in LML at all locations caused YSW:YSH to increase (Fig. 22).

4.3.4 Theoretical SL for harvest at slow growth regions defined by shape (SL_{ty}).

Mean LMLy of the four fast growth regions (Actaeon Is., The Nuggets, Black Is., Louisa Bay) was 2.62 (±2.58-2.66). SL_{ty} calculated from this value estimated that in order for Hunter Island Northern and Southern locations to be fished at a similar shape as the fast growth regions a SL of 110.1 mm (±108.3–111.9 mm) would be required (Table 13). At the Hunter Island Points (SL_{ty} = 121.7 mm, ±119.8-123.6 mm) and Wallaby Point (SL_{ty} = 119.2 mm, ± 117.6-120.7 mm) the SL_{ty} is similar to the current LML (120 mm) (Table 13). At both West Point (SL_{ty} = 121.4 mm, ±119.0- 123.9 mm) and Swan Island (SL_{ty} = 114.6 mm, ±113.0-116.2 mm), SL_{ty} model suggested a decrease in LML by approximately ≈ 6 mm and 12 mm respectfully (Table 13).

Table 13. Summary table of the size at maturity (SAM), shape at maturity (SAMy), legal minimum length (LML), shape at legal minimum length (LMLy) and calculated optimum shape at shell length based on fast growth shape (SLty) of blacklip abalone shells from ten sites (three zones) in Tasmania. 95% C.I. are shown for SAM and SAMy, while confidence intervals for SLty are standard error. SLty indicates the SL required in slow growth regions to produce shell shapes equivalent to the mean fast-growth LMLy (below dotted line).

Zone	Location	SAM Ld50	SAM Lower C.I.	SAM Upper C.I.	SAMy	SAMy Upper C.I.	SAMy lower C.I.	LML	LMLy	LMLy -5 mm	LMLy + 5 mm	SL$_{ty}$	SL$_{ty}$ lower C.I.	SL$_{ty}$ upper C.I.
NTH	HI Northern	80.6	78.2	82.4	3.23	3.28	3.19	120	2.42	2.52	2.31	110.1	108.3	111.9
NTH	HI Southern	81.5	77.3	84.3	3.23	3.32	3.17	120	2.42	2.52	2.32	110.4	108.7	112.1
NTH	HI Points	88.2	85.5	90.8	3.27	3.32	3.22	120	2.65	2.75	2.56	121.7	119.8	123.6
NTH	HI Wallaby Pt	98.2	95.7	100.1	3.12	3.18	3.03	120	2.30	2.72	2.48	119.2	117.6	120.7
NTH	West Point	89.3	87.7	94.3	3.11	3.13	3.03	127	2.54	2.61	2.46	121.4	119.0	123.9
NTH	Swan Island	97.9	95.7	99.8	3.01	3.07	2.97	127	2.33	2.45	2.21	114.6	113.0	116.2
WST	Louisa Bay	127.9	125.0	130.0	2.86	2.92	2.81	140	2.60	2.70	2.50			
WST	Black Island	128.3	124.4	131.5	2.75	2.82	2.69	140	2.55	2.63	2.46			
EST	Actaeon Island	119.6	116	123.3	3.06	3.13	2.99	138	2.72	2.81	2.63			
EST	The Nuggets	101.3	96.6	105.5	3.42	3.53	3.33	138	2.62	2.73	2.51			

4.3.5 Theoretical growth rate estimates and LML_{ct}

Theoretical growth rates calculated at size at maturity increased from 11 mm in Hunter Island North to 13.2 mm in Black Island for the first year post-size at maturity (Table 14). Second year growth rates post-size at maturity were smaller than the first year increasing from 6.7 mm at Hunter Island North to 7.7 mm at Black Island and Louisa Bay. LML_{ct} estimates based on these growth rates varied between locations from a low of 91.1 mm (Hunter Island North) to 147.9 mm (Black Island) (Table 14). In all Northern sites LML_{ct} was significantly lower than current LML, while the model suggested that the current LML in the Western Zone sites at Louisa Bay and Black Island was too low (Table 14). In the Eastern Zone the current 138-mm LML of is equal to that of the LML_{ct} for Actaeon Island while The Nuggets LML_{ct} is significantly lower than this value (Table 14).

Table 14. Summary table of the size at maturity (SAM), theoretical growth increments of blacklip abalone after the 1st year post-SAM (ΔL_1), 2nd year post-SAM (ΔL_2) and theoretical corrected legal minimum length (LML_{ct}) and legal minimum length (LML) for blacklip abalone shells from 10 regions (3 zones) around Tasmania. Confidence intervals of 95 % are shown in parentheses.

Zone	Site	SAM	ΔL_1	ΔL_2	LML_{ct}	LML
NZ	HI Northern	80.6 (78.2–82.4)	11.0 (10.9–11.1)	6.7 (6.7-6.8)	91.1 (88.2–93.2)	120
NZ	HI Southern	81.5 (77.3-84.3	11.1 (10.9-11.2)	6.8 (6.7 – 6.8)	92.1 (87.1–95.5)	120
NZ	HI Points	88.2 (85.5–90.8)	11.4 (11.2–11.5)	6.9 (6.8–6.9)	100.1 (96.9–103.2)	120
NZ	HI Wallaby Point	98.2 (95.7–101.9)	11.8 (11.7–12.0)	7.1 (7.0–7.1)	112.0 (109.0–116.4)	120
NZ	West Point	89.3 (87.7–94.4)	11.4 (11.3–11.6)	6.9 (6.9–7.0)	101.4 (99.5–107.4)	127
NZ	Swan Island	97.9 (95.7–99.8)	11.8 (11.7–11.9)	7.1 (7.0–7.1)	111.6 (109.0–113.9)	127
WZ	Louisa Bay	127.9 (125–130)	13.1 (13.0–13.2)	7.7 (7.6–7.7)	147.4 (143.9-149.9)	140
WZ	Black Island	128.3 (124.4–131.5)	13.2 (13.0-13.0)	7.7 (7.6–7.8)	147.9 (143.2–151.7)	140
EZ	Actaeon Island	119.6 (116–123.3)	12.8 (12.6–12.9)	7.5 (7.4–7.6)	137.5 (133.2–141.9)	138
EZ	The Nuggets	101.3 (96.6–105.5)	12.0 (11.7–12.1)	7.1 (7.0–7.2)	115.7 (110.1–120.7)	138

A comparison between current LML and the LML_{ct} model was made to assess how shell shape may change if theoretical estimates of LML were used as a management method (Fig. 23). At all Hunter Island locations shell shape significantly increased under the LML_{ct} model, as did The Nuggets, Swan Island and West Point. The increased SL associated with the LML_{ct} at Louisa Bay and Black Island meant that YSW:YSH decreased in these locations (Fig. 23). Only Actaeon Island saw no change in shell shape under the LML_{ct}.

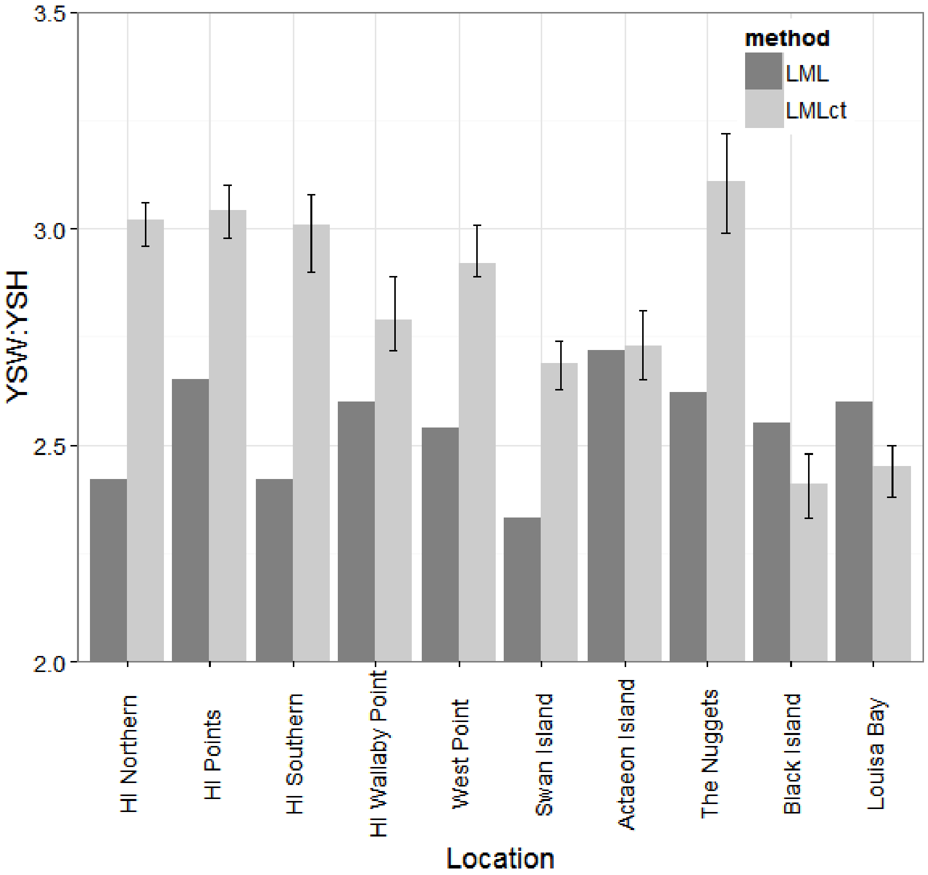

Fig. 23. Comparison of shell shape (YSW:YSH) between current legal minimum length (LML) and theoretical legal minimum length (LMLtc) for blacklip abalone in Tasmania. LMLtc – theoretical corrected LML, using measured size at maturity and derived growth rates for two years post-size at maturity to estimate LML. Error bars show 95 % confidence intervals.

4.4 Discussion

Size at maturity demonstrated spatial variation across both broad and fine spatial scales. The Western and Eastern Zone locations had larger size at maturity than the Northern Zone, and within the Northern Zone size at maturity was location dependent. Sexual maturity in abalone is principally determined by age and therefore size at maturity is associated with growth rate (Day and Fleming 1992; Prince et al., 2008). Size at maturity indicates that the Northern Zone locations were significantly slower growing than those from the Eastern and Western Zones, and this was supported by the low estimates of growth measured at Hunter Island in this study (Chapter 2). The spatial variation in size at maturity observed here is characteristic of abalone populations world-wide (Day and Fleming 1992; Mayfield and Saunders, 2008) and is attributable to spatial variability in environmental factors (Helidoniotis and Haddon, 2013). Size at maturity may have a seasonal component (Tarbath, 2003b) and because sampling was conducted opportunistically throughout the year, our estimates of size at maturity may be affected. Size at maturity samples were typically skewed towards larger mature fish meaning a paucity of data points between 1% and 99% maturity. The skewness of the datasets was not sufficient at any site to prevent calculation of size at maturity, but the low number of repeats around the Ld50 value may have affected how adequately the sample size at maturity reflects that of the broader population. All samples, except The Nuggets, met data quality criteria suggested in previous studies of the Tasmanian populations (Helidoniotis and Haddon, 2013). However, current research examining the effect of sample size around the Ld50 suggests that size at maturity is sensitive to the proportion of data around this value (C. Mundy pers. comm.). Where size at maturity was estimated from low proportions of data around Ld50 (e.g. The Nuggets), interpretation of the calculated size at maturity and confidence intervals must be considered with a degree of caution.

