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Executive Summary

Historically, size limits in Tasmania's blacklip abalone fishery have fluctuated in response to varying perceptions of the status of stocks. Concerns about over-fishing in the east and south led to an increase in size limits in 1987, and progressive reductions in the annual landed catch. However, the common state-wide size limit was inappropriate for all Tasmanian abalone stocks because there is a trend towards smaller average size and slower growth rates from south to north, and the increase in size limit meant that much of the abalone stocks in northern Tasmania became inaccessible to the fishery because they did not grow large enough. Catch-rates fell, and subsequently catches decreased in that region. During the 1990's, effort shifted from the north to the east and south-east.

The introduction of zoning to the fishery in 2000 provided a more refined regulatory structure by which the fishery could be controlled. It provided a means of management of the fishery over a smaller spatial scale so that yields could be increased while better protecting stocks. It was suggested that zoning could be used to increase yields from the northern areas of the State where the stocks were under-fished. The region had formerly provided a significant part of the State's catch, and TAFI was requested to look at ways that might lead to the revival of the fishery there, particularly by using size limits smaller than those operating elsewhere in the State. This study was subsequently established to develop estimates of potential levels of annual catch and size limits under which the fishery could be operated with minimal levels of risk to stocks.

At very high levels of fishing pressure, where most legal-size abalone are taken, reproduction is almost entirely dependent on those abalone below the size limit. Part of the rationale behind size limits is that they ensure that sufficient egg production is provided by the fraction of the population smaller than the size limit to sustain the population, even at intensive levels of fishing. In the Tasmanian abalone fishery a recent approach has been to set size limits to allow at least two years growth (and potential reproduction) from the size at which abalone become sexually mature, but incomplete knowledge of the spatial variation of these parameters has limited its application. Nevertheless, it is noted that in parts of the fishery where the size limit is much larger than the size at maturity there has been less concern about sustainable levels of fishing than parts where the size at maturity is much closer to the size limit.

Abalone populations at more than 80 sites in northern coastal waters were sampled and estimates of median size at maturity were developed from each sample. Estimates of growth rate and maximum average size were developed from aged shells from samples collected at 20 of those sites. By using these parameters, we were able to develop estimates of successive mean shell length by site for the years following onset of sexual maturity. These successive mean shell lengths were used to provide information about the degree of protection provided to a region by a range of potential size limits i.e. the number of years taken for populations to reach the size limit once they had matured.

Historically, while annual catches from the north of the State were highly variable, there are no indications that they had approached unsustainable levels. Thus it was assumed that estimates of potential yields from the north could be developed using the mean of annual catches taken at the original (smaller) size limit. By using the length-frequency composition of the samples converted to weight, the proportion of the population at each 1-mm size class was calculated, from which we were able to proportionally adjust the yields to suit different size limits.

A range of potential geographical boundaries for a northern zone was developed. The criteria used to establish boundaries included that they be easily recognised (e.g. headlands, rivers etc.), not cross productive reefs, accommodate gross differences in regional variation of biological parameters, and be compatible with the existing catch reporting spatial descriptors. Accordingly, yields and size limits were developed for regions encompassed by Arthur River, Green Point and Woolnorth Point in the west, and Musselroe Point and Eddystone Point in the east. Because Furneaux Group blacklip populations mature at and grow to a smaller size, it was suggested that a smaller size limit would improve yields in that region.

A Northern Zone was established between the Arthur River in the west and Musselroe Point in the east. A size limit of 132 mm was adopted for the West Coast between Arthur River and Woolnorth Point, 127 mm for the remainder. The fishery opened on 1 January 2001 with a TAC of 280 tonnes. The Eastern Zone TAC was adjusted to 1120 tonnes and the Western Zone to 1260 tonnes, producing a net increase of 70 tonnes production over the previous year.

The size limit and yield estimates and the consequent sustainability of this fishery rely on the integrity of biological parameters, which have been observed to vary with large-scale changes in abundance. Should fishable stocks become heavily depleted, it is possible that growth rates, maximum average sizes and median size at maturity may all increase, thus reducing the level of protection provided by the size limit. Consequently sites reserved from fishing were established in each of the four main regions of the Northern Zone, with the intention that changes in biological parameters be regularly monitored.

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1. Introduction

Two methods are used in the Tasmanian abalone fishery to protect stocks from overfishing: a legal minimum size limit and a total allowable catch (TAC). The rationale behind the minimum size limit is that it ensures sufficient egg production in the fraction of the population smaller than the size limit to sustain the population, even at intensive levels of fishing. Fishing intensity, in turn, is controlled by the size of the TAC. As the TAC increases, then fishing and its effect upon abalone stocks increases. At low levels of fishing intensity, when stock depletion is moderate, it may not matter greatly at what size the stocks are fished. Because few abalone are removed from the population, there will always be a sufficient quantity of mature reproducing abalone to maintain levels of egg production that will sustain population levels.

At higher levels of fishing intensity, there are fewer uncaught legal-size abalone to contribute to egg production, and size limits become more important. At very high levels of fishing pressure, where most legal-size abalone are taken, reproduction is almost entirely dependent on those abalone below the size limit. For this reason TAC's need to be set in conjunction with appropriate size limits. The legal minimum size limit has historically been set to ensure that stocks have sufficient reproductive capacity to sustain fishing at the TAC. In the Tasmanian abalone fishery, the traditional approach has been to set size limits at a size that allows at least two years growth (and potential reproduction) from the size at the onset of sexual maturity.

Historically, size limits in Tasmania's blacklip abalone fishery have fluctuated in response to varying perceptions of the status of stocks. Concerns about over-fishing in the east and south led to a 5-mm (from 127 mm to 132 mm) increase in size limits in 1987, and progressive reductions in TAC. Unfortunately, the common state-wide size limit was inappropriate for all Tasmanian abalone stocks because the size at onset of sexual maturity and growth rates of blacklip abalone are spatially highly variable. There is a trend towards smaller average size and slower growth rates from south to north, and from west to east. The increase in size limit meant that much of the abalone stocks in northern Tasmania became inaccessible to the fishery because they did not grow large enough. Catch-rates fell, and subsequently catches dwindled in that region. During the 1990's, effort shifted from the north to the east and south-east.

The introduction of zoning to the fishery in the year 2000 provided a mechanism of regional control of the abalone catch. In 1999 the abalone industry suggested that zoning could be used to increase yields from the northern areas of the State where the stocks were believed to be under-fished. Biological advice was sought as to the appropriate size limits and yields for a potential northern zone for blacklip abalone. The aims of this study were to:

- Determine appropriate size limits for blacklip abalone in northern Tasmania
- Suggest appropriate yields of blacklip abalone from the region
- Identify the most appropriate boundaries for the proposed Northern Zone.

2. Methods

2.1 Field Sampling Procedures

Blacklip abalone populations from the north of the State have been regularly surveyed since 1988. While some of the data from these surveys was directly applicable to the current study, it became apparent that more information about size, growth and maturity status was needed, particularly from areas where production had declined since the implementation of the increased size limit. An intensive population-sampling program was undertaken in 1999.

Samples of blacklip abalone were collected from sites that were considered representative of local populations or, on the advice of local divers, representative of likely fishing grounds. One of the main criteria in selecting sites was that abalone should be present in quantities that would attract commercial fishing. We were particularly interested in sites where abalone grew larger than those from surrounding areas, since these stocks would become less protected if fished at a lower size limit. We also needed to gauge the variability of growth and maximum size within a region i.e. if a region held predominately small abalone, to what extent should several isolated patches of large abalone be protected? A final criterion for selecting sites was proximity to topographical features (long beaches, headlands), which were potential size limit boundaries.

The intention of sampling was to produce information about both the size at which abalone became sexually mature (size at maturity) and how fast they grew. Sampling was undertaken by divers breathing through surface supply apparatus (hookah), operating from runabouts and dinghies.

For size-at-maturity samples, all abalone of length greater than 50 mm were kept. About 200 individuals were collected from each site. Length and maturity status of each abalone in the sample was noted. Maturity status (whether male, female or immature) was determined for each abalone by visual inspection of the intact gonad. If gonad (either testis or ovary) could be discerned abalone were considered to be sexually mature. The series of figures below illustrate the guidelines used to determine sex and maturity status of blacklip abalone.

In mature male abalone (Figure 1) the gonad is lightly coloured (usually ranging from off-white to a very pale pink) and is clearly differentiated from the purple digestive gland. In mature female abalone (Figure 2) the gonad tissue ranges from grey to dark green in colour and can also be readily identified from the much darker digestive gland. Eggs are visible at low magnification.

In most cases, immature abalone (Figure 3) are readily identifiable, because differentiation of the digestive gland is yet to take place i.e. the digestive gland remains purple throughout. Occasionally samples yielded abalone verging on maturity. By slicing a section from the tip of the gonad and comparing it with samples from mature and immature abalone the extent of maturity could be gauged. Unless gonad material could be discerned, it was categorised as immature.

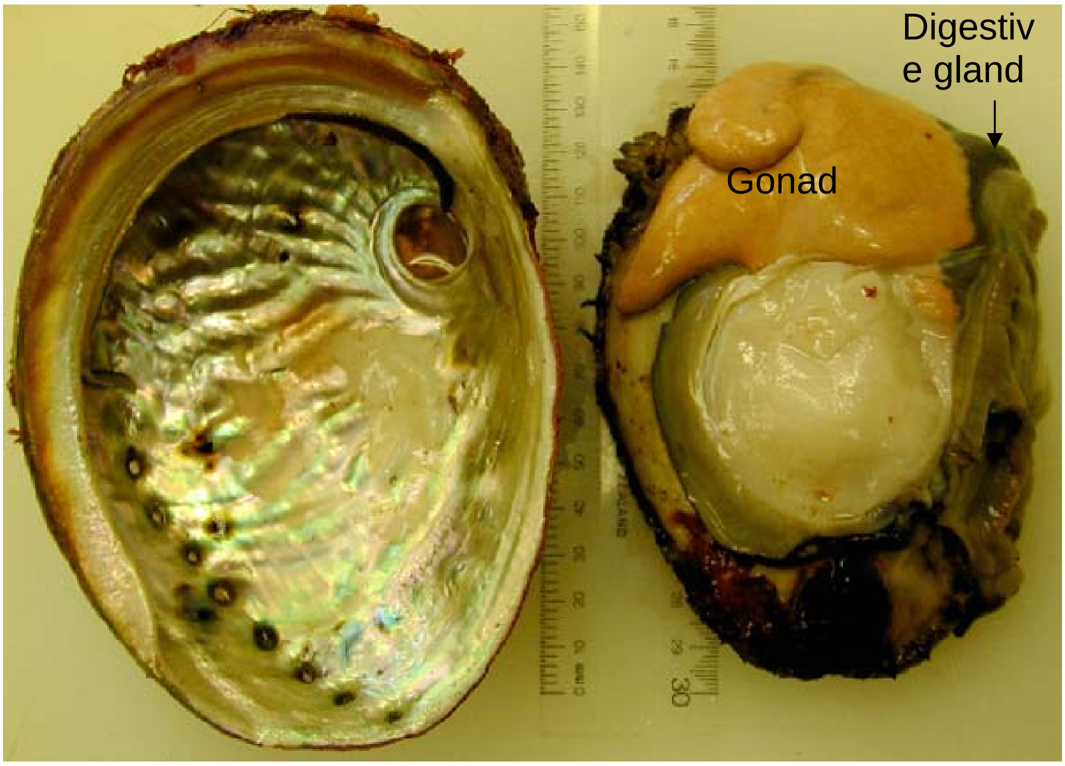


Figure 1. Male blacklip abalone, showing (in the upper part of the photo) the off-white coloured gonad tissue, which is clearly distinguished form the adjacent digestive gland.