Differences in growth rates and size at maturity have previously been attributed to variability in shape of blacklip abalone, and morphological markers have been promoted as a potential tool for fisheries management (Mayfield and Saunders, 2008). This study found that the binomial YSW + YSH model was unreliable in determining OLD grade shells outside the locations from which it was derived. The binomial YSW + YSH model was based on the Hunter Island region and appeared valid when tested within the three primary locations producing estimates of 50% of OLD grade shell at least 18 mm above size at maturity at these sites. It estimated that > 75% of shells were OLD grade at the LML (120 mm). However, when the model was applied to the secondary sample locations, the SL at 50% OLD grade fell below the size at maturity in all but one sample (The Nuggets). At most secondary locations, size at maturity was reached only when the percentage of OLD shell was > 90%, and at one location where 99% of shells were OLD grade (Louisa Bay). Given that size at maturity represents 50% population maturity, it is unlikely that >90% of shells can be OLD grade at size at maturity, and implies that the binomial model incorrectly classified shells, and that the classification of shell grade is regionally specific. It suggests that the shell grade model is unsuitable as a diagnostic tool for abalone stock management beyond regions on which it is defined and cannot be used as a model on which LML reviews can be based. Even at a fine spatial scale, the binomial model classification failed to provide valid 50% OLD grade values for Wallaby Point at Hunter Island , where the SL at 50% OLD shell size was less than size at maturity further highlighting that the model is specific to the locations from which it is calculated. The poor shell grade classification would imply either that the classification of TSF shell grade is site specific and not transferrable between locations or that the original TSF classification on which it is based is not definable by morphometric attributes alone.

The allometric shape model (YSW:YSH) showed significant variation between locations with differing sizes of maturity. This result is similar to the spatial variability in blacklip abalone shape found in Victoria (Day et al., 2005) and South Australia (Mayfield and Saunders, 2008). This study showed an inverse linear relationship between YSW:YSH to SL, suggestive of a common morphological response of abalone to increased maturity. This agrees with previous research which proposed that newly emerged fish were flat and oval in shape while mature abalone were rounder and bowl-like (Prince et al., 2008; Saunders et al., 2009b). However, the differences in the slopes of the YSW:YSH to SL relationship between locations in this work imply that this shape response is spatially dependent. We postulate that the reduction of YSW:YSH with increasing SL is a response to increased metabolic emphasis on reproductive capacity over growth, where growth in SL slows with expanding shell volume to incorporate reproductive organs (Prince et al., 2008). Although data is limited below 50 mm SL, we speculate that the common intercept of shell shape between locations found in this study suggests a single shape at settlement. While both size at maturity and shell shape at maturity (SAMy) varied significantly between locations demonstrating that site-specific differences in shell growth and shape are taking place at early life stages and implying that shape is not solely a response to maturation. The allometric shape variation at maturity between locations suggests that the allometric shape model would be unsuitable as an alternative method for estimating size at maturity and that doming indices cannot be considered a reliable indicator of maturity.

The regression of the allometric shape model against SL demonstrates a systematic approach to assessing how shell shape would change with adjustment of LML. At each of the Northern Zone locations, the LML_{ct} was estimated to be significantly lower than the current LML. The LML_{ct} is based on the two-year rule size-limit management policy, and suggests that the current LML allows the abalone in in these locations more than two years growth. The reduction in size limit at all these sites would substantially increase the YSW:YSH ratio of shells meaning smaller flatter wider shells would be available to the fishery. In the LML_{ct} model, estimates of the second year growth increment at Hunter Island sites were higher than growth increments estimated from the recent tagging study associated with the depletion experiment (see Chapter 2). This suggests either that that the LML_{ct} model is over-estimating growth, or that the tag-recovery data was exceptional.

Fishing to selected shell shapes was explored as a management strategy as it has the potential to improve both meat-weight returns and the quality of live product in slow growth areas. In the worked example, a mean shape at legal minimum length (LMLy) was calculated from locations with high growth rates. Using the linear equation of YSW:YSH against SL for each location it was possible to calculate the SL at which the shape (SL_{ty}) of slow growth locations would equal that of the faster growth areas LMLy. The LMLy of faster growth locations was 2.62 at their respective LMLs. To produce a similar shape at the Hunter Island Northern and Southern locations, the SL_{ty} would need to be 110 mm; at Hunter Island Points and Wallaby Point the SL_{ty} would be similar to the current LML (120 mm) 122 mm and 119 mm respectfully. Also in the Northern Zone a SL_{ty} of 121 mm at West Point and 115 mm at Swan Island would produce shells of similar shape to the current LMLy of fast growth regions. This method has the potential to harvest more preferred shapes of abalone from parts of the fishery where low-grade abalone are prevalent. However, there are a number of key issues which need to be resolved before this type of model could be adopted:

a. Would a common LMLy be appropriate? The linear model of YSW:YSH against SL shows divergence of shape between locales from a small size (60 mm) and size at maturity is not uniform. Consequently, fishing to a common shape would cause unequal periods of growth between size at maturity and LML for different regions. Any adoption of a SL_{ty} could only be employed provided that the two year rule of maturity is not affected. Theoretical estimates of LML based on growth (Helidoniotis and Haddon, 2013) may provide the start point for this process but these estimates would need to be verified before there would be sufficient evidence to allow such contemplation.
b. How to define an appropriate LMLy? This work used the mean LMLy from the ‘fast growth’ samples but whether this is an appropriate characteristic is debateable. For example, some fish processors may prefer shell shapes that maximize processed meat returns against whole weight, while others may want larger abalone.

c. Setting the LML from shape would make commercial sense only if the shape set for the SL_{ty} met market needs to provide a viable meat recovery weight for both fresh and processed markets. These factors are outside the scope of this study, but they require consideration.
d. Improved levels of abalone shape data would be required, with widespread acceptance in all abalone factories and processing plants to accept responsibility to measure SL, SW and SH from a subsample of every diver's catch, and for fishers to accurately report the precise catch location. A key assumption in any factory based assessment of stock is that what passes through the factories is representative of a region. If a processor is receiving only a proportion of fished stock from any population, or only certain catches are being recorded then the measure of quality will be biased and unusable as a fishery performance measure.

4.5 Summary

We assessed the capacity of the binomial model and allometric shape model to be used as management tools for triggering management reviews of the current LML. We found that the binomial model was too site-specific and subjective and therefore unable to produce reliable interpretations of shell grade making it unsuitable as a management tool. The allometric shape model detected spatial variability in shape at size at maturity, and linear changes in shape with size by location, which provides evidence of why the binomial model failed to produce valid shell grades. This work suggests that shape models are unreliable as predictors of maturity and therefore cannot be used as a proxy for size at maturity. We proposed the allometric shape model as an additional tool to assist in predicting how shell shape may change in response to LML adjustments, but not as a method of setting LML alone. We provided a worked method of estimating SL by shape to maximise shell shape marketability in slow growth regions based on preferred shell shapes, which may be considered provided that the two year rule of maturation is met. The characteristics of these shapes would be defined by market forces, perhaps to enhance meat recovery yields, or to improve quality of live-market product.

4.6 References

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5. Conclusion

5.1 Benefits and Adoption

The lack of evidence for a density-dependent increase in growth, meat quality or yield from this study indicates that a reduced size limit is not an effective management practice to increase productivity in this part of the fishery. It is also likely that the density reduction strategy will be ineffective in other parts of the blacklip fishery which share similar biophysical parameters to those found at Hunter Island, and consequently density reduction and reduced size limits should not be considered as a management tool to improve productivity in these areas.

Adoption of the TSF shell age classification as a measure of shell age by industry is not recommended by this study. The subjective nature of its implementation if adopted could lead to poor management decisions which may affect the fishery’s future sustainability. The allometric shape model developed in this work highlighted the variability of allometric growth in abalone and suggests that any morphometric fisheries management tools must consider size independence in order to be effective. Importantly the variability in shape at maturity indicates that visual assessment of shape is not a precise measure of maturity or age and that use of shell appearance to define a population’s status is questionable and should be treated with caution. Evidence from this work indicates that morphometric analysis has the potential to be used as a performance measure within the fishery management framework but only if size is eliminated as a factor first. The allometric shape model present here is a concept model which if adopted by industry could provide a factory-based method of collecting spatially-defined abalone shell-quality data. This would deliver information about changes in the stock structure through time and space and could benefit fishery managers through the provision of information about changes in shell shape indicative of changes in abalone stock structure. This would become important in the monitoring of stock response to changes in LML and TACC.

5.2 Further Development

Further research at the Hunter Island study sites has been requested by industry because they considered it possible that the population response to density reduction may become more evident as young abalone grow into the fishery in coming years. This work may be possible through allocation of research funds provided by the Tasmanian State Government during the next three years, although any future work will be dependent on the State Government’s research priorities. The modification of the existing market measuring program at fish processors in the region to collect data for the allometric shape model will be discussed with the processing sector, and may be adopted by some processors on a voluntary basis.

5.3 Planned Outcomes

The lack of density-dependent effect on growth and product quality during the three-year period of this study suggests that manipulating the TAC-LML interaction does not necessarily increase productivity within a region and therefore no change in practice is recommended by this work . Fishery managers need to be aware that responses by stocks to thinning are complex and that its uses as a management tool may have unintended consequences.

The collection of allometric shape model measurements by fish processors would significantly reduce future research costs in obtaining shell shape data, and would allow testing of the model at broader spatial and temporal scales. Collection of this data would also allow future development of further morphometric performance measures which may assist in measuring fishery sustainability.

5.4 Linkages with CRC Milestone Outputs

The allometric shape model meets the CRC milestone outputs 1.4.1 and 1.4.2 by providing an efficient quantitative tool for evaluating shell quality, which may provide information about the response of stocks to changes in fishery practices, and enable managers to predict how future decisions will impact product quality.

5.5 Conclusion

This project had four primary objectives.

Objective 1: Quantify density-dependent effects on wild abalone growth and meat quality.
We could not detect density-dependent effects on wild abalone growth and meat quality during the period of the study. Industry’s view that it may take more time for density-dependent effects to become apparent will require further work at the study sites.

Objective 2: Develop a statistical tool for classification of shell age.
Development of a morphometric statistical tool for the determination of shell grade, based on Tasmanian Seafoods Pty Ltd (TSF) methods was achieved. This model was found unsuitable for management purposes. Improved accuracy in shell classification was achieved with a modified version of the TSF method (binomial model) but the improved model was found to be site dependent and not transferable between populations. We provided the allometric shape model as an alternative to the shell grade model. The allometric shape model was able to define changes in shell shape independent of shell size, and estimate shell length for ‘optimum’ shell shapes from samples across a range of sites in the Tasmanian fishery.

Objective 3: Use length-based models to test the adequacy of shell age performance measures
We found that shell age performance measures were unreliable and consequently developed the allometric shape model (see above: Objective 2). There was an inverse linear relationship between allometric shape and shell length, suggestive of a common morphological response of abalone to increased maturity, and this response was spatially dependent. That the allometric shape model did not find a common shape at size at maturity suggested shell morphometrics were not suitable for defining size at maturity or consequently being used as a shell age performance measure.

Objective 4: Use length-based models to determine the sustainability and cost-effectiveness of an LML that optimises the proportion of 'old' shell within 5 mm of the LML.

We assessed the capacity of the binomial model and allometric shape model to be used as management tools for triggering management reviews of the current LML. We found that the binomial model was unable to produce reliable interpretations of shell grade making it unsuitable as a management tool. The allometric shape model detected spatial variability in shape at size at maturity, and linear changes in shape with size by location, which provides evidence of why the binomial model failed to produce valid shell grades. This work suggests that shape models are unreliable as predictors of maturity and therefore cannot be used as a proxy for size at maturity. We proposed the allometric shape model as an additional tool to assist in predicting how shell shape may change in response to LML adjustments, but not as a method of setting LML alone.

Summary:

This project successfully reduced the density of Hunter Island abalone of shell length ≥110 mm at three experimental sites by commercial fishing to catch rates of approx. 20 kg/hr. This reduction of density had no significant effect on growth rates, size at maturity and product quality within these sites over the duration of this study. It suggests that in the short term, stock size above the LML is not imposing a density-dependent effect on stock below the LML and by extension, management strategies to remove older and larger abalone through increased TACs and/or reduce LMLs will not necessarily increase growth in sub-legal abalone. Shell-grade classifications defined by TSF cannot be reliably modelled by morphometric characteristics alone and are unsuitable for management purposes. We proposed the allometric shape model as an additional tool to assist in predicting how shell shape may change in response to LML adjustments, but not as a method of setting LML alone. We provided a worked method of estimating SL by shape to maximise shell shape marketability in slow-growth regions based on preferred shell shapes, which may be considered provided that the two- year rule of maturation is met. The characteristics of these shapes would be defined by market forces, perhaps to enhance meat recovery yields, or to improve quality of live-market product.

6. Appendices

6.1 Appendix 1 – Intellectual Property

There are no issues concerning intellectual property relating to this research project.

6.2 Appendix 2 – Staff

David Tarbath – Principal Investigator, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Dr Caleb Gardner - Sustainable Marine Research Collaboration Agreement (SMRCA) Director, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Dr Hugh J. Jones – Research Assistant, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Dr Craig N. Mundy – Research Fellow, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Dr Klaas Hartmann – Research Fellow, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Sarah-Jane Pyke – Technical Officer, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

David Faloon - Technical Officer, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Mike Porteus - Technical Officer, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Luisa Forbes- Technical Officer, Institute for Marine and Antarctic Studies – Fisheries and Coasts Centre.

Dr Craig Sanderson – Research Assistant, Institute for Marine and Antarctic Studies.

6.3 Appendix 3 – Site habitat descriptions

Sites 1 & 2

- Most wave exposed of the three pairs of sites, open westerly aspect.
- High relief reef (slabs, boulders) interspersed with low relief, small rocks and sand patches.
- Comparatively low diversity of plants compared with the other two regions. Mostly *Durvillaea potatorum*, although where less exposed to swell action some of the fucoid complex were present incl.: *Cystophora moniliformis, Cystophora subfarcinata (?), Cystophora platylobium* and *Carpoglossum confluens.*
- High levels of coverage of encrusting and articulated coralline algae.
- Abalone were patchily distributed at depths ranging between 4-10 m being highly concentrated at the base of boulders particularly at Site 2. At both sites, some large expanses of reef overlain with rubble were apparently scoured clean by wave action – no abalone present.

Sites 5 & 6

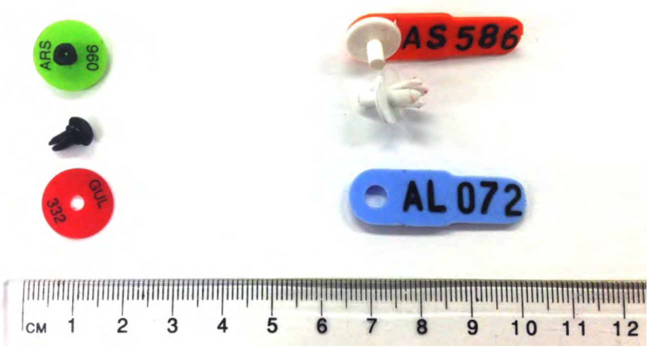
- Moderately wave exposed sites, westerly aspect, but partially sheltered from swell by Cape Cuvier.
- Laminated/striated rock, low relief, rock and rubble – little sand. Fucoid association: *Cystophora moniliformis, Cystophora subfarcinata (?), Cystophora platylobium, Carpoglossum confluens, Sargassum sp., Sierococcus axillaris, Perithalia caudata.*
- *Durvillaea potatorum* on top of the rocks.
- Site 6 distinguished from Site 5 by having a lot of *Phyllospora comosa.*
- Site 5 has extensive gullies. Abalone were patchily distributed but mainly within gullies (Site 5) and amongst the rubble (Site 6), also amongst the striations of the reef at both sites. Abalone appeared to be limited to the near-shore parts of the reef at depths 3-6 m.

Sites 3 & 13

- Most wave protected of the sites, sheltered northerly aspect.
- Steeply shelving fringe reef to sand edge. Large slabs and boulders, interspersed with smaller boulders.
- Most diversity of algae found at these sites incl. fucoid association: *Cystophora moniliformis, Cystophora subfarcinata (?), Cystophora platylobium, Carpoglossum confluens, Sargassum sp., Sierococcus axillaris, Perithalia caudata, Halopteris.*
- *Durvillaea potatorum* on top of the rocks.
- Also, *Homeostrichus olsenii, Caulerpa sp., Plocamium augustum (?), Asparagopsis armata,*
- Greater coverage of encrusting corallines than articulated corallines at these sites.
- Most abalone were found at the reef edge (approx. depth 6-7 m).

6.4 Appendix 4 –Abalone tags image and table of growth rates.

a. The growth study used ‘Floy’ brand disc tags for abalone ≤ 90 mm shell, length, and sheep ear tags for larger abalone.

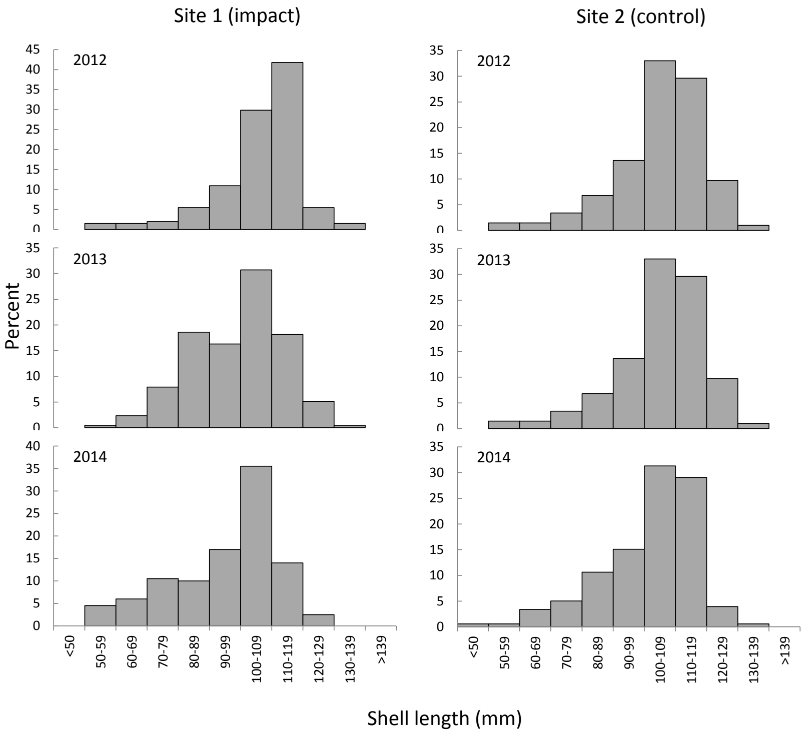


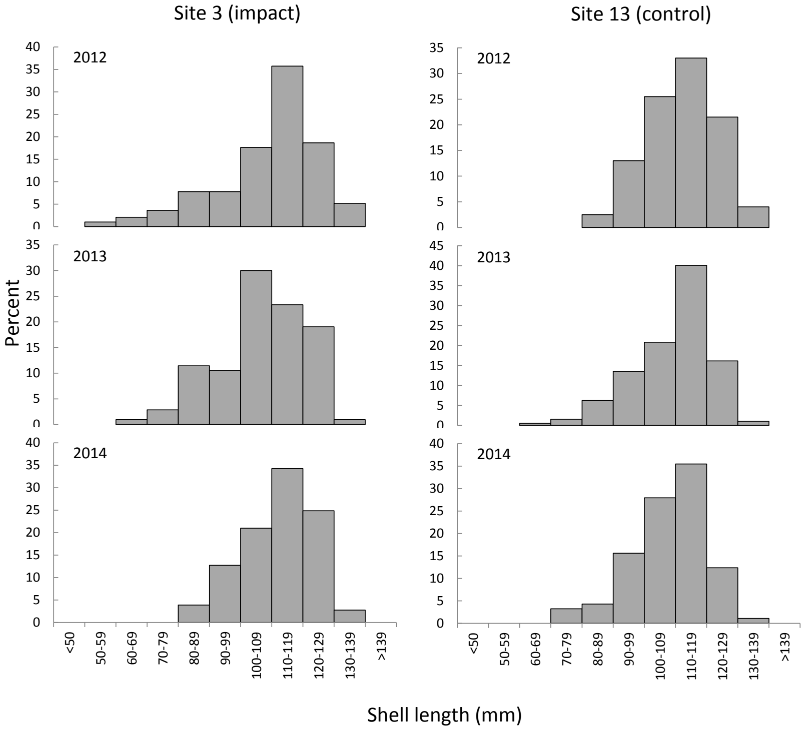
b. Growth rates (with bootstrapped 95% C.I.) from the six study sites, Hunter Island, 2013-2014, using Francis’ (1988) derivation of the von Bertalanffy growth model. L_∞ and K are the conventional von Bertalanffy growth parameters, ga and gb refer to expected annual growth increments at 90 mm and 110 mm respectively, and nu describes growth variability.