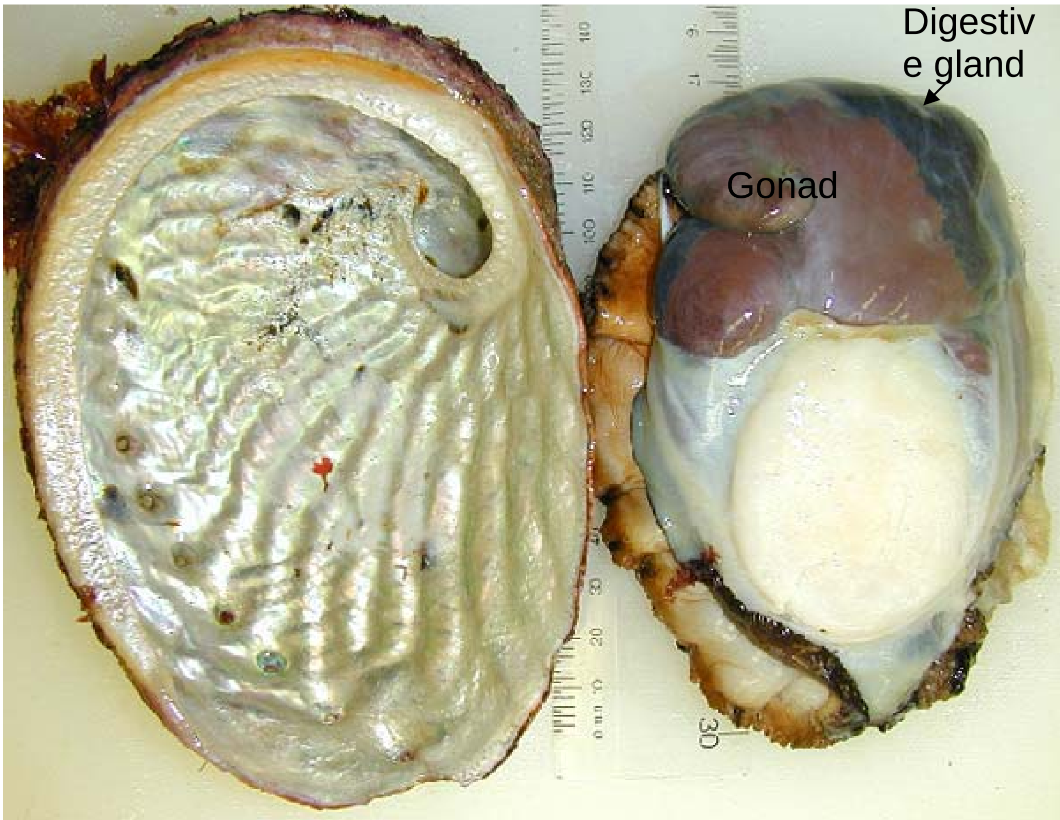


Figure 2. Female blacklip abalone, showing the light purple gonad (lower part of the photo) which is strongly differentiated from the adjacent darker digestive gland.

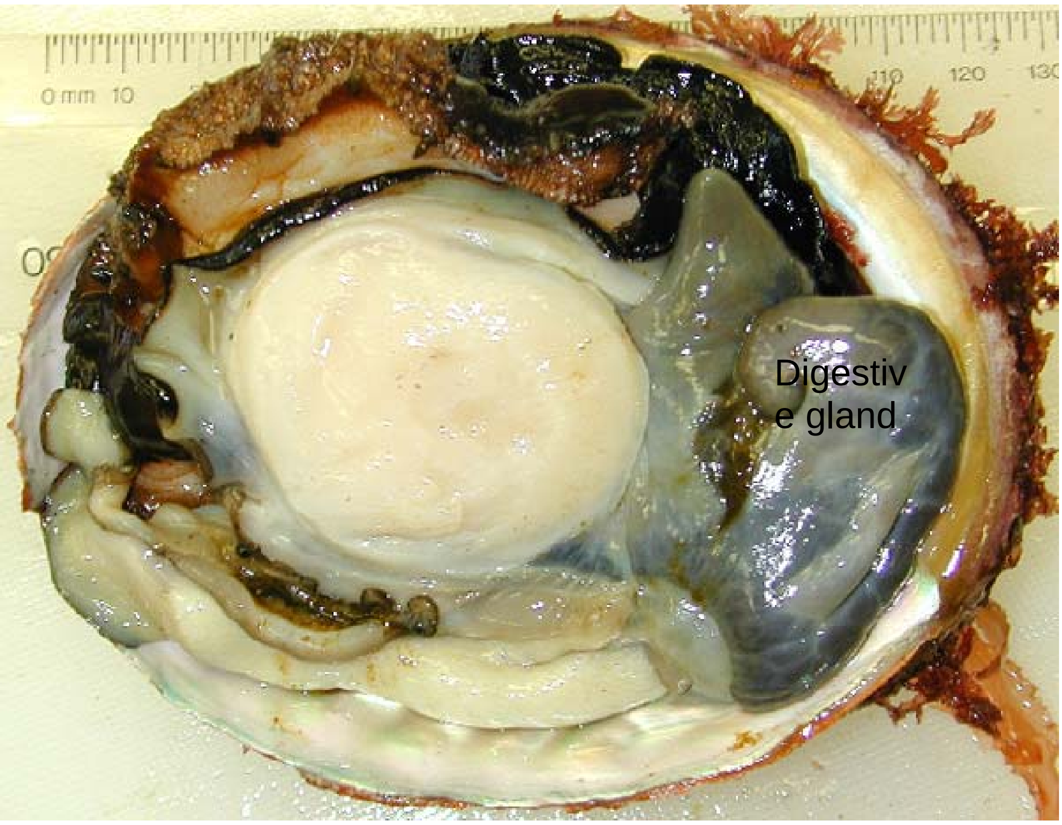


Figure 3. Immature blacklip abalone, showing the undifferentiated tissue of the digestive gland and gonad.

Growth rates were estimated from aged shells. Ageing samples were also collected by exhaustive searching of reef, but because length information from all age classes in a population was needed, all abalone encountered were collected. About 400 abalone were collected for each ageing sample. Samples of this size were required because of the large variation in growth rates between individual abalone, and also because it was expected that a proportion of the abalone would be impossible to age because of damage to the shell by boring parasites. Ageing samples were also used for size-at-maturity analysis.

Abalone populations were surveyed in four regions: the Furneaux Group, King Island, North East and North West (Figure 4).

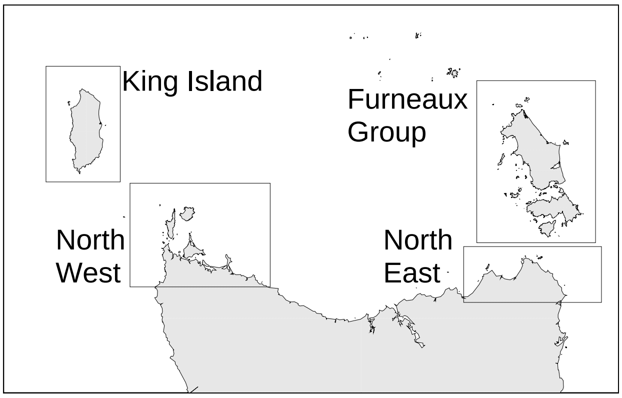


Figure 4. Northern Tasmania, showing the four regions from which samples were collected.

Samples were collected from the West Coast as far south as Smith's Gulch (between Gannet and Ordnance Points), and from there northward to the Arthur River, including Couta Rocks, Temma Harbour, Sundown Point and Sarah Anne Rocks. Between the Arthur and Green Point (Marrawah), we sampled seven sites, including Church Rock and Australia Point, where we were told to expect large abalone. Specimens were retained for ageing at Smiths Gulch, Couta Rocks, Sundown Point, Australia Point, Church Rock, West Point and Mount Cameron West. At all these sites, sampling was conducted inshore, in shallow water, during low swell and sea conditions (Figure 5).

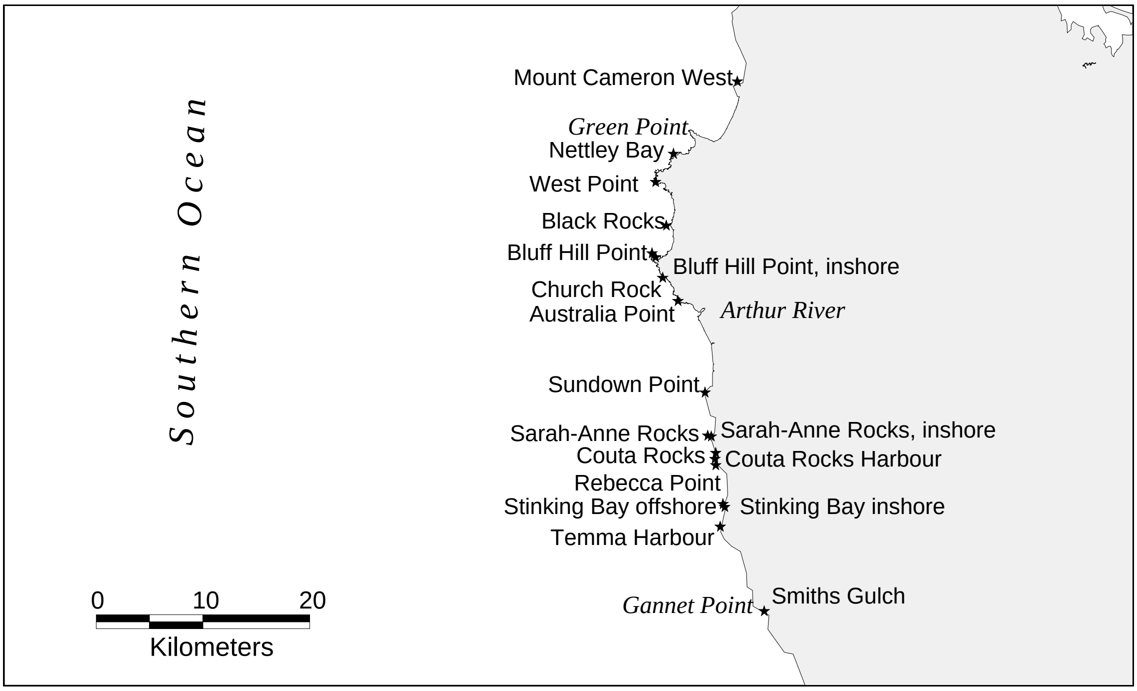


Figure 5. Sites sampled on the northern part of the West Coast, south of Marrawah. Sampling sites are shown with an asterisk, topographical features are shown in italic type.

Another seven sites were sampled between Green Point and Woolnorth Point (Figure 6). At Mount Cameron West, abalone were collected along the northern shore of the headland. The sites at Bluff Point, Hippo Point and Suicide Bay were selected because we believed that they held larger abalone than usually found along this part of the coast.

Further north, blacklip abalone were collected from between Trefoil Island and the mainland. Quantities of small blacklip abalone were found along the narrow reef on the east coast of the northern side of Hunter Island, south of Cape Keraudren. Previous work in the area had shown that the northern part of Hunter Island's west coast had quantities of abalone, although they were quite small, so sampling in this area was restricted to a site at Cuvier Point. Larger abalone were found along the shore on the west coast of this island south of Cuvier Point, an area which is currently fished at the 132-mm size limit (Figure 6).

Although aware that commercial quantities of blacklip abalone were caught at Three Hummock Island, the Petrels and Albatross Island, we were unable to collect abalone in these areas. Specimens were retained for ageing at Mount Cameron West, Bluff Point, Hippo Point, Suicide Bay, Little Trefoil Island, Cape Keraudren and Stack Island.

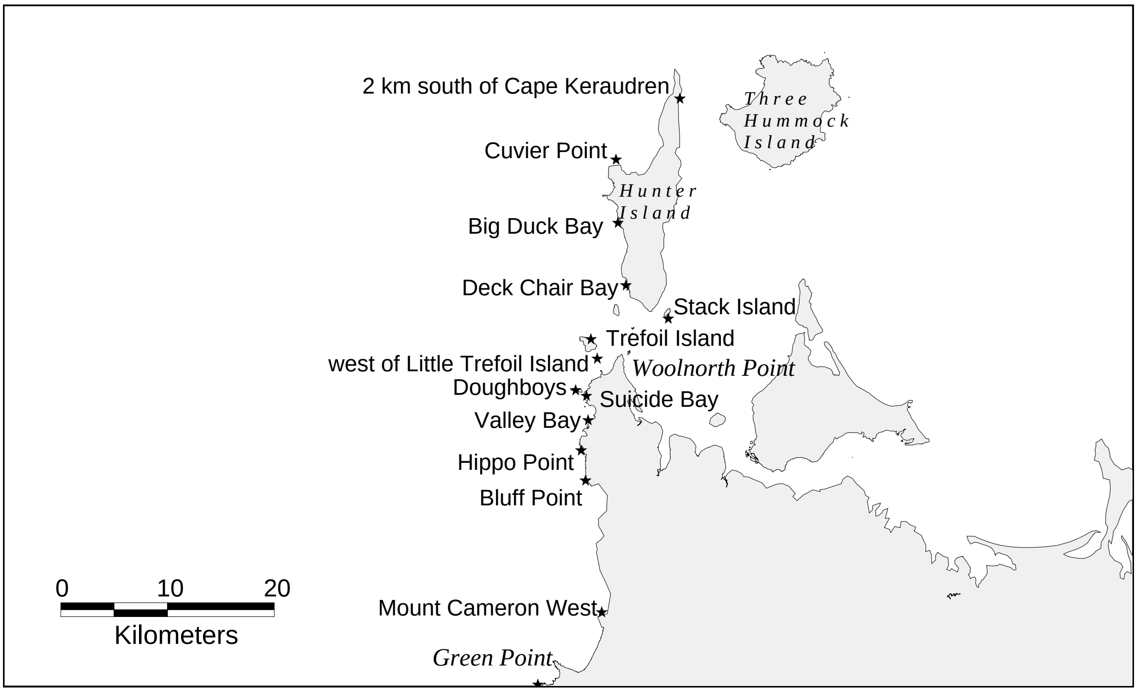


Figure 6. Sites sampled in North West Tasmania, from Green Point north to Woolnorth Point, and around Hunter and Trefoil Islands.