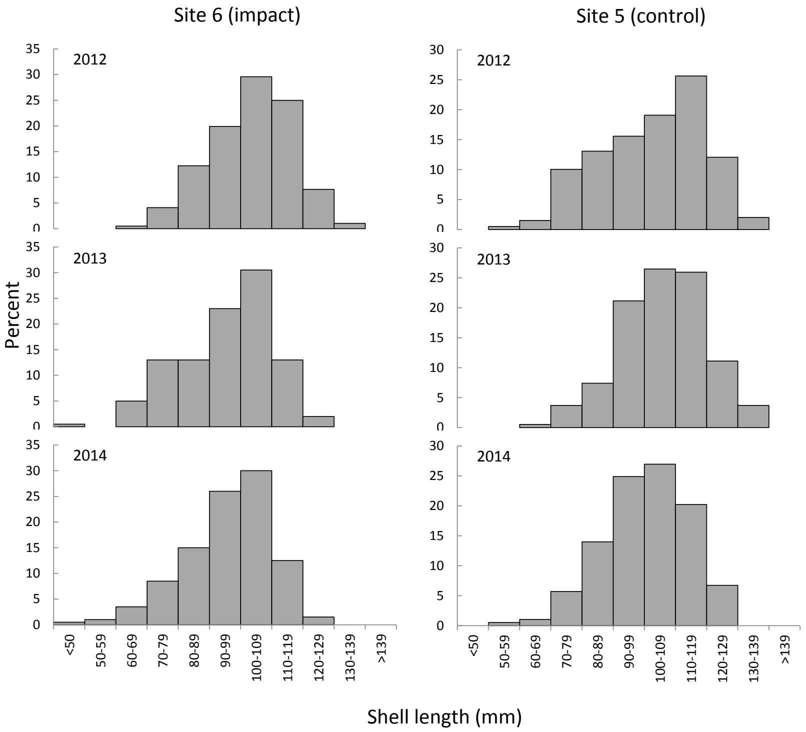
	Impact sites		Control sites	
Southern sites	Site 1		Site 2	
	2013	2014	2013	2014
Linf	126.58	115.48	120.21	125.25
K	0.09	0.27	0.11	0.18
ga (90 mm)	3.31 (2.68-4.10)	6.12 (3.77-7.29)	3.23 (2.67-3.61)	5.87 (4.28-6.73)
gb (110 mm)	1.50 (0.62-1.59)	1.32 (0.93-2.30)	1.09 (-0.68-1.39)	2.54 (-0.63-3.43)
nu	0.84	1.05	0.83	0.94
number	31	49	50	39
range (mm)	67-122	76-119	70-125	66-125
Points sites	Site 3		Site 13	
	2013	2014	2013	2014
Linf	133.58	131.67	134.33	127.98
K	0.16	0.16	0.08	0.08
ga (90 mm)	6.49 (5.49-8.66)	6.13 (5.51-8.85)	3.45 (2.31-6.16)	2.96 (2.43-4.34)
gb (110 mm)	3.51 (2.98-3.98)	3.18 (1.04-4.03)	1.90 (1.35-2.47)	1.40 (0.84-1.57)
nu	0.84	0.90	0.96	0.98
number	61	34	79	29
range (mm)	80-126	86-132	75-134	90-134
Northern sites	Site 6		Site 5	
	2013	2014	2013	2014
Linf	129.76	122.49	137.07	120.74
K	0.07	0.09	0.05	0.10
ga (90 mm)	2.55 (2.30-2.70)	2.74 (2.18-3.52)	2.48 (2.18-3.01)	2.91 (2.54-3.35)
gb (110 mm)	1.27 (0.99-1.32)	1.05 (0.44-1.29)	1.43 (1.07-1.45)	1.01 (0.04-1.24)
nu	0.83	0.90	0.89	0.97
number	84	32	56	72
range (mm)	65-125	76-119	79-131	61-131

6.5 Appendix 5 – Size structure for size-at-maturity analyses

Sampling was conducted in September 2012, September 2013 and May 2014. Samples were collected haphazardly, taking all abalone encountered until approx. 200 were collected. Density reduction occurred between the 2012 and 2013 sampling.

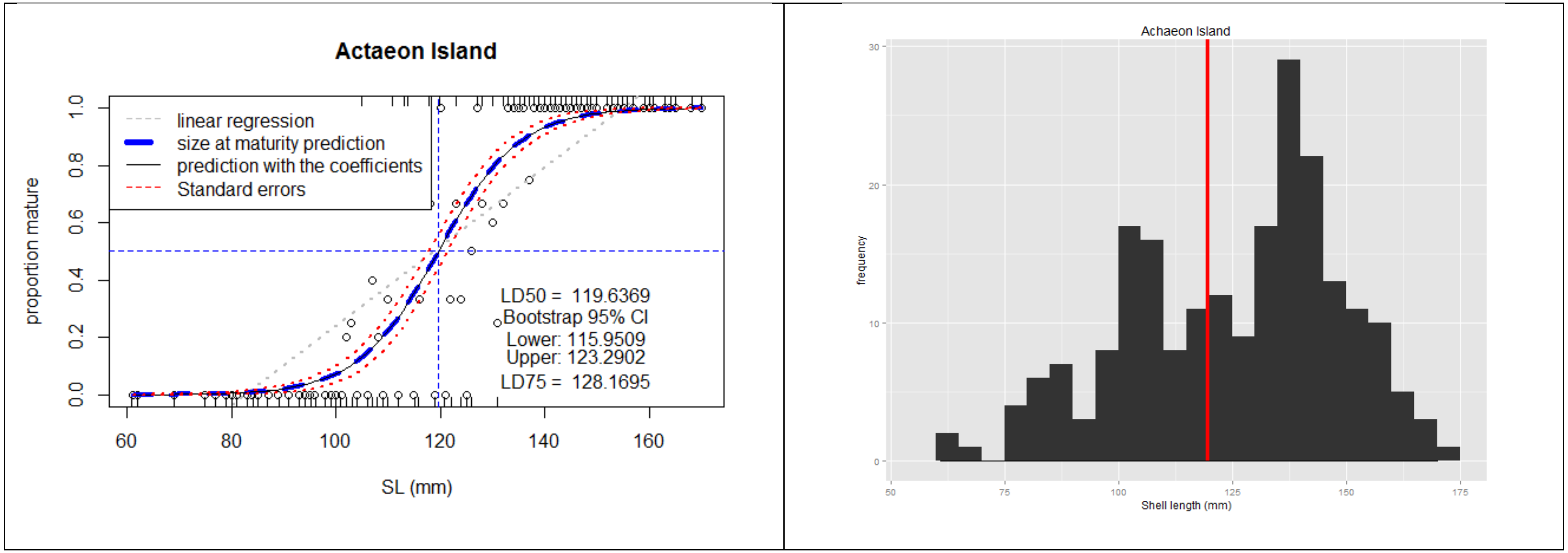


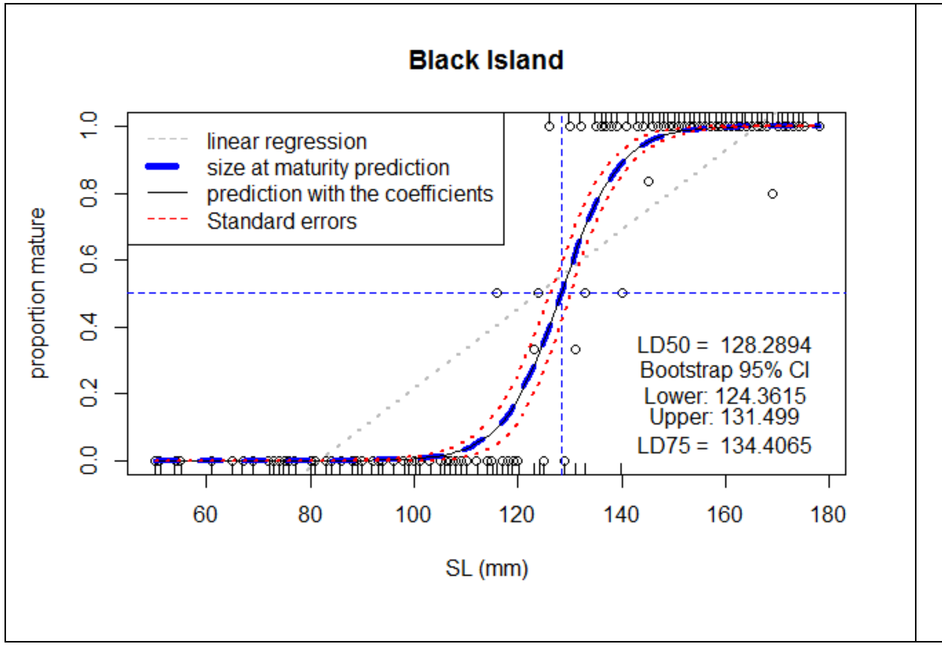


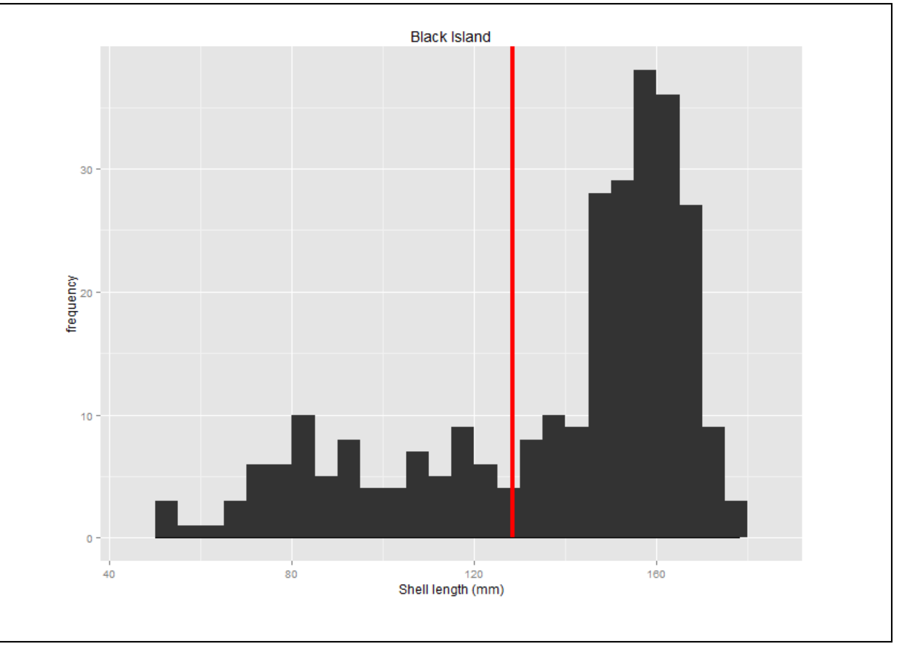

Site 6 (impact)
Site 5 (control)
2012
2013
2014
Percent
0
5
10
15
20
25
30
35
<50
50-59
60-69
70-79
80-89
90-99
100-109
110-119
120-129
130-139
>139
Shell length (mm)

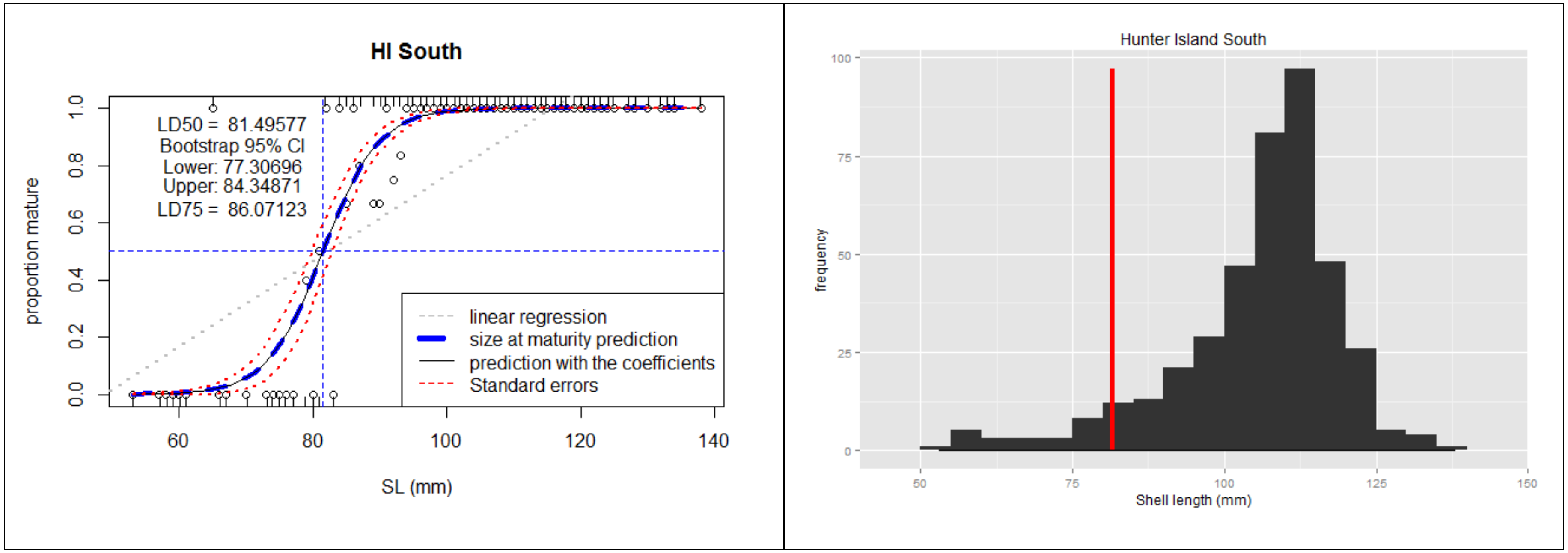
6.6 Appendix 6 – Size at maturity binomial plots.