On King Island (Figure 7), the area around Currie Harbour was extensively sampled as this area had supported a strong fishery at the 127-mm size limit. In the south, six sites were sampled between Cataraqui Point and Stokes Point. Larger abalone were found to the east of Stokes Point, although in smaller quantities. Specimens were retained for ageing at Waterwitch Reef, Cataraqui Point, Caves Creek and Sandblow Point. Two sites were sampled at Stokes Point, and three sites were sampled immediately north of Currie Harbour.

In the Furneaux Group (Figure 8), sampling mainly focussed on the north and north-west of Flinders Island, around Babel and adjacent islands on the east coast, and on the south-east coast of Cape Barren Island. However, samples were also collected from islands in the west of the Furneaux Group, in Franklin Sound and on Cape Barren Island at Long Island, G.V.H. Point and Cape Sir John on the west coast, and Shag Rocks on the east coast. Specimens were retained for ageing at Cape Frankland, Old Man Head, Cape Barren, Passage Island and Cat Island. An earlier study collected samples from Gull Island, near Cape Barren.

In the North East (Figure 9), sampling was undertaken between Waterhouse Island and Ironhouse Point, south of St Helens. Previous work has shown that in Bass Strait waters (west of Cape Portland), blacklip abalone tend to be quite small (Nash *et al.*, 1994), and in the early part of the fishery when the size limit was smaller, never produced significant catches. Consequently, most of our fieldwork was done east of Cape Portland. Specimens were retained for ageing at George Rocks and Eddystone Point. A further site was sampled at Foster Islands (near Cape Portland), but no immature abalone were collected. Sampling was undertaken at Croppies Point, Waterhouse Island, the four sites south of Eddystone Point, and at Ironhouse Point (south of St Helens and not shown here) as part of earlier studies.

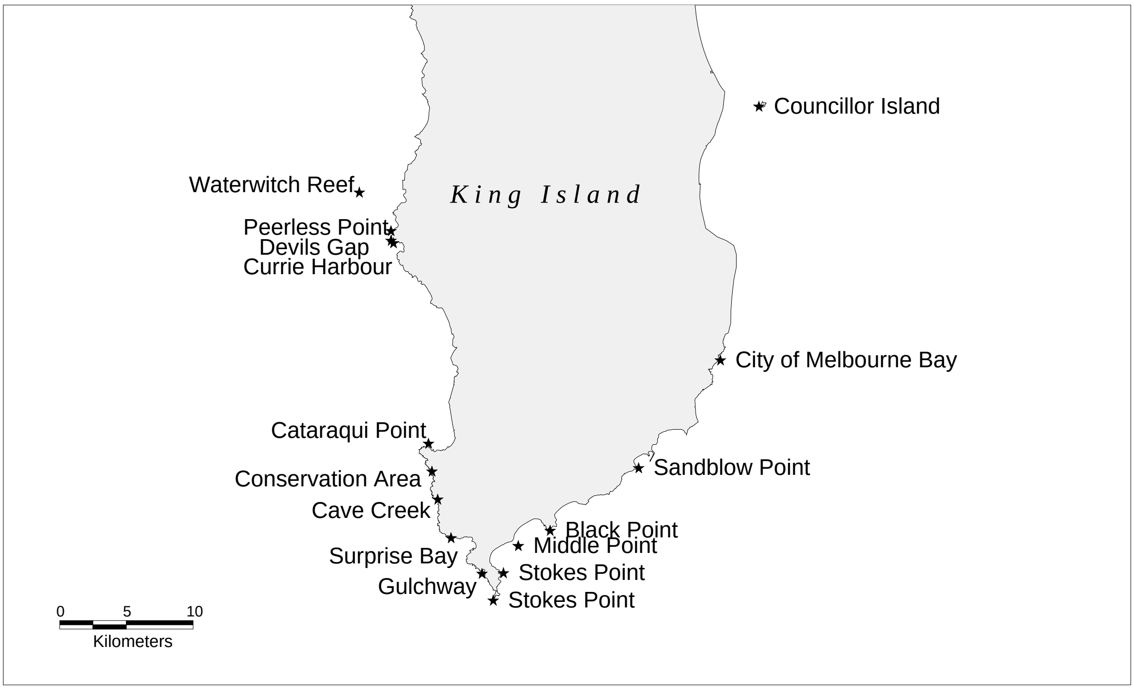


Figure 7. Sites sampled around King Island.

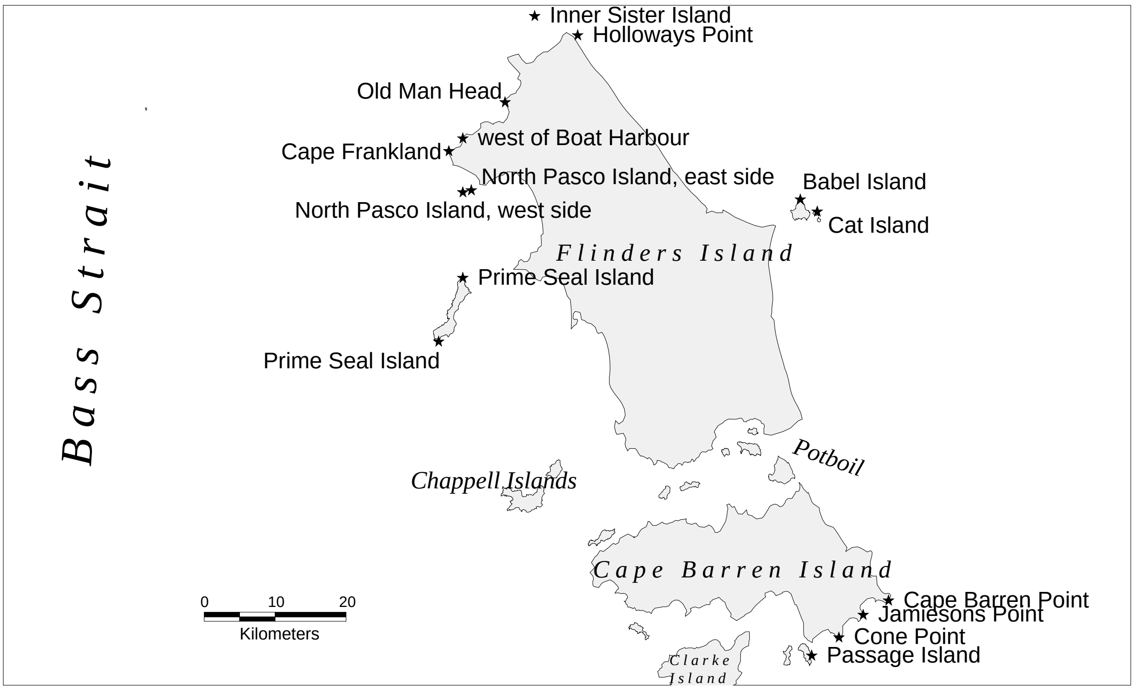


Figure 8. Sites sampled in the Furneaux Group.

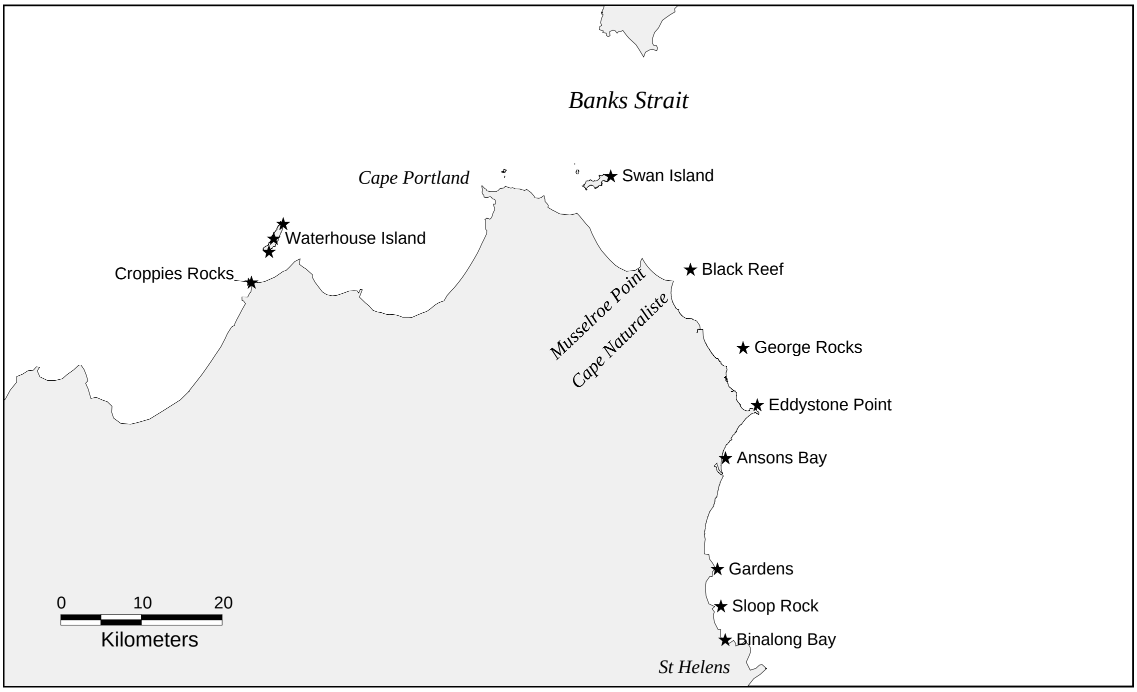


Figure 9. Sites sampled in the North East.

Surveys in the Furneaux Group and at King Island were conducted from the 5 metre dinghy *Poolta*, launched from the 20 m vessel *Challenger* (which was used as a mother-ship). In the North West and North East the surveys were conducted from the dinghy, the 6 metre aluminium runabout *Lowinna* and the 7 metre shark cat *Wobbegong II*. All abalone collected were either taken to the mother-ship or the nearest abalone processing facility, where they were kept frozen until their return to Hobart. At the Taroona laboratories the abalone were stored at -30 °C until they were processed.

2.2 Laboratory Procedures

2.2.1 Sexual Maturation

In this study, size at maturity refers to the size class at which 50 % of individuals were mature. It was found that abalone generally mature at age, regardless of their size (Nash, 1990). Usually then, samples for maturity analysis taken from the same population over time could be expected to produce the same or similar sizes at maturity. If growth rates between populations in a region are similar, then size at maturity will be similar. It also follows that large, fast growing abalone tend to have a large size at maturity, while small, slow growing abalone have a small size at maturity.

The 50 % or median level of maturity was used, because there was some variation at the size at which abalone mature. Abalone growth rates, even at an early age, vary widely among individuals (Day and Fleming, 1992). Our sampling shows that size at maturity is equally variable, but provided the size range over which maturity takes place is small (e.g. 80 – 120 mm), then the 50 % level of maturity describes the population adequately.

Figure 10 illustrates the concepts behind size at maturity. The curved line shows the fit of the data to the logistic function described in Equation 1. A perpendicular line drawn to intercept the curved line at 50 % maturity meets the horizontal (shell length) axis at 101.7 mm (i.e. the size at 50 % sexual maturity in this sample is 101.7 mm). Note that in this example, abalone are first maturing at 95 mm, and that 100 % maturity does not occur until after 117 mm. The sample is comprised 228 abalone collected at Sundown Point (North West Tasmania) and represents the percentage mature in 1-mm size-classes between 70 and 130 mm.

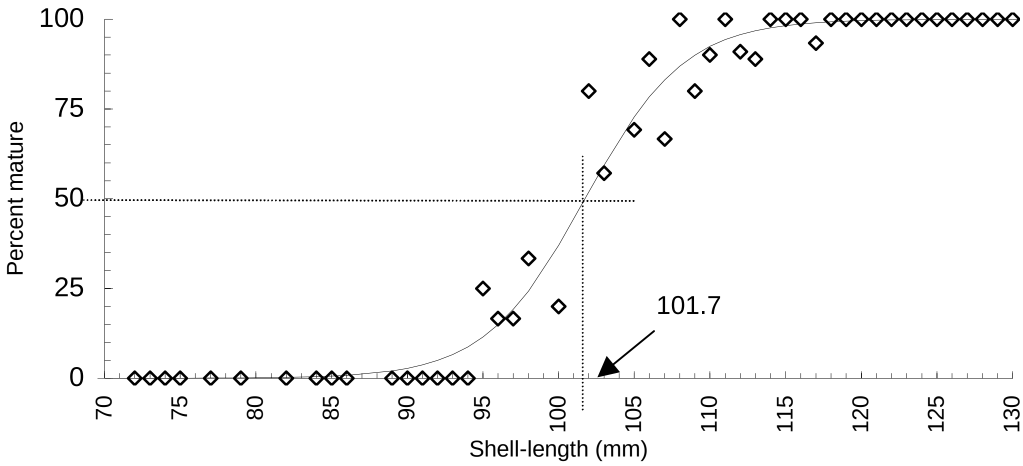


Figure 10. An example showing the concepts behind size at maturity.