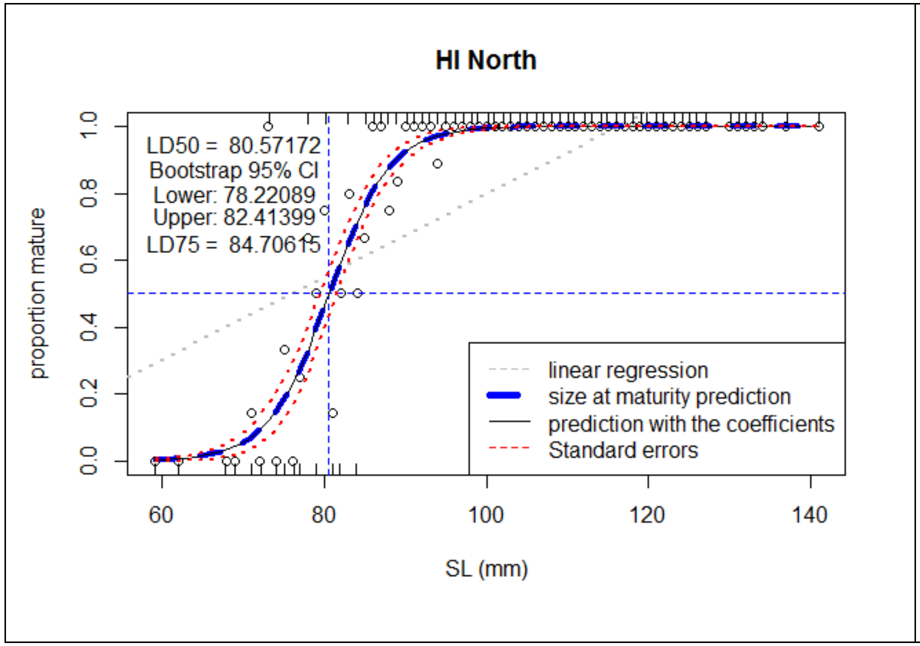
Size at maturity binomial plots for selected Tasmanian sites, with accompanying size frequency histograms. Red line on histogram represents size at maturity.

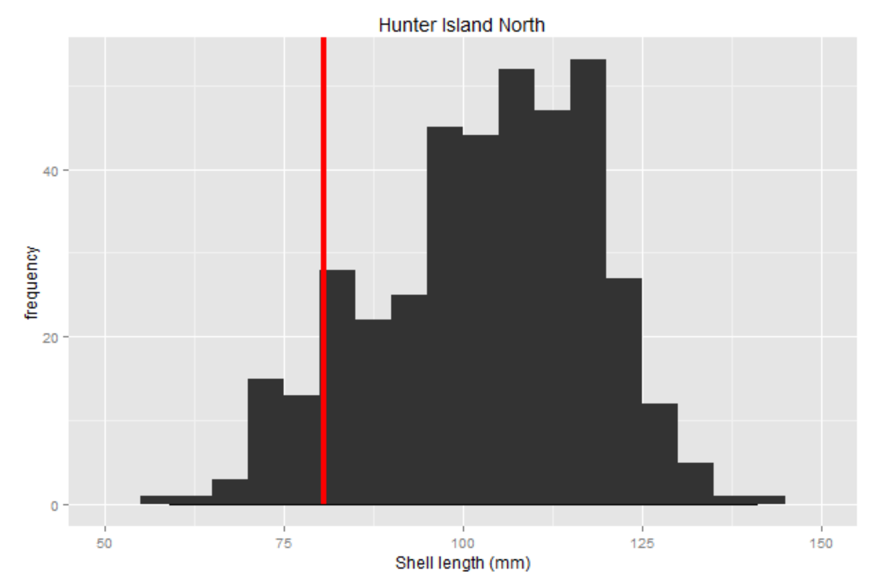


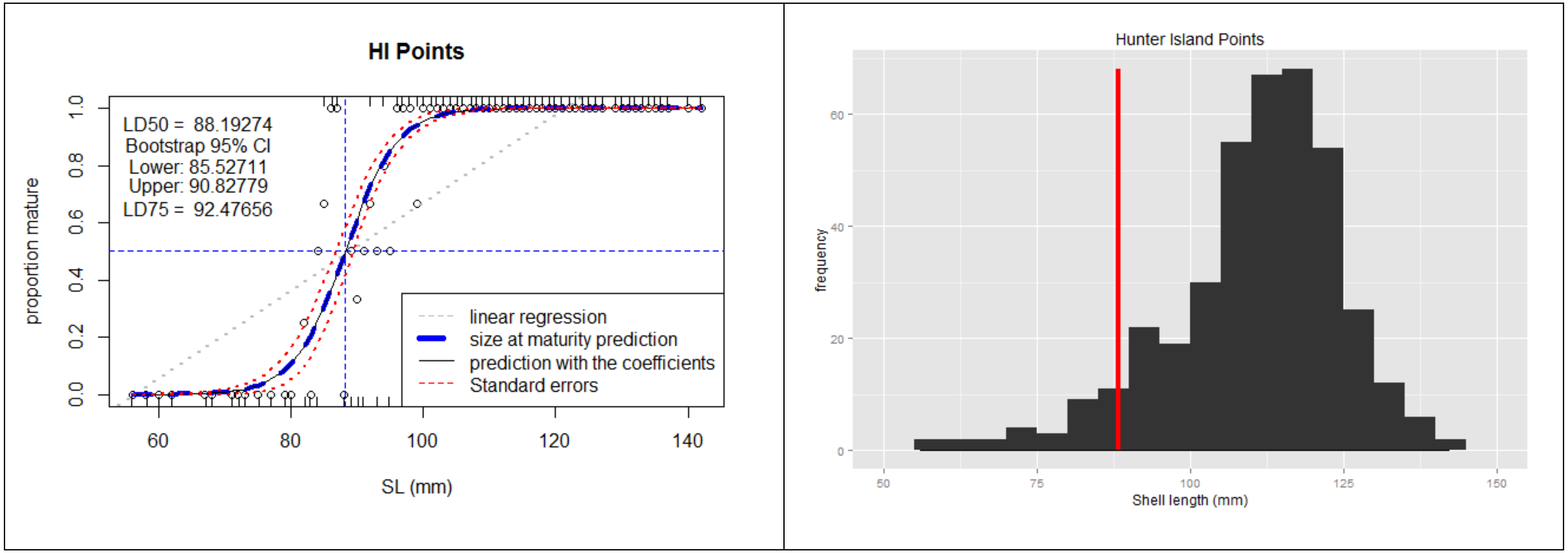

Black Island
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
60
80
100
120
140
160
180
SL (mm)
LD50 = 128.2894
Bootstrap 95% CI
Lower: 124.3615
Upper: 131.499
LD75 = 134.4065

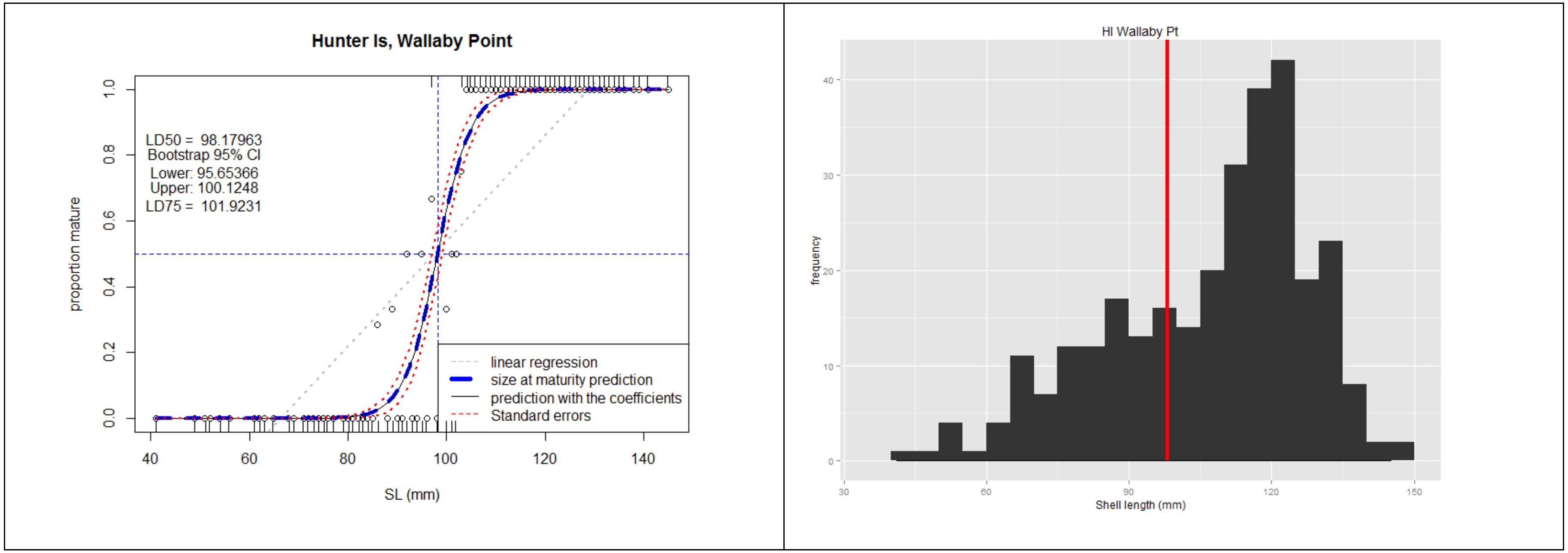

Black Island
frequency
0
10
20
30
40
80
120
160
Shell length (mm)