Rates of maturation by size were determined by logistic regression of the maturation data (number mature, number sampled by size-class, where size-class is one millimetre) to the logistic equation using *Genstat*:

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

Equation 1

where p is proportion mature, x is length (or age), and c and d are parameters of the logistic function. The 50 % size at sexual maturity and 95 % confidence intervals were calculated by the FIELLER procedure in *Genstat*.

2.2.2 Age and Growth Estimation

Shells from 20 sites were examined for ageing. Age of abalone shells was determined by counting rings laid down in the spire of the shell. While sites were selected randomly from among those sampled, we rejected some samples. We were unable to age shells that had been heavily attacked by parasites, and unfortunately, most of the emergent blacklip abalone from northern Tasmanian waters were parasitised to some degree, some sites being worse affected than others.

The length of each shell was recorded and then prepared for ageing by a four stage process, which involved:

- cutting a section through the spire to expose a cross section of the ring structure
- polishing with fine grit wet-and-dry paper using water as a lubricant/ washing medium
- etching with weak hydrochloric acid
- highlighting the rings with a carbonate stain (Figure 11).

The shell sections were examined under a microscope, and the number of rings and clarity of reading for both sides of the section were noted (Figure 12). Clarity was recorded on a scale of 1 (worst) to 5 (best), and while indicating ease of reading, reflected shell quality, absence of borers and the degree to which the number of rings on the left hand side of the section matched the right hand side. Ring-counts from the right hand side of shells with clarity of three or greater were used in the analysis. Few shells were completely free of borers, but satisfactory readings could be achieved by following growth rings around badly bored sections. The number of growth rings was assumed to be indicative of the age (in years) of the abalone.

Growth curves were fitted by non-linear regression of age-length couplets using *Genstat*. The von Bertalanffy growth function (VBGF) of the form:

$$L_t = L_\infty \cdot [1 - e^{-k(t-t_0)}]$$

Equation 2

was used to describe growth, where L_t is the length of the abalone at age t, L_∞ is asymptotic or average maximum length, t_0 is the theoretical age at which L, the length of the abalone is zero, and k is the coefficient of growth.

Figure 11. The process of making growth rings visible involves etching the shell sections with weak hydrochloric acid, then applying a stain to the surface so that the bands are highlighted.

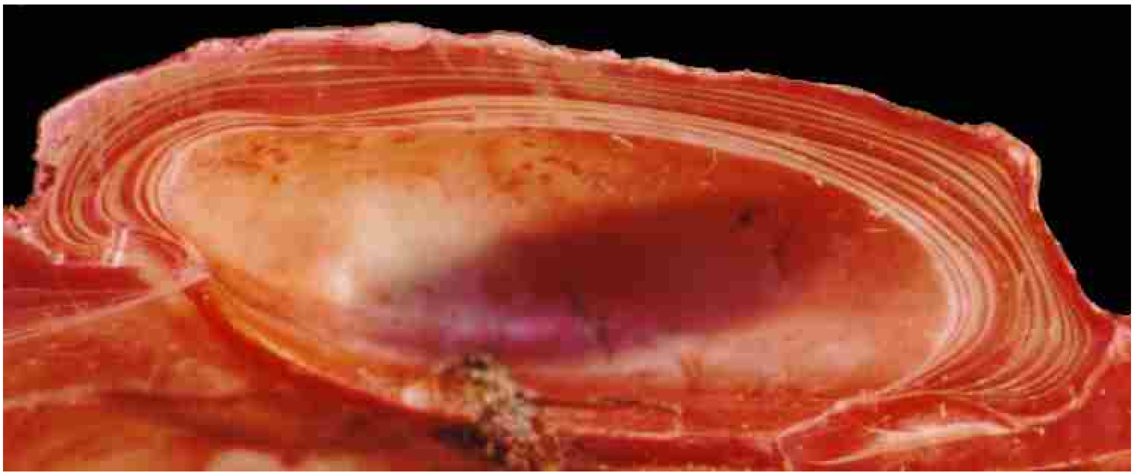


Figure 12. Stained section through a blacklip abalone shell, showing alternating dark and light bands. The age of the shell is estimated from the number of dark bands on the right-hand side of the section.

2.2.3 Morphometry

Where shells were retained (for growth analyses), the following morphological data were recorded for each abalone:

- whole weight
- shucked meat weight
- dry shell weight
- shell length
- shell width, and,
- vertical shell height.

Weight and length data were fitted to the power equation:

$$\text{whole weight} = a.\text{length}^b$$

Equation 3

where a and b are parameters of the power relationship.

2.3 Estimation of Protection Provided by Size limits

The degree of protection offered by size limits was evaluated in terms of the number of years it took to grow to legal size following maturation, for each of the sampled populations. Where populations were not aged, they were assigned growth parameters calculated for the most appropriate of the 20 sites where ageing was undertaken, using criteria such as distance between aged and un-aged populations and differences in size at maturity. Using the VBGF, the mean length at years 1 to 10 following maturation were calculated. This indicated the protection afforded each population for various size limits.

Growth parameters from tag-recapture studies were also used to estimate the level of protection provided for a range of size limits. These parameters were derived from studies of blacklip abalone undertaken in Bass Strait (Tarbath, 1999b), the northern part of the West Coast and the North East (Tarbath, 1999a).

2.4 Estimation of Appropriate Yields

A model was developed that estimated sustainable yields for any size limit. Essentially, the model estimated yields at different size limits from the proportion of the population that contributed to historical yields at the 127-mm size limit. This model depended upon two key assumptions:

- annual catches from the north of the state taken at the 127-mm size limit between 1975 and 1986 were generally sustainable
- fishing effort was at such low levels when sampling was undertaken that the size-composition of samples approximated those of unfished populations.

The method of estimating yield involved four steps, explained in detail below, using the following figures to provide an example of the method.

Step 1 modified size-composition data from each region. The raw data, plotted at 1-mm intervals, was un-evenly distributed (Figure 13):

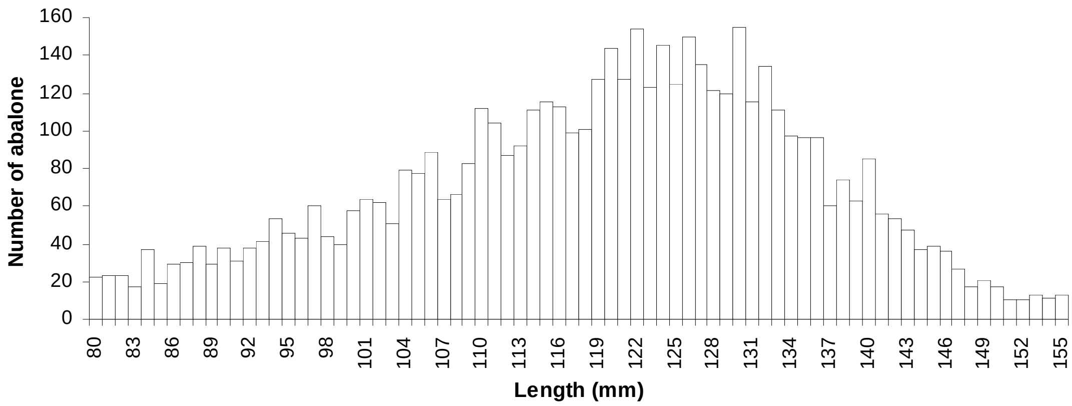


Figure 13. Size-composition of abalone collected from all sites within a region.

The extreme value probability density function (Equation 4)

$$f(x) = \left(1/b\right)e\left[\left(x-a\right)/b\right].e\left\{-e\left[\left(x-a\right)/b\right]\right\}$$

Equation 4

(where *x*, *a* and *b* are parameters of the function) was fitted to each region's size composition data by least squared residuals (Figure 14).

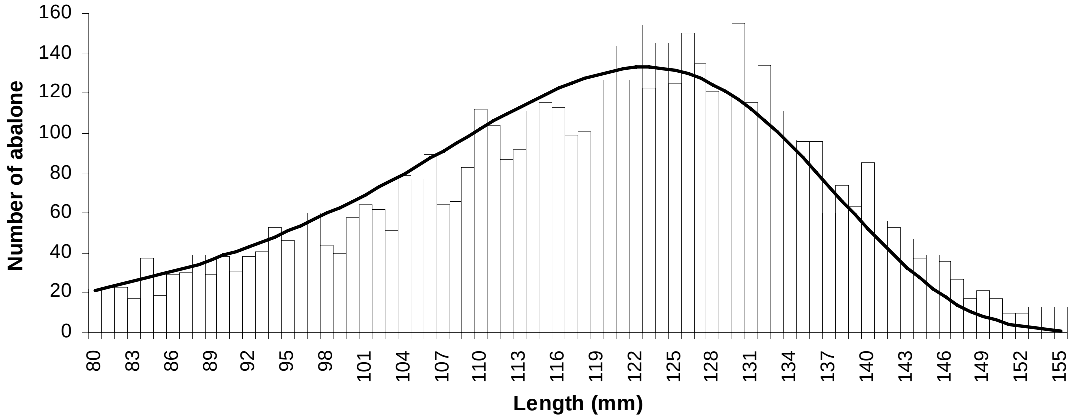


Figure 14. The extreme value probability density function fitted to size-composition data.

This provided a smooth distribution of the size composition (Figure 15):

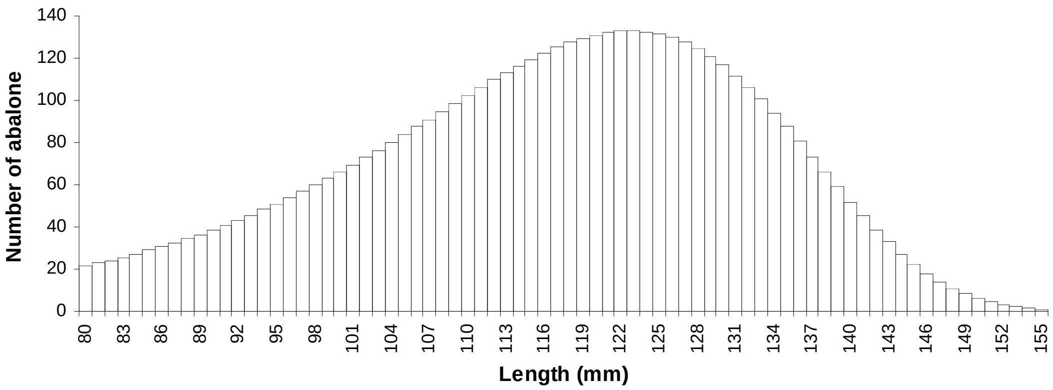


Figure 15. Size-composition data after fitting the extreme value probability density function.

Step 2 converted the size-composition to a weight-composition, using the parameters of the length-weight relationships from Section 2.2.3, an example of which is shown below (Figure 16):

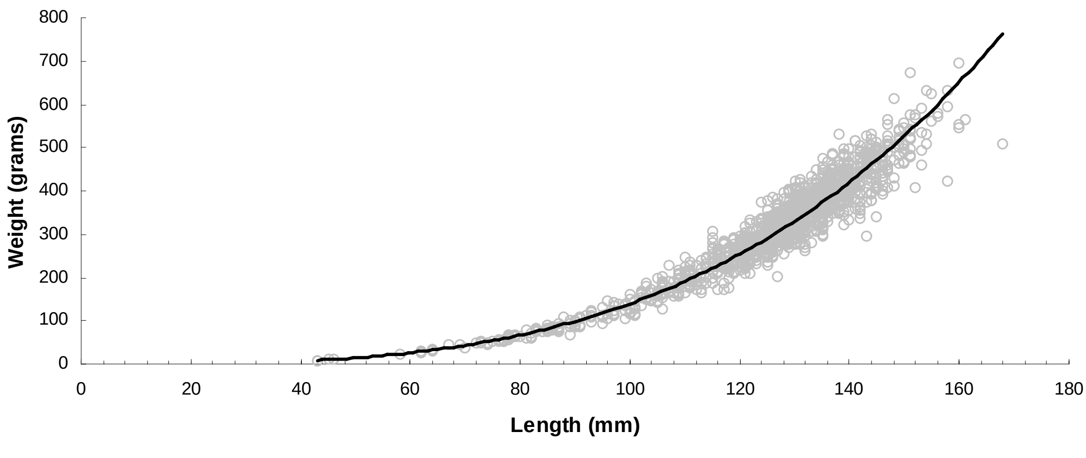


Figure 16. Abalone length-weight data, to which has been fitted a power function of the form $a.\text{length}^b$.