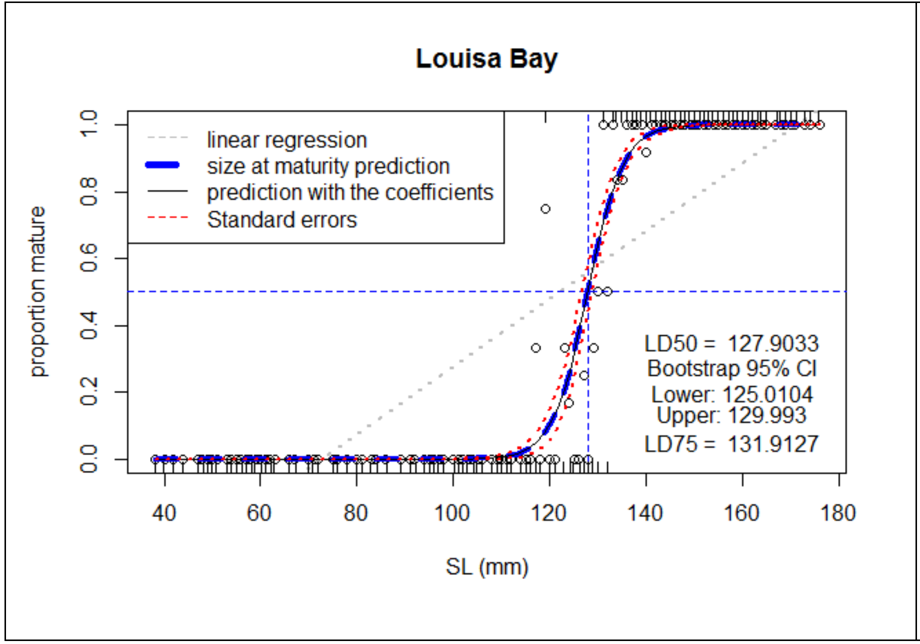

HI South
LD50 = 81.49577
Bootstrap 95% CI
Lower: 77.30696
Upper: 84.34871
LD75 = 86.07123
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
60
80
100
120
140
SL (mm)
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors
Hunter Island South
frequency
0
25
50
75
100
50
75
100
125
150
Shell length (mm)

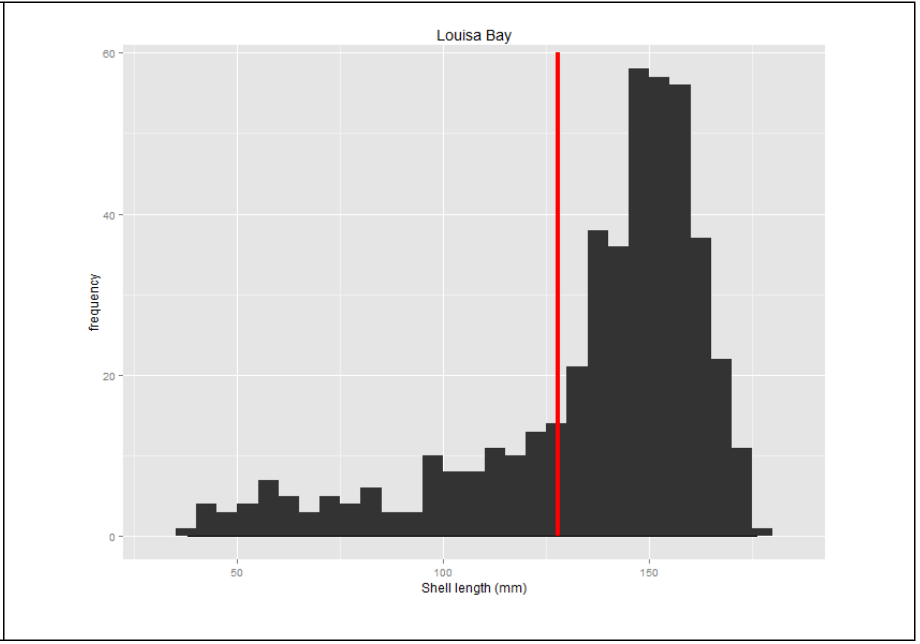

HI North
LD50 = 80.57172
Bootstrap 95% CI
Lower: 78.22089
Upper: 82.41399
LD75 = 84.70615
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
60
80
100
120
140
SL (mm)
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors

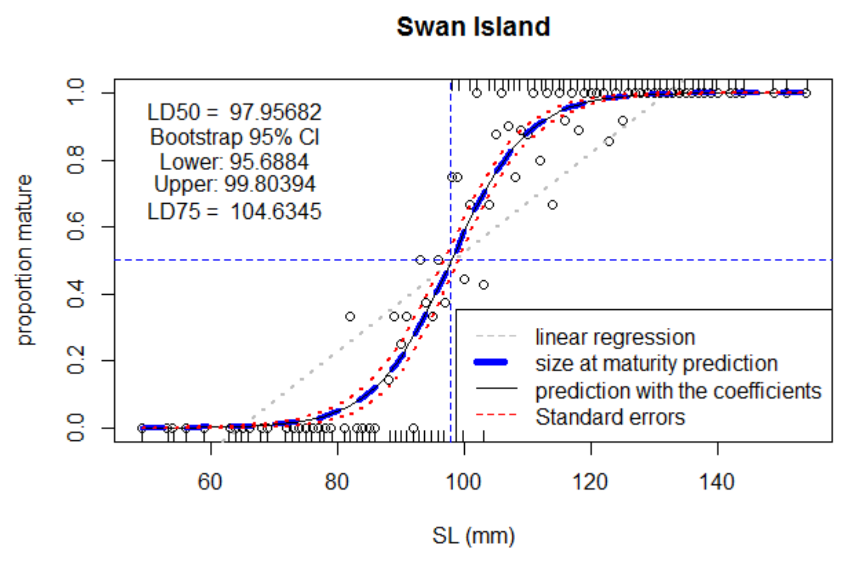

Hunter Island North
frequency
0
20
40
50
75
100
125
150
Shell length (mm)

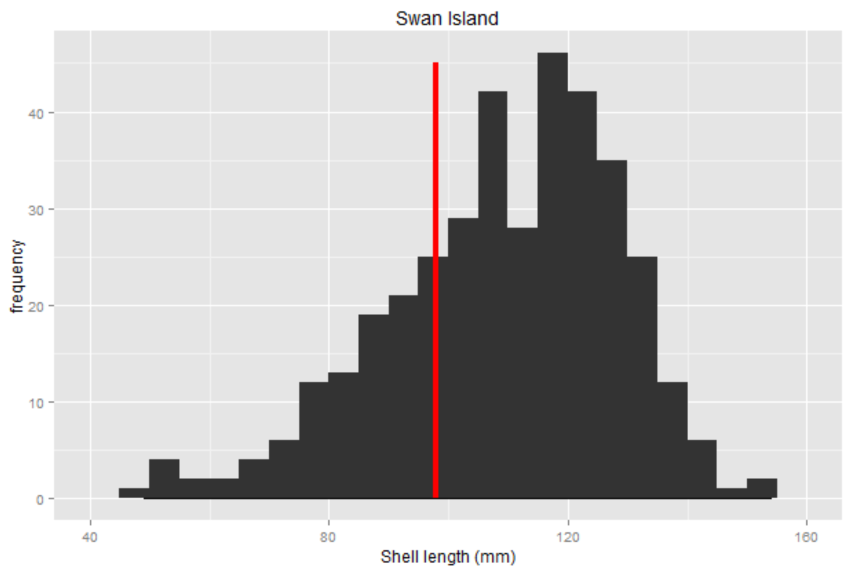

HI Points
LD50 = 88.19274
Bootstrap 95% CI
Lower: 85.52711
Upper: 90.82779
LD75 = 92.47656
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
60
80
100
120
140
SL (mm)
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors
Hunter Island Points
frequency
0
20
40
60
50
75
100
125
150
Shell length (mm)

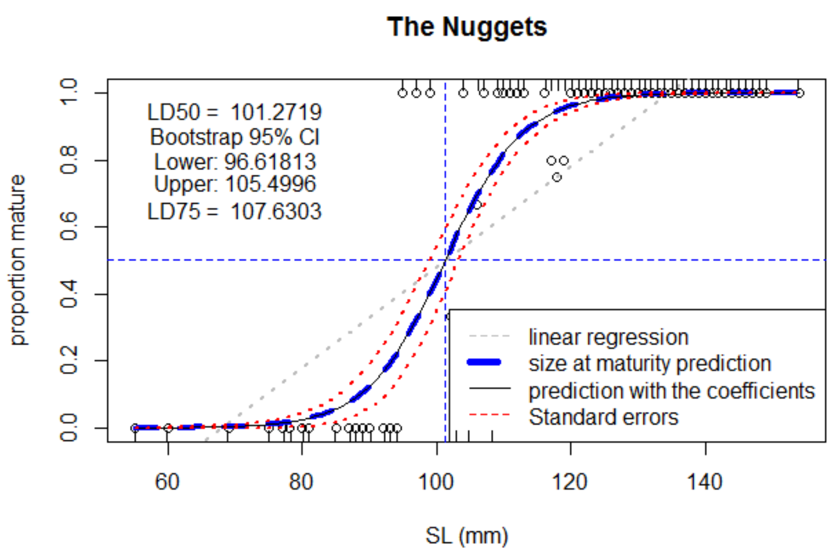

Hunter Is, Wallaby Point
LD50 = 98.17963
Bootstrap 95% CI
Lower: 95.65366
Upper: 100.1248
LD75 = 101.9231
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
40
60
80
100
120
140
SL (mm)
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors
HI Wallaby Pt
frequency
0
10
20
30
40
30
60
90
120
150
Shell length (mm)

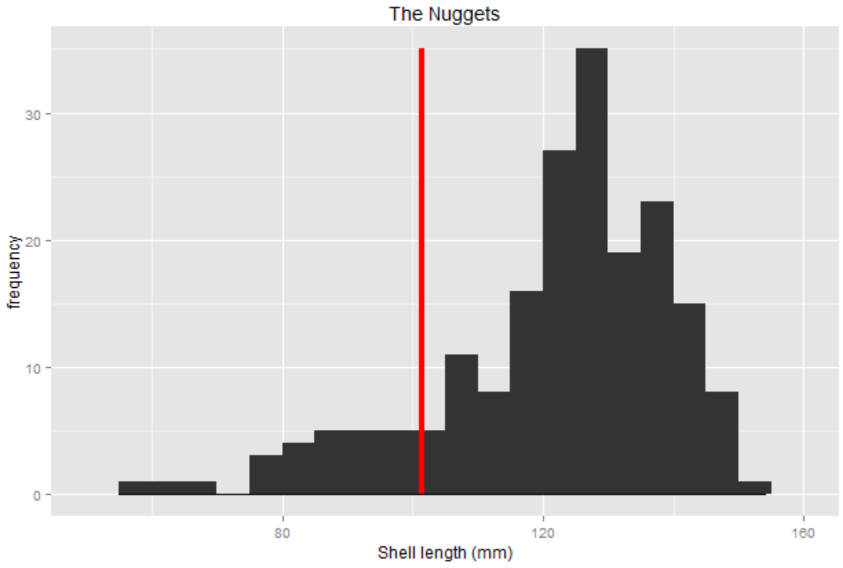

Louisa Bay
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors
LD50 = 127.9033
Bootstrap 95% CI
Lower: 125.0104
Upper: 129.993
LD75 = 131.9127
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
40
60
80
100
120
140
160
180
SL (mm)