Multiplication of the number of abalone in each size-class by the average weight of abalone in that class generated a weight-distribution profile (Figure 17). Note the mode shifted from 122 mm in the size-composition to 128 mm in the weight-composition profile because of the non-linearity of the length-weight relationship.

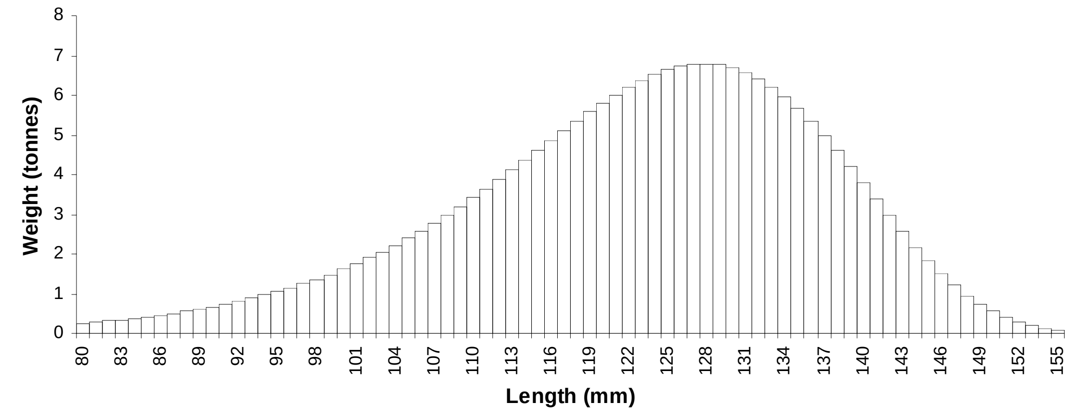


Figure 17. The composition by weight of each size-class.

The third step calculated a cumulative-weight distribution as a percentage of the total weight of the stock. This means that, starting with the largest abalone, the sum of the weights progressively increased for each 1-mm size-class (Figure 18). The percent-cumulative weight distribution provided an index of the relative weight contributed by each size-class.

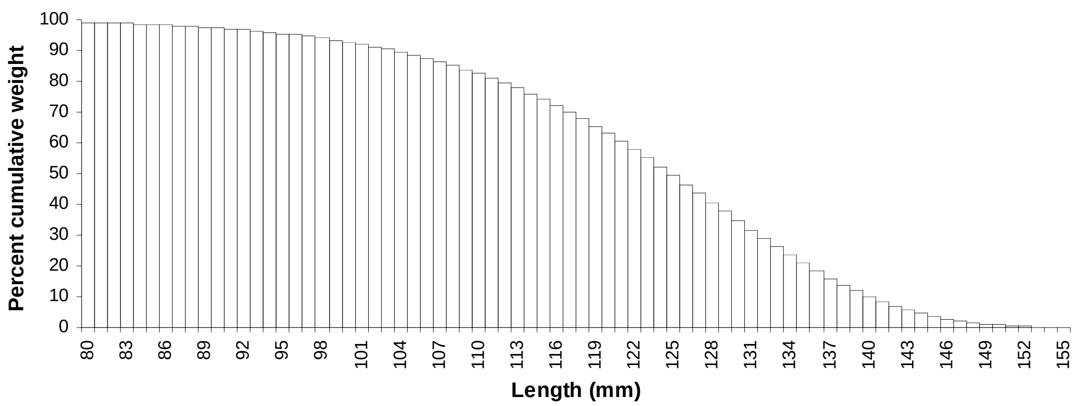


Figure 18. The cumulative weight, by 1-mm size-class, shown as a percentage of sample mass.

The final step calculated the yield from the fishery. It was assumed that size-composition of the stock relative to the size of fishable biomass remained constant. Because the average annual catch or yield from the fishery at 127 mm was known, the yield at any other size could be estimated.

The yield was calculated as the product of the yield at 127 mm multiplied by the proportion of the cumulative weight at that size limit relative to the cumulative weight at 127-mm size limit, or

$$Yield_{new-size} = Yield_{127mm} \frac{\%\,Weight_{new-size}}{\%\,Weight_{127mm}}$$

Equation 5

In this particular example, the proportion of the total weight of the stock above the 127-mm size limit was 44 %. If the size limit was reduced to 120 mm, the proportion of the total weight of the stock above the size limit became 63 % (Figure 19).

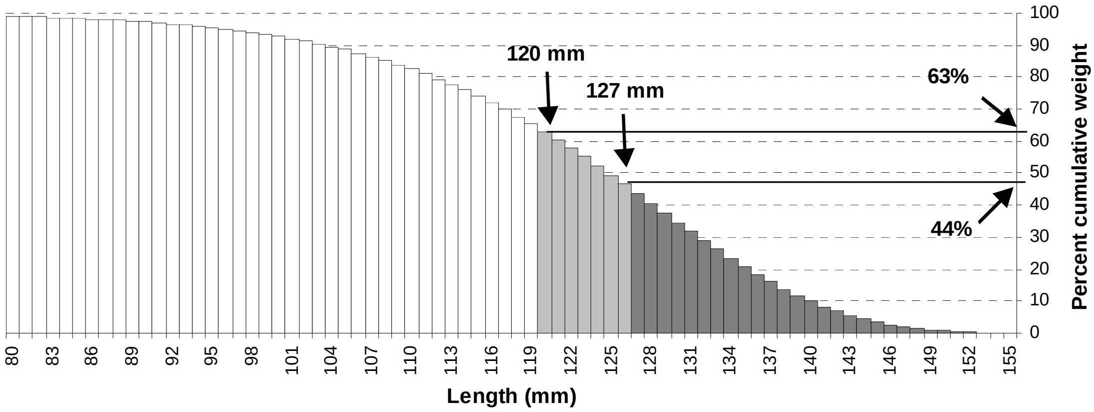


Figure 19. The percentage cumulative weight, showing the proportion of the weight of the stock at 127 mm, relative to the proportion of the weight of the stock at 120 mm.

If the average annual catch at the 127-mm size limit was 100 tonnes, then the expected yield at a 120-mm size limit would be

100 tonnes × 63% / 44%, or 144.3 tonnes.

By increasing (or decreasing) the size limit, potential yields could be estimated, e.g. at 80 mm the catch was 229.2 tonnes, at 125 mm,113.4 tonnes, and at 132 mm, 66.4 tonnes. The rate of change in yield is greatest between 110 and 140 mm, because this is where the confluence of abundance and weight per individual abalone is maximised.

Critical to the success of this process of estimating yield is the assumption that in northern Tasmania, annual catches were generally sustainable when the stock was fished with the 127-mm size limit. However, some years (particularly between 1983 and 1987) annual catches were at extraordinarily high levels, and were probably unsustainable. In other years, catches were extraordinarily low, influenced more by fleet dynamics rather than low abundance. The option of excluding these atypical catches when calculating the average annual catch was provided. Atypical catches were defined conservatively as annual catches that were ± 1 standard deviation from the average.

Yields in tonnes were calculated for each of the four northern regions and then combined to estimate the total yield for various configurations of a northern fishing zone. The annual catch for each region was calculated by summing the average annual catch (1975-1986) of the component blocks within a region. Catches fluctuated, but tended to increase in amount over this period, in line with catches state-wide (Table 4).

Preliminary analysis of size-composition, maturity and growth data indicated marked sub-regional differences between sampling sites in the North West and North East. Size-at-maturity and growth analyses suggested that there were natural boundaries in the North West and North East that did not necessarily coincide with statistical block boundaries (Figure 20), but which could be useful size limit boundaries. Potential yields were calculated for these sub-regions.

These natural boundaries occurred near Green Point in the North West and Musselroe Point in the North East. In both cases, they fell approximately halfway along the coastline of a statistical block. It was assumed that fishing effort (and catch) was evenly distributed either side of the natural boundaries, and that annual catches for these smaller regions could be estimated by halving the average annual catch of the block where the natural boundary lay, and adding it to the remaining blocks within the region. In the North West, fishing effort was relatively evenly distributed along the coast of Block 5, either side of Green Point, and consequently this approach should have provided a sound estimate of potential yield. In the North East, however, most of the catch came from Block 31. The distribution of fishing effort there prior to the 1987 size limit increase is unknown. Currently, the greater proportion of catch is taken from south of Musselroe Point, but whether this merely reflects the difficulties of fishing at a size limit that is too high for abalone populations in the northern part of that block is unknown. Consequently, this approach could cause over-estimation of the potential yield from the North East if the boundary was set at Musselroe Point.

3. Results

The data from over 80 sites is presented, of which 72 were recently sampled for this study. At 20 of these sites, shells were retained for ageing and subsequent growth analysis. A total of 22,301 abalone were collected.

Large quantities of abalone were found at most of the sampled sites, consistent with reported low levels of fishing effort and mortality. Exceptions occurred in the Furneaux Group, where at some sites blacklip abalone were either entirely absent, or present only in small quantities. These sites were inshore on the west of Flinders Island, the Chappell Islands, the west of Cape Barren Island between Long Island and Cape Sir John, and at Shag Rocks in the east. Between Holloways Point and the Potboil, blacklip abalone were found in quantity only in the area about Babel Island. Large quantities of blacklip were found at the four sites in the south-east of Cape Barren Island.

3.1 Sexual Maturation

3.1.1 Onset of Sexual Maturity

For the purpose of analysis, the greater the number of immature and mature abalone around the transitional size, the more robust the resulting estimate of size at maturity. Practically, samples that included about 50 immature abalone produced sound results and such samples could typically be obtained from a random sample of 200 abalone. However, the proportion of immature to mature abalone in a sample varied, and samples from some sites (particularly exposed habitat) contained very few immature abalone, and requiring further sampling to collect an adequate number of smaller abalone.

Size at maturity varied considerably between regions. Abalone from the Furneaux Group and the North East (especially north of Musselroe Point) consistently matured at smaller sizes than those from further south in the North East, the North West and King Island regions (Figure 20).

Among recently collected samples, size at maturity ranged from 75.0 – 77.8 mm at Waterhouse Island in the North East to 120.4 mm at a site in Mawson Bay (Black Rocks), in the North West (Table 2). Among samples collected in the late 1980's, size at maturity was smallest in eastern Bass Strait. Samples collected from Croppies Point (68.2 mm) and Waterhouse Island (76.0 mm) in the North East, and Gull Island (78.3 mm) and Babel Island (two sites, 68.4 mm and 70.5 mm) in the Furneaux Group demonstrate that blacklip abalone from these regions have consistently matured at a smaller size than in other Tasmanian waters.

At the remaining sites in the North East south of Musselroe Point, size at maturity increased from 99.3 mm at Black Reef to 107.4 mm at Eddystone Point. Samples collected in previous studies between Eddystone Point and St Helens indicated that abalone from some sites matured at sizes similar to Eddystone Point, although sites with smaller maturing abalone were also found along this shore (Table 2).

At King Island, large quantities of blacklip abalone were found around the south and south-west shores of the island (statistical blocks 3 and 4). Sampling took place between Waterwitch Reef in the west and Councillor Island in the east. Size at maturity fluctuated by as much as 20 mm over short distances, but was generally smallest in the south between Cataraqui Point and Seal Bay, and larger in the north around Currie Harbour.

In the far North West, size at maturity ranged from 88.9 mm at Stack Island to 107.1 mm at Hippo Point. Size at maturity clearly increased south of Green Point, and between there and the Arthur River, ranged between 105.8 mm (Bluff Hill Point) and 120.4 mm (Black Rocks, in Mawson Bay). Abalone matured at larger sizes south of Bluff Hill Point (Church Rock and Australia Point) (115.4 and116.4 mm), and at West Point and Nettley Bay (110.5 and117.5 mm). South of the Arthur River, samples collected at exposed sites tended to have high lengths at maturity (eg Sarah Anne Rocks offshore: 109.8 mm), while samples collected in the shelter of bays tended to be much smaller (eg Sarah Anne Rocks inshore:100.5 mm). Although only one sample was collected south of Gannet Point (Smiths Gulch), the proportion of large abalone in the sample was much greater than elsewhere, and consequently, size at maturity may be larger here than further north.

Size at maturity for each site was grouped by region (Figure 20). In the North East, north of Cape Naturaliste, size at maturity was distinctly smaller than further south. In the North West there was some overlap, as the categories of size class suggest, but generally, blacklip abalone north of the sub-block boundary near Green Point matured at a smaller size than those further south.

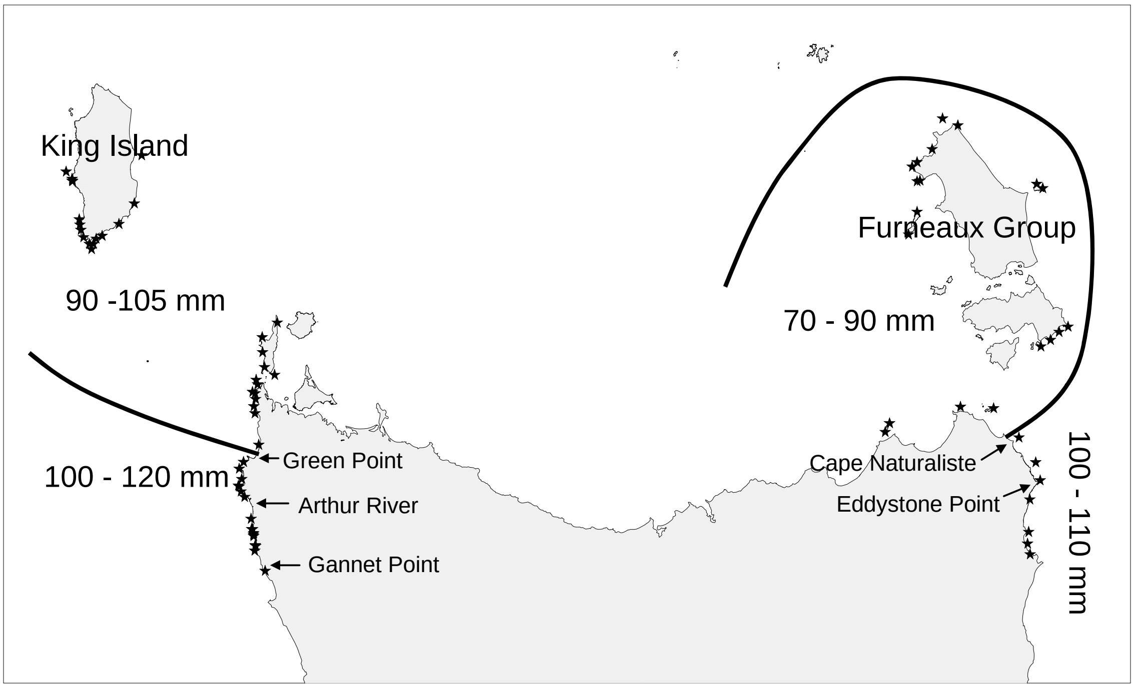


Figure 20. Grouping of sample sites by size at maturity. The position of sites is shown by asterisk. Some prominent landmarks near the group boundaries are shown.

3.2 Age and Growth Estimation

3.2.1 Growth estimation from aged shells

The results from the analyses of samples of aged shells are shown in Table 1. The t_0 values were mostly larger than could be expected. This stemmed from both inadequate representation of small abalone in the samples, and the poor fit of VBGF to age-length data. Fitting of the VBGF to the data is shown in Figure 21 and Figure 22.

The proportion of abalone shells in each sample that could be aged ranged from 38.0 % at George Rocks (North East) to 86.4% at Stack Island, in the North West (Table 1). Generally, samples from the North West and King Island contained higher proportions of shells that could be aged, while samples from the North East and the Furneaux Group contained lower proportions. Sites exposed to moderate levels of fishing (Eddystone Point, Smiths Gulch, Australia Point) also had shells which were of good quality. The ability to age a shell was diminished by physical abrasion of the spire, extensive boring of the shell by polychaetes or other physical damage.

Table 1. Growth parameters

Derived from samples of aged shells, the growth parameters L_{∞}, k and t_0 from Equation 2, their standard errors, the sample size n and the percentage of shells that could be aged are presented below. Growth parameters for Babel Island and Waterhouse Island from an earlier (1988) study (Nash *et al.*, 1994) are also included for comparison. The values marked * are not available.

Region	Site	L_{∞}	s.e.	k	s.e.	t_0	s.e.	n	Percent aged
Furneaux Group									
	Cape Frankland	115.6	2.4	0.19	0.03	2.01	0.92	383	40.1
	Old Man Head	118.5	8.8	0.15	0.05	1.17	1.65	320	66.9
	Babel Island	146.0	*	0.14	*	2.86	*	422	68.2
	Cat Island	129.0	3.5	0.21	0.03	2.24	0.56	311	55.0
	Cape Barren	110.5	3.1	0.19	0.03	1.20	0.65	338	45.6
	Passage Island	130.3	4.0	0.19	0.03	0.78	0.76	400	58.8
North East									
	Waterhouse Island	121.6	*	0.15	*	2.55	*	127	91.0
	George Rocks	135.7	3.6	0.22	0.04	2.02	0.76	415	38.0
	Eddystone Point	146.5	2.8	0.25	0.02	1.86	0.33	387	82.1
	Ironhouse Point	146.4	3.7	0.26	0.04	0.56	0.45	316	74.7
King Island									
	Waterwitch Reef	138.8	2.7	0.17	0.02	1.70	0.51	274	75.6
	Cataraqui Point	122.6	3.1	0.15	0.02	1.05	0.82	305	54.9
	Caves Creek	134.7	4.4	0.21	0.02	3.24	0.50	231	74.5
	Sandblow Point	130.9	1.3	0.27	0.03	3.26	0.52	353	64.5
North West									
	Cape Keraudren	116.6	7.2	0.17	0.07	0.18	2.48	380	54.8
	Stack Island	131.5	4.7	0.20	0.04	0.60	1.07	191	86.4
	Little Trefoil	139.9	1.8	0.23	0.02	1.24	0.47	342	75.0
	Suicide Bay	143.1	8.2	0.20	0.04	1.79	1.37	324	83.6
	Hippo Point	129.8	3.9	0.19	0.03	1.67	0.70	315	81.9
	Bluff Point	141.1	4.1	0.16	0.02	1.55	0.64	305	75.1
	Mount Cameron	135.5	4.3	0.20	0.01	2.06	0.44	411	54.0
	West Point	126.3	4.9	0.21	0.05	1.70	1.09	312	50.6
	Church Rock	134.4	3.2	0.23	0.04	3.01	0.94	315	70.8
	Australia Point	140.1	1.2	0.26	0.02	-0.08	0.29	349	77.1
	Sundown Point	127.5	3.4	0.19	0.03	1.81	0.56	428	63.2
	Couta Rocks	139.7	2.4	0.27	0.07	1.11	1.40	235	75.7
	Smiths Gulch	140.8	3.0	0.28	0.03	3.18	0.30	394	76.1

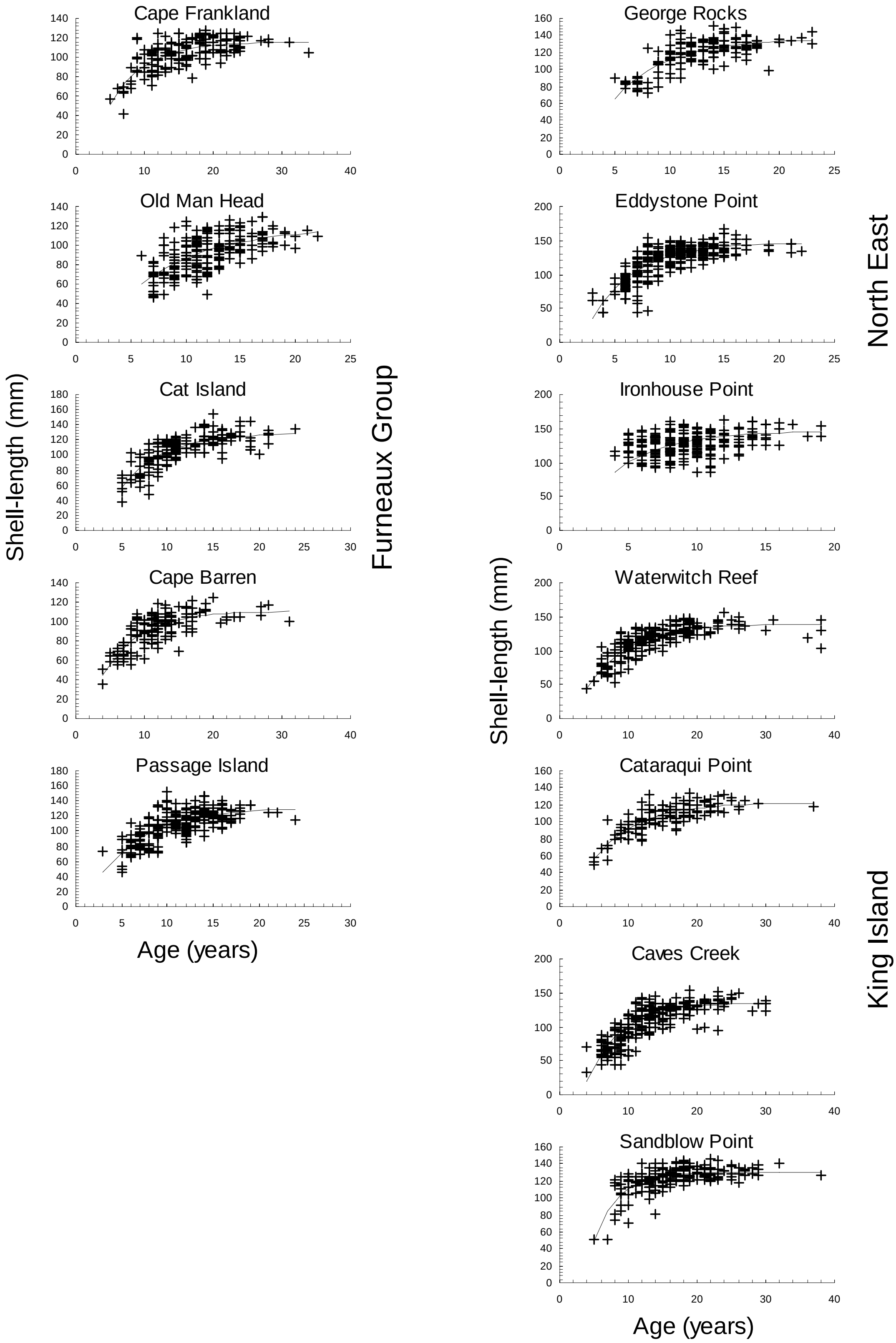


Figure 21. Fits of age-at-length data to the von Bertalanffy growth function from sites in the Furneaux Group, North East Tasmania and King Island.

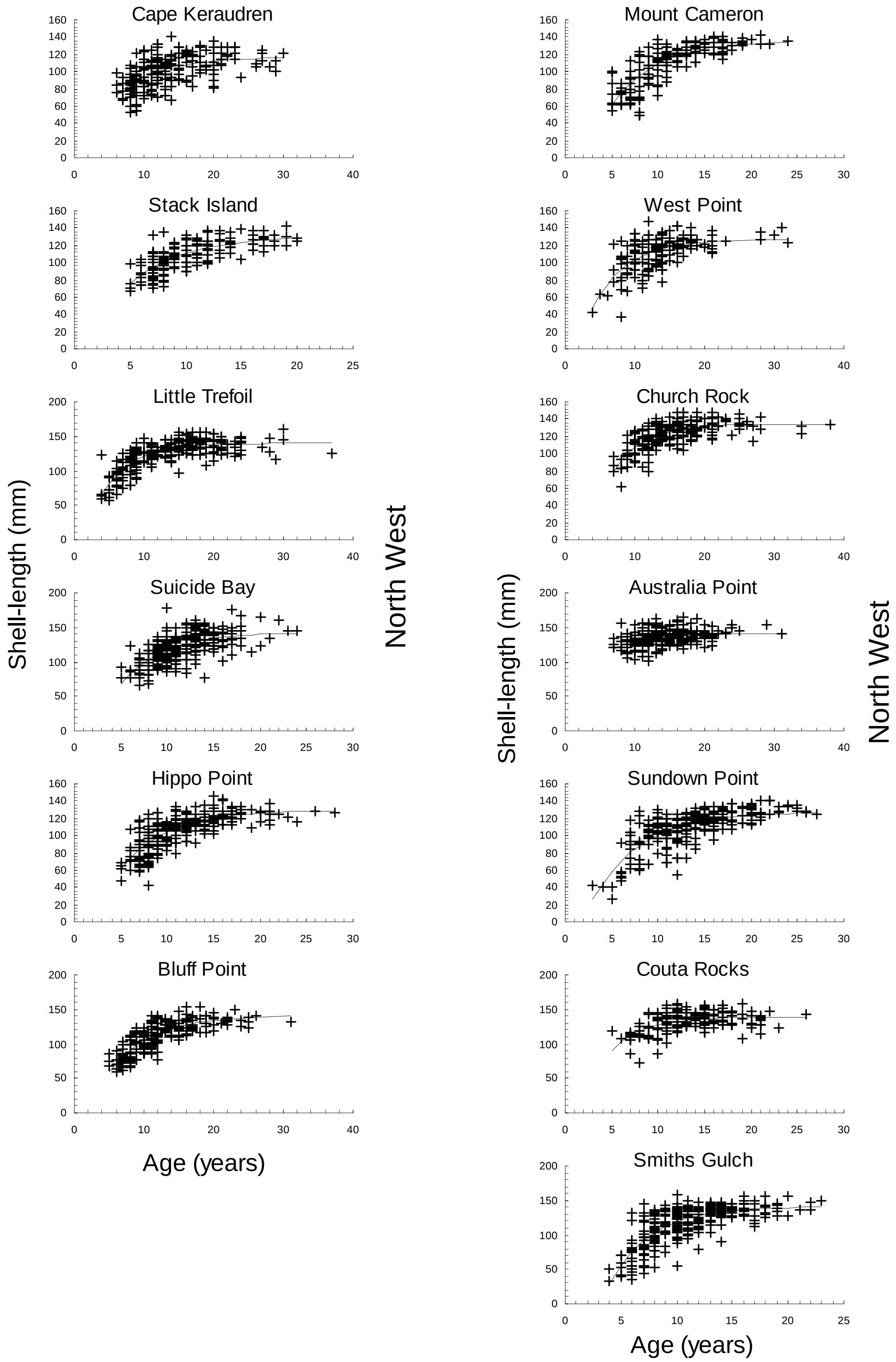


Figure 22. Fits of age-at-length data to the von Bertalanffy growth function from sites in North West Tasmania.