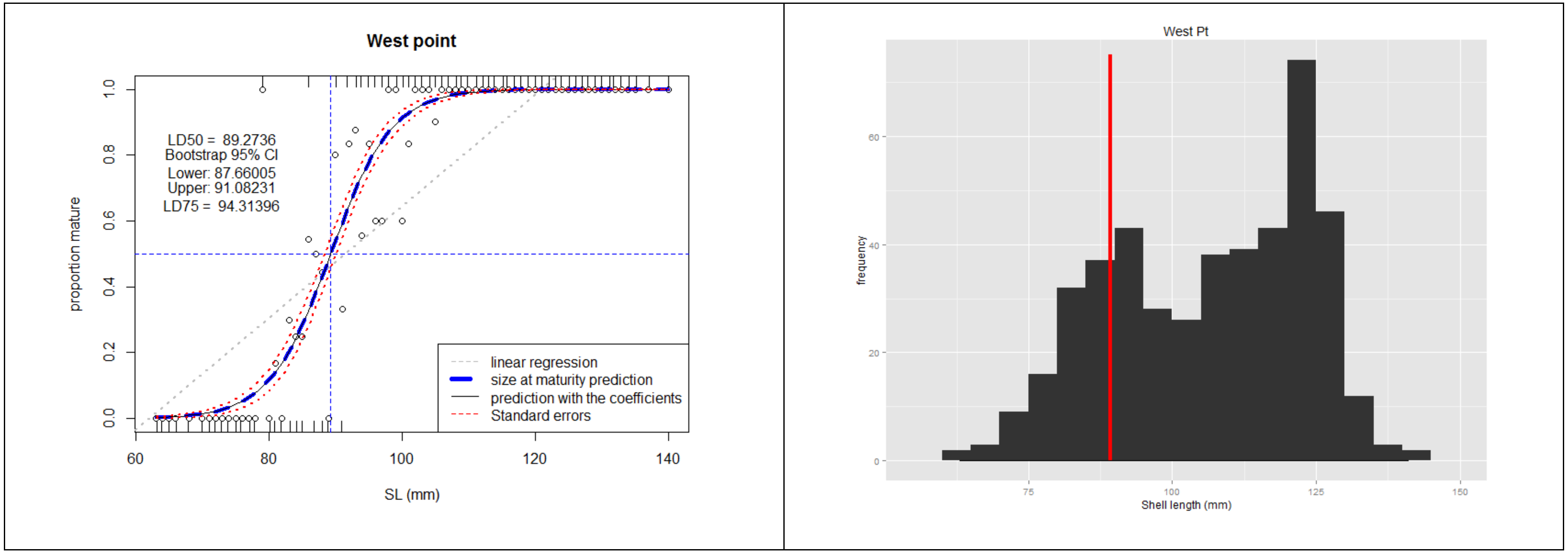

Louisa Bay
frequency
0
20
40
60
50
100
150
Shell length (mm)


Swan Island
LD50 = 97.95682
Bootstrap 95% CI
Lower: 95.6884
Upper: 99.80394
LD75 = 104.6345
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
60
80
100
120
140
SL (mm)
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors


Swan Island
frequency
0
10
20
30
40
40
80
120
160
Shell length (mm)

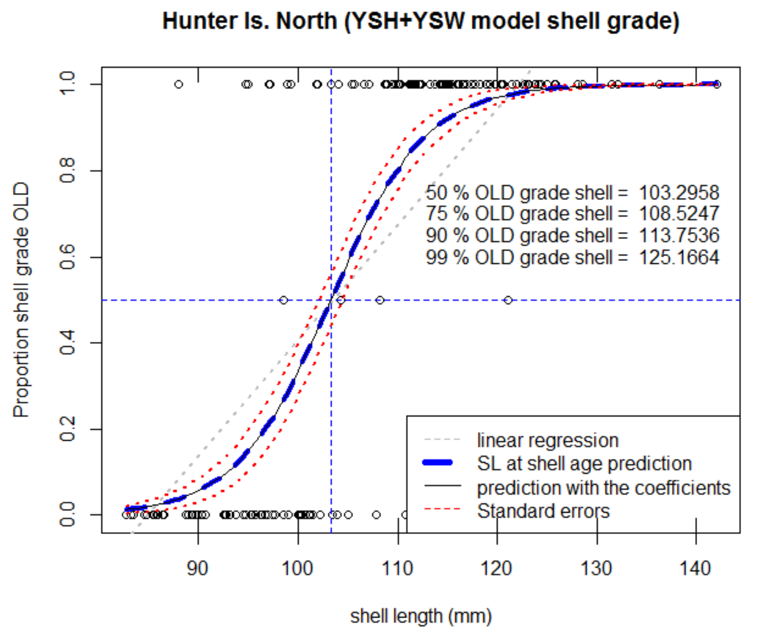

The Nuggets
LD50 = 101.2719
Bootstrap 95% CI
Lower: 96.61813
Upper: 105.4996
LD75 = 107.6303
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
60
80
100
120
140
SL (mm)

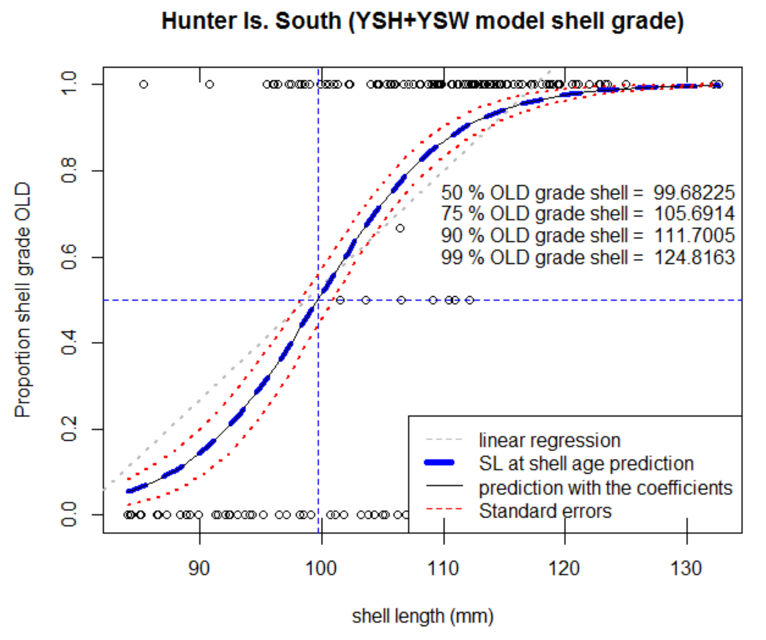

The Nuggets
frequency
0
10
20
30
80
120
160
Shell length (mm)

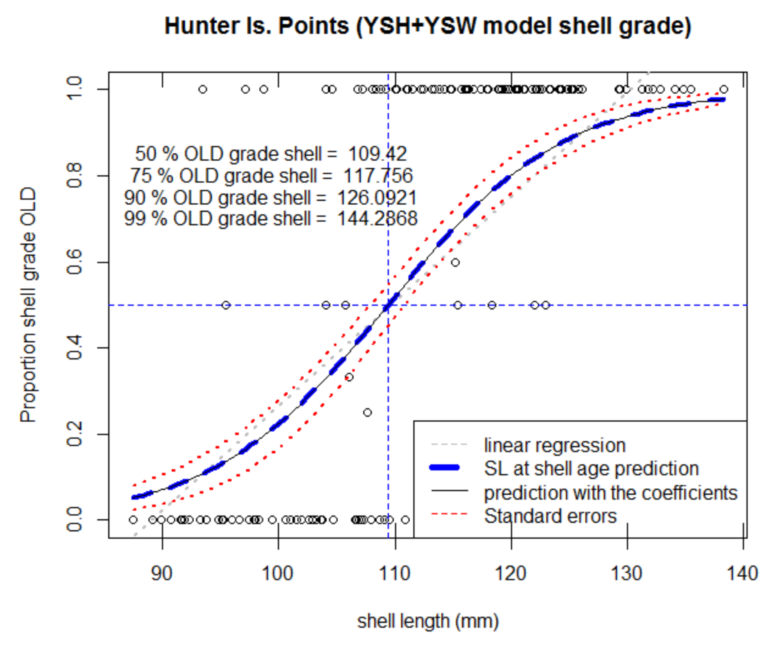

West point
proportion mature
0.0
0.2
0.4
0.6
0.8
1.0
60
80
100
120
140
SL (mm)
LD50 = 89.2736
Bootstrap 95% CI
Lower: 87.66005
Upper: 91.08231
LD75 = 94.31396
linear regression
size at maturity prediction
prediction with the coefficients
Standard errors
West Pt
frequency
0
20
40
60
75
100
125
150
Shell length (mm)

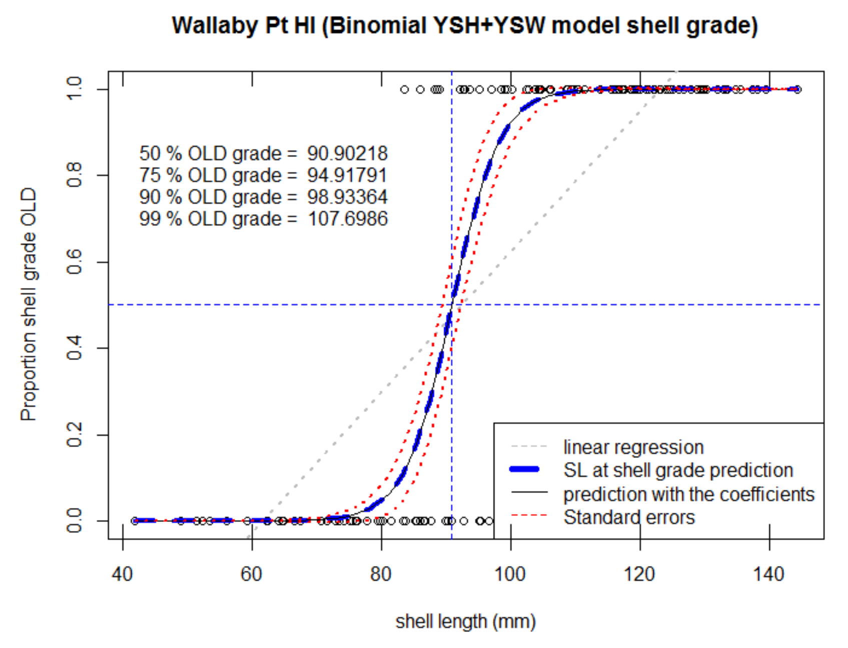
6.7 Appendix 7 – Shell grade binomial plots

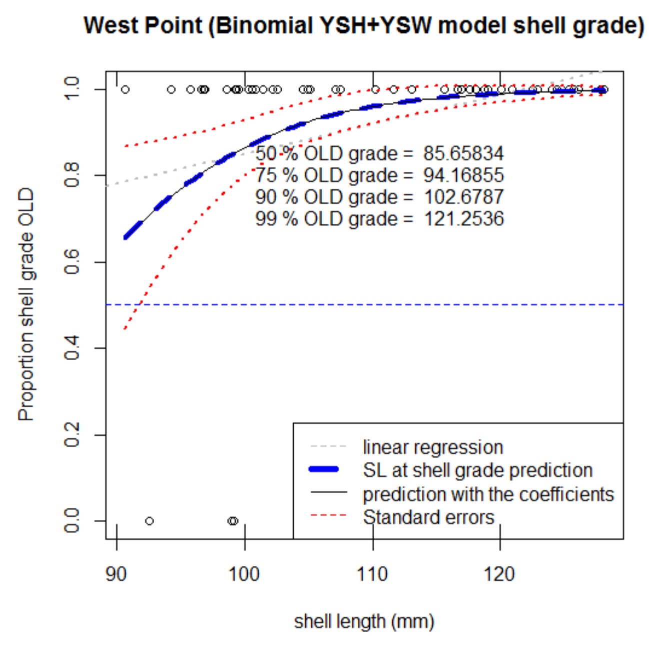
Shell grade binomial plots for selected Tasmanian regions calculated from standardised shell height and shell width binomial model.