3.3 Estimation of Protection Provided by Size limits

Table 2 shows estimates of annual shell lengths for the 10 years following the onset of sexual maturity listed by site, grouped by region. Mean sizes were calculated for sub-regions and regions where potential size limit boundaries lay (Arthur River, Green Point and Woolnorth Point in the west, and Cape Naturaliste and Eddystone Point in the east). Matching the proposed size limit to the mean sizes at each region, then looking up the corresponding number of years at that length produced estimates of the degree of protection offered by size limits. It should be stressed that although the mean size at some of these sites may be less than 132 mm after 10 years, there may still be scope for a fishery due to individual variability in length-at-age and localised high abundance of abalone

Table 2. Estimated shell length following onset of sexual maturity, in millimetres by year
Sites are grouped by region, showing size at maturity and growth parameters used to calculate successive years growth from that size, for 10 years, by site. The mean size for regions and sub-regions indicates degree of protection afforded populations, for a particular size limit.

Region	Site	Length at 50% sexual maturity (mm)	von Bertalanffy growth parameters		Estimated length 1 to 10 years following sexual maturation (mm)									
			k	L_∞	1	2	3	4	5	6	7	8	9	10
North West														
	Cape Keraudren	89.8	0.17	116.6	94	98	101	103	105	107	108	110	111	112
	Cuvier Point	94.6	0.17	116.6	98	101	103	105	107	109	110	111	112	113
	Deck Chair Bay	98.0	0.23	139.9	107	113	119	123	127	129	132	133	135	136
	Big Duck Bay	100.9	0.23	139.9	109	115	120	124	128	130	132	134	135	136
	Stack Island	88.9	0.20	131.5	97	103	108	112	116	119	121	123	124	126
	Trefoil Island, north side	89.2	0.20	131.5	97	103	108	112	116	119	121	123	125	126
mean size: sites north of Woolnorth Point					100	106	110	113	116	119	121	122	124	125
	Little Trefoil Island, west of	100.9	0.23	139.9	109	115	120	124	128	130	132	134	135	136
	Doughboys	90.4	0.20	135.5	99	105	111	115	119	122	124	126	128	129
	Suicide Bay	104.4	0.20	135.5	110	115	118	122	124	126	128	129	130	131
	Hippo Point	107.1	0.19	129.8	111	114	117	119	121	123	124	125	126	126
	Valley Bay	88.3	0.20	135.5	97	104	110	114	118	121	124	126	128	129
	Bluff Point	105.4	0.16	141.1	111	115	119	122	125	127	129	131	133	134
	Mount Cameron	94.9	0.20	140.1	103	110	115	120	123	126	129	131	133	134
mean size: sites north of Green Point					103	109	113	117	120	122	124	126	127	128
	Nettley Bay	117.5	0.26	140.1	123	127	130	132	134	135	136	137	138	138
	West Point	110.5	0.21	126.3	113	116	118	119	121	122	123	123	124	124
	Black Rocks	120.4	0.26	140.1	125	128	131	133	135	136	137	138	138	139
	Bluff Hill Point, inshore	83.1	0.19	127.5	91	97	102	107	110	113	116	118	119	121
	Bluff Hill Point	105.8	0.21	126.3	110	113	115	117	119	120	122	122	123	124
	Church Rock	115.4	0.23	134.4	119	122	125	127	128	130	131	131	132	132
	Australia Point	116.4	0.26	140.1	122	126	129	132	134	135	136	137	138	138
mean size: sites north of Arthur River					107	112	116	119	122	124	126	127	128	129
	Sundown Point	101.7	0.19	127.5	106	110	113	115	118	119	121	122	123	124
	Sarah-Anne Rocks	109.8	0.27	139.7	117	122	126	130	132	134	135	136	137	138
	Sarah-Anne Rocks, inshore	100.5	0.19	127.5	105	109	112	115	117	119	120	122	123	123
	Couta Rocks Harbour	101.2	0.19	127.5	106	110	113	115	117	119	121	122	123	124
	Couta Rocks, inshore	105.6	0.19	127.5	109	113	115	117	119	120	122	123	124	124
	Couta Rocks, south end	115.9	0.27	139.7	122	126	129	132	134	135	136	137	138	138
	Temma Harbour, south	99.3	0.19	127.5	104	108	112	114	117	118	120	121	122	123
	Stinking Bay inshore	93.2	0.19	127.5	99	104	108	111	114	117	118	120	121	122
	Stinking Bay offshore	110.0	0.27	139.7	117	122	126	130	132	134	135	136	137	138
	Smiths Gulch	113.6	0.28	140.8	120	125	129	132	134	136	137	138	139	139
mean size: sites south of Arthur River					111	115	118	121	123	125	127	128	129	129

Region	Site	Length at 50% sexual maturity (mm)	von Bertalanffy growth parameters k	L_{∞}	Estimated length 1 to 10 years following sexual maturation (mm) 1	2	3	4	5	6	7	8	9	10
Furneaux Group														
	Inner Sister Island, west side	75.4	0.15	118.5	81	87	91	95	98	101	103	106	107	109
	Holloways Point	81.5	0.15	118.5	87	91	95	98	101	103	106	107	109	110
	Old Man Head	85.6	0.15	118.5	90	94	98	100	103	105	107	109	110	111
	Boat Harbour	84.9	0.15	118.5	90	94	97	100	103	105	107	108	110	111
	Cape Frankland	85.2	0.19	115.6	90	95	98	101	104	106	108	109	110	111
	North Pasco Island, east	81.0	0.19	115.6	87	92	96	99	102	105	106	108	109	110
	North Pasco Island, west	79.0	0.19	115.6	85	91	95	98	101	104	106	108	109	110
	Prime Seal Island, south	86.7	0.19	115.6	88	93	97	100	103	105	107	108	110	111
	Prime Seal Island, north	82.7	0.19	115.6	92	96	99	102	104	106	108	109	110	111
	Babel Island	83.3	0.21	129.0	92	99	105	109	113	116	118	120	122	123
	Cat Island, north side	95.3	0.21	129.0	102	107	111	114	117	119	121	123	124	125
	Gull Island	78.8	0.19	110.5	84	89	93	96	98	100	102	104	105	106
	Cape Barren	92.2	0.19	110.5	95	98	100	102	103	105	106	106	107	108
	Jamiesons Point	83.5	0.19	130.3	92	98	104	108	112	115	118	120	122	123
	Cone Point	83.6	0.19	130.3	92	98	104	108	112	115	118	120	122	123
	Passage Island, east	86.2	0.19	130.3	94	100	105	110	113	116	119	121	122	124
mean size: all sites Furneaux Group					90	95	99	103	106	108	110	112	113	114
North East														
	Croppies Point	68.2	0.19	110.5	76	82	87	91	94	97	99	101	103	104
	Waterhouse Island	76.0	0.19	110.5	82	87	91	94	97	99	101	103	104	105
	Waterhouse Island, south	75.0	0.19	110.5	81	86	90	94	97	99	101	103	104	105
	Waterhouse Island, north	77.8	0.19	110.5	83	88	92	95	98	100	102	103	105	106
	Swan Island, Ladys Bay	82.6	0.19	130.3	91	98	103	108	112	115	118	120	122	123
mean size: sites north and west of Musselroe Point					83	88	93	96	100	102	104	106	107	109
	Black Reef	99.3	0.22	135.7	106	112	117	121	124	126	128	129	131	132
	George Rocks	101.6	0.22	135.7	108	114	118	122	124	127	128	130	131	132
	Eddystone Point	107.4	0.25	146.5	116	123	128	132	135	138	140	141	142	143
mean size: sites north of (including) Eddystone Point					93	99	103	107	110	113	115	116	118	119
	Ansons Bay	94.4	0.22	135.7	103	109	114	119	122	125	127	129	130	131
	Gardens	107.6	0.25	146.5	116	123	128	132	135	138	140	141	142	143
	Sloop Rock	92.3	0.22	135.7	101	108	113	118	121	124	126	128	130	131
	Binalong Bay	108.1	0.25	146.5	117	123	128	132	135	138	140	141	142	143
	Ironhouse Point	103.5	0.26	146.4	113	121	127	131	135	137	139	141	142	143
mean size: sites south of Eddystone Point					109	116	121	125	129	131	133	135	136	137
King Island														
	Waterwitch Reef	102.9	0.17	138.8	109	113	117	121	123	126	128	130	131	132
	Peerless Point	94.7	0.17	138.8	102	107	112	116	120	123	125	127	129	131
	Devils Gap	92.5	0.17	138.8	100	106	111	115	119	122	125	127	129	130
	Currie Harbour, north head	96.6	0.17	138.8	103	109	113	117	121	124	126	128	130	131
	Cataraqui Point	88.9	0.15	122.6	94	98	101	104	107	109	111	112	114	115
	Conservation Area	96.5	0.21	134.7	104	110	114	118	121	124	126	128	129	130
	Caves Creek	102.2	0.21	134.7	108	113	117	121	123	125	127	129	130	131
	Surprise Bay, north	78.2	0.15	122.6	84	90	94	98	102	105	107	109	111	113
	Gulchway	87.9	0.15	122.6	93	97	100	104	106	108	110	112	114	115
	Stokes Point	85.9	0.15	122.6	91	95	99	102	105	108	110	112	113	114
	Stokes Point, east	101.4	0.27	130.9	108	114	118	121	123	125	126	127	128	129
	Middle Point	89.1	0.17	138.8	97	103	109	114	118	121	124	126	128	130
	Black Point	90.8	0.17	138.8	98	105	110	114	118	121	124	126	128	130
	Sandblow Point	105.1	0.27	130.9	111	116	119	122	124	126	127	128	129	129
	City of Melbourne Bay	96.9	0.27	130.9	105	111	116	119	122	124	126	127	128	129
	Councillor Island	91.9	0.27	130.9	101	108	114	118	121	123	125	126	127	128
mean size: all sites King Island					100	106	110	114	117	120	122	123	125	126

3.4 Morphometry

Size-compositions of abalone populations sampled in each region are shown in Figure 23. The size-composition from North East Tasmania is distinctly bi-modal, reflecting the influence of smaller abalone from Waterhouse Island.

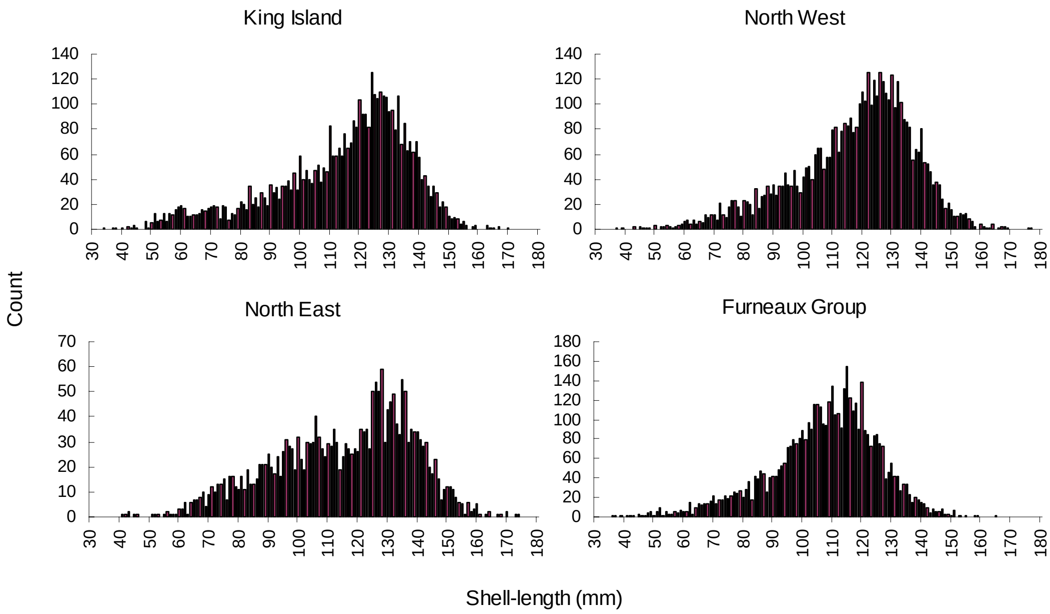


Figure 23. Size-composition of abalone caught in each region, by 1-mm size-class. Sample size was 3924 at King Island, 5609 in the North West, 2198 in the North East and 4415 at the Furneaux Group.