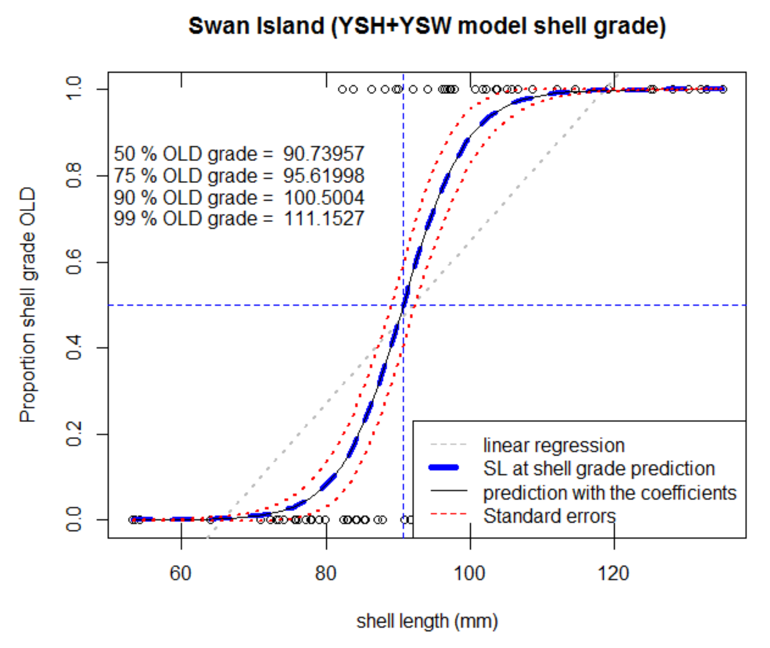



Hunter Is. Points (YSH+YSW model shell grade)
Proportion shell grade OLD
0.0
0.2
0.4
0.6
0.8
1.0
90
100
110
120
130
140
shell length (mm)
50 % OLD grade shell = 109.42
75 % OLD grade shell = 117.756
90 % OLD grade shell = 126.0921
99 % OLD grade shell = 144.2868
linear regression
SL at shell age prediction
prediction with the coefficients
Standard errors

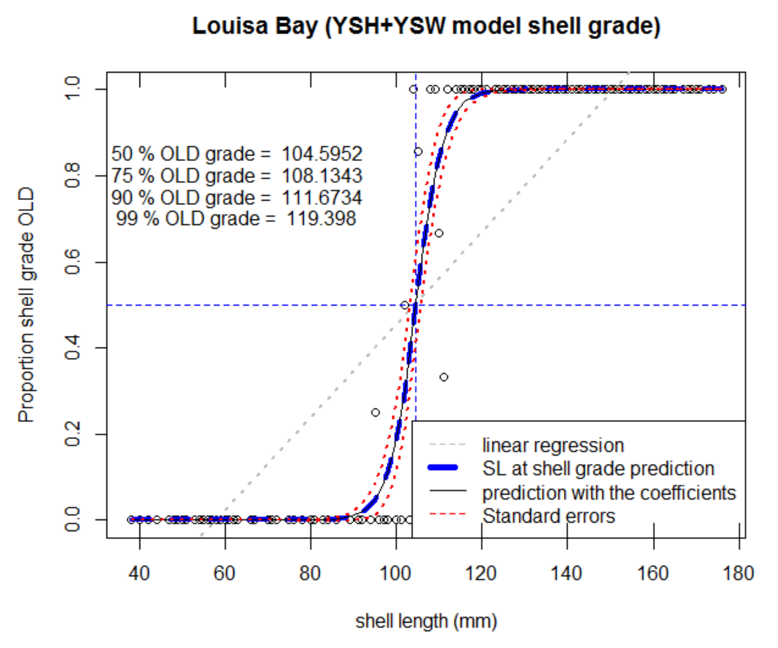

Wallaby Pt HI (Binomial YSH+YSW model shell grade)
Proportion shell grade OLD
0.0
0.2
0.4
0.6
0.8
1.0
40
60
80
100
120
140
shell length (mm)
50 % OLD grade = 90.90218
75 % OLD grade = 94.91791
90 % OLD grade = 98.93364
99 % OLD grade = 107.6986
linear regression
SL at shell grade prediction
prediction with the coefficients
Standard errors

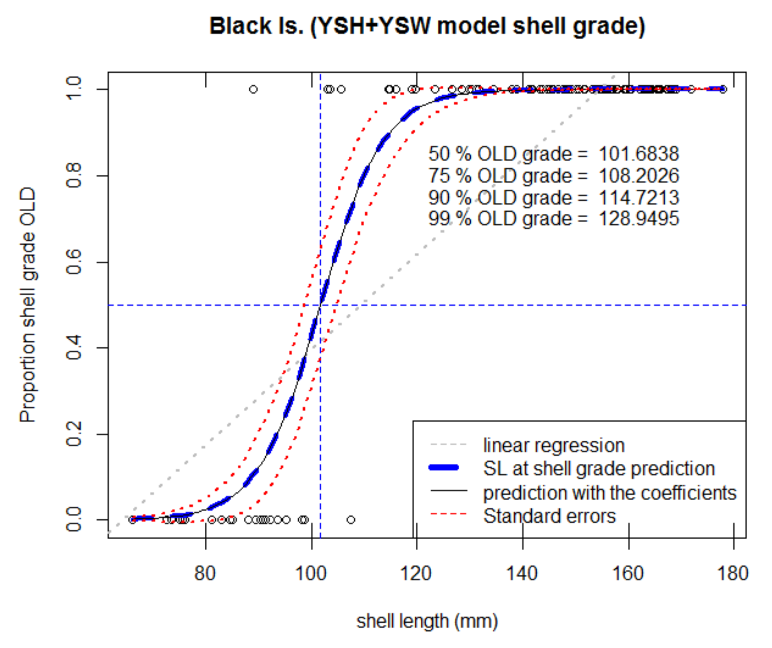


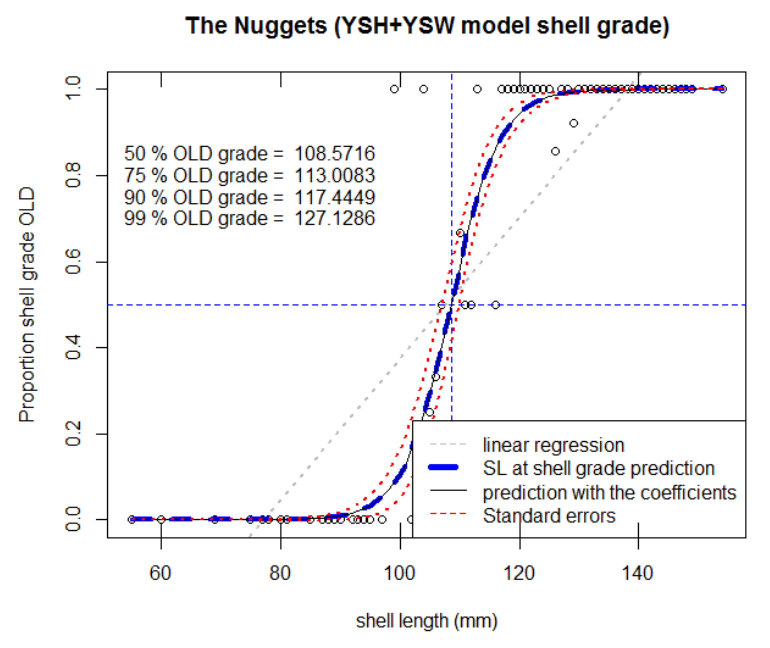
West Point (Binomial YSH+YSW model shell grade)



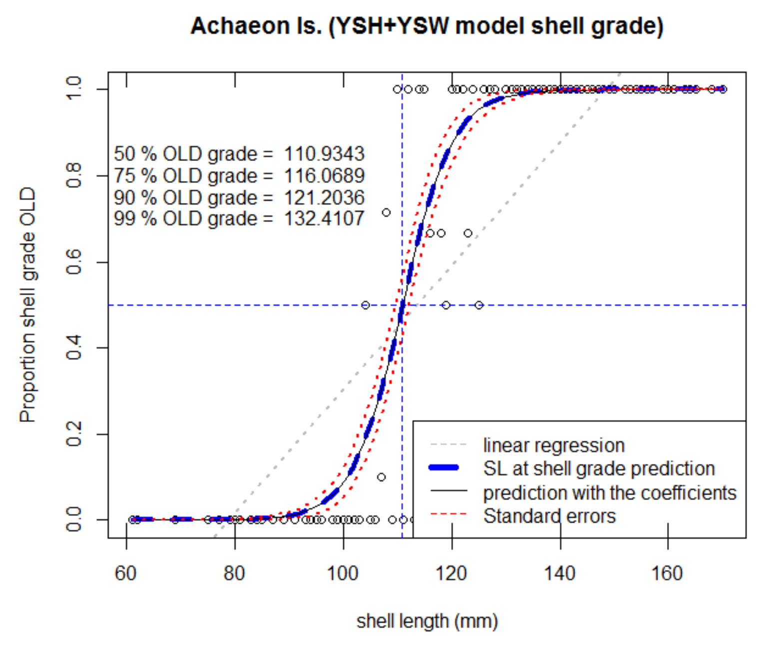
Swan Island (YSH+YSW model shell grade)


Louisa Bay (YSH+YSW model shell grade)
50 % OLD grade = 104.5952
75 % OLD grade = 108.1343
90 % OLD grade = 111.6734
99 % OLD grade = 119.398
Proportion shell grade OLD
0.0
0.2
0.4
0.6
0.8
1.0
40
60
80
100
120
140
160
180
shell length (mm)
linear regression
SL at shell grade prediction
prediction with the coefficients
Standard errors


Black Is. (YSH+YSW model shell grade)
50 % OLD grade = 101.6838
75 % OLD grade = 108.2026
90 % OLD grade = 114.7213
99 % OLD grade = 128.9495
Proportion shell grade OLD
0.0
0.2
0.4
0.6
0.8
1.0
80
100
120
140
160
180
shell length (mm)
linear regression
SL at shell grade prediction
prediction with the coefficients
Standard errors



The Nuggets (YSH+YSW model shell grade)



Achaeon Is. (YSH+YSW model shell grade)