The relationship between shell length and whole weight at each of the regions is shown in Table 3 and Figure 24.

Table 3. Relationship between shell length and whole weight

For each region, the relationship between shell length and whole weight is shown. *a* and *b* are constants in the equation whole weight = $a \times (\text{shell length})^b$. r^2 = coefficient of determination, *n* = sample size.

	a	*b*	r^2	*n*
King Island	0.00004	3.2543	0.97	1138
North West	0.00004	3.2533	0.96	4263
North East	0.00004	3.2760	0.96	813
Furneaux Group	0.00008	3.1138	0.97	1757

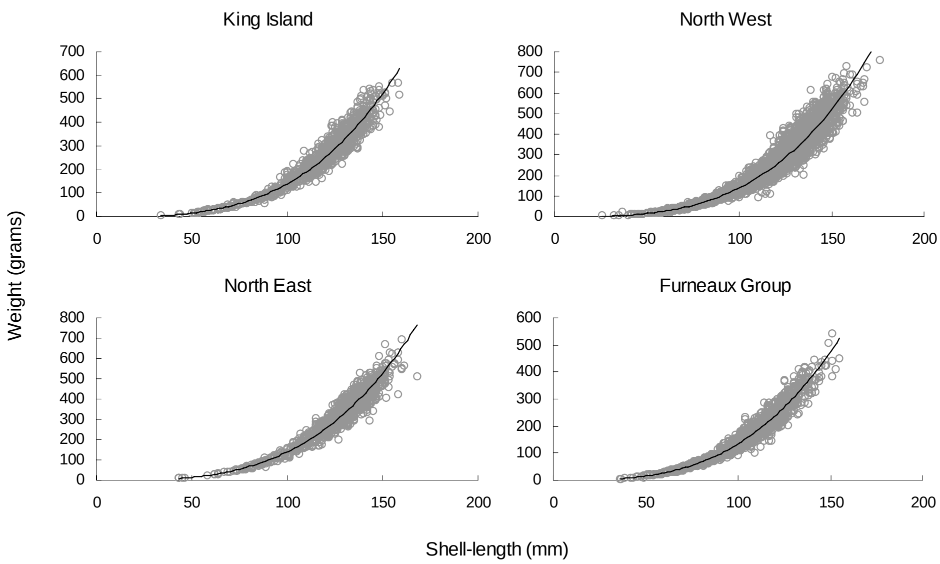


Figure 24. Regional relationships between shell length and whole weight.

3.5 Estimation of Appropriate Yields

Table 4 lists annual catches used to develop potential yields. Note that the size limit was 127 mm until 1987, and that later catches were taken at the 132-mm size limit.

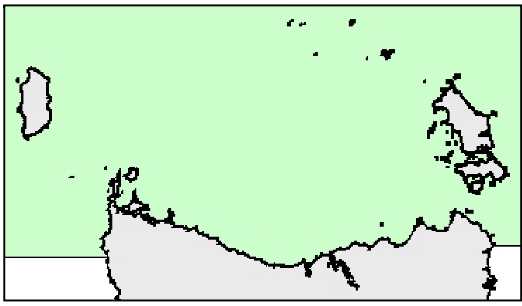
Table 4. Annual catches of blacklip, from the four regions of Northern Tasmania 1975 - 1986 Average annual catches, both with and without with extreme catches (i.e. catches greater than one standard deviation from the mean catch). Excluded catches are shown in bold type. North West* (coast north of Green Point) and North East* (coast north of Musselroe Point) catches are calculated for smaller regions from part block totals, where regional boundaries fell within a statistical reporting block.

		Regional catch (tonnes)						Total
	Year	North West	North West*	King Island	Furneaux Group	North East	North East*	catch (tonnes)
127 mm size-limit	1975	61	42	74	28	36	20	199
	1976	92	69	99	9	54	30	254
	1977	75	50	113	21	61	34	270
	1978	89	57	105	24	115	63	333
	1979	119	77	47	15	67	37	248
	1980	103	57	90	12	109	57	314
	1981	164	104	70	11	60	34	305
	1982	174	114	72	12	54	30	312
	1983	299	186	107	14	101	56	521
	1984	**441**	**286**	101	13	84	46	639
	1985	**421**	262	81	13	179	93	694
	1986	**465**	**332**	76	21	179	97	741
132 mm size-limit	1987	341	243	182	14	61	34	598
	1988	263	179	128	15	101	53	507
	1989	142	98	36	5	28	15	211
	1990	122	81	42	1	21	11	186
	1991	127	79	53	2	23	12	205
	1992	99	61	34	2	16	10	151
	1993	80	47	31	4	15	8	130
	1994	66	42	16	4	22	11	108
	1995	70	39	26	3	25	13	124
	1996	67	36	12	0	20	10	99
	1997	63	35	26	0	34	18	123
	1998	70	40	6	2	16	9	94
	1999	74	46	17	6	44	25	141
Average Annual Catch:								
1975-86		209	136	86	16	92	50	403
1975-86 (extremes excluded)		131	102	86	16	92	50	325

Yield estimates for five different size limits are presented for four different combinations of regions and boundaries (Tables 5 – 8). The first size limit is the current situation (i.e. 132 mm). The protection given by each size limit indicates the number of years of potential reproduction allowed before growth through the size limit makes abalone vulnerable to fishing (estimated in Table 2). The condition “extreme catches removed” indicates whether yields were calculated from the average of all catches at the 127 mm size limit (No), or from catches falling within one standard deviation of the mean catch (Yes). Potential yields from a northern fishery are given, together with the necessary changes to yields from the Eastern and Western Zones to allow for catch transferred from these zones to the North (the current average annual catch at the 132 mm size limit was subtracted from those zones TAC's). When allocating Northern Zone TAC to quota units, some rounding of unit values will take place: hence these yields are provisional and may change slightly.

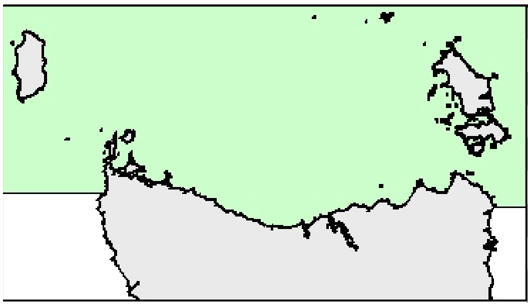
Table 5 shows estimated potential yield for size limits between 132 and 115 mm from the northern coast between the Arthur River in the North West and Eddystone Point in the North East. Boundaries fell on the sub-block boundary between 5C and 5D (Arthur River) and the block boundary between Blocks 30 and 31 (Eddystone Point).

Table 5. Arthur River to Eddystone Point: projected yield at five size limits

Area	Extreme catches removed	Size limit (mm)	Years protection	Potential yield (tonnes) North	West	East
	No	132	12	292	1189	1109
	Yes	132	12	236	1245	1109
	No	127	7	404	1189	1109
	Yes	127	7	325	1245	1109
	No	125	6	448	1189	1109
	Yes	125	6	360	1245	1109
	No	120	4	549	1189	1109
	Yes	120	4	441	1245	1109
	No	115	2	632	1189	1109
Arthur River - Eddystone Point	Yes	115	2	508	1245	1109

The area covered by Table 6 was reduced when compared with that of Table 5. The western boundary was moved northward to the beach at Marrawah, between Green Point and Mount Cameron (the boundary between statistical sub-blocks 5B and 5C), where there was a boundary between size at maturity groups (Figure 20).

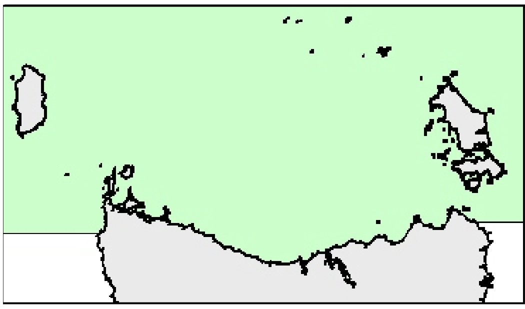
Table 6. Green Point to Eddystone Point: projected yield at five size limits

Area		Size-limit	Years	Potential yield (tonnes) North	West	East
	132	132	12	129	1319	1145
	127	127	10	196	1319	1145
	125	125	9	224	1319	1145
	124	124	8	239	1319	1145
	123	123	7	253	1319	1145
	122	122	7	267	1319	1145
	121	121	6	280	1319	1145
	120	120	6	294	1319	1145
	No	115	3	537.57	1246	1109
Green Point - Eddystone Point	Yes	115	3	476	1270	1109

A further reduction in coastline occurred in Table 7. The eastern boundary was moved north from Eddystone to Musselroe Point, to match the reduction in size at maturity seen in samples of abalone collected from further north. Musselroe Point is not a sub-block boundary. The closest sub-block boundary lies further south at Cape Naturaliste, but, being surrounded by reef, with considerable stocks of abalone located further north and offshore at Black Reef, was considered unsuitable for a boundary.

Most of the catch from the North East is currently taken from the coast between Eddystone Point and Musselroe Point in Block 31. The coast north of Musselroe Point, with some exceptions, is either beach and holds no abalone, or the abalone are small. Projected yields from the North East at the Musselroe Point boundary used catch data based upon Block 31 catches. Consequently, these yields may over-estimate the resource.

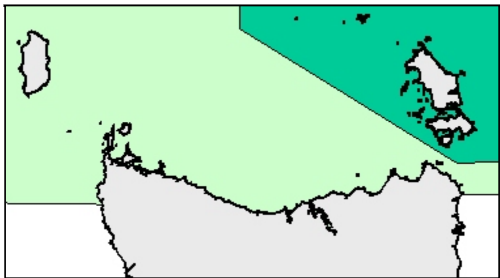
Table 7. Green Point to Musselroe Point: projected yield at five size limits



Area	Extreme catches removed	Size limit (mm)	Years protection	Potential yield (tonnes) North	West	East
	No	132	12	199	1246	1144
	Yes	132	12	176	1270	1145
	No	127	8	290	1246	1144
	Yes	127	8	254	1270	1145
	No	125	7	326	1246	1144
	Yes	125	7	286	1270	1145
	No	120	4	413	1246	1144
	Yes	120	4	361	1270	1145
	No	115	3	487	1246	1144
Green Point - Musselroe Point	Yes	115	3	426	1270	1145

Table 8. Arthur River to Eddystone Point, with smaller size limits within the Furneaux Group: projected yield at varying size limits

This scenario uses a combination of two size limits: a larger size limit on mainland Tasmania (Main) and King Island and a smaller size limit within the Furneaux Group (Offshore).



Area	Extreme catches removed	Size-limit (mm) Main	Offshore	Protection given by size-limit (yrs) Main	Offshore	Potential yield (tonnes) North	West	East
Arthur River - Eddystone Point, but smaller size in Furneaux Group	No	132	127 125 120 115	12	12 12 12 10	302 308 324 340	1189	1109
	Yes	132	127 125 120 115	12	12 12 12 10	246 251 266 281	1245	1109
	No	127	125 120 115	7	12 12 10	410 426 442	1189	1109
	Yes	127	125 120 115	7	12 12 10	331 345 361	1245	1109
	No	125	120 115	6	12 10	464 480	1189	1109
	Yes	125	120 115	6	12 10	375 390	1245	1109
	No	120	115	4	10	565	1189	1109
	Yes	120	115	4	10	456	1245	1109

Finally, the option of operating two reduced size limits in northern Tasmania is presented (Table 8), with a smaller of the two size limits operating around the Furneaux Group and Bass Strait islands (except King Island). Abalone in this region were substantially smaller than elsewhere in the north. Only at the smallest of the suggested size limits (115 mm) does the Furneaux Group become a significant blacklip fishery. Boundaries for the larger size limit were placed at the Arthur River and Eddystone Point. The boundary between the two smaller size limits is well defined, and falls between the Furneaux Group and the North East in Banks Strait.

These tables are complex, containing much information. They are best compared by fixing the options (i.e. extreme catches removed, selecting a size limit) as in the example below (Table 9). It shows the potential yield (in tonnes) from a northern zone at four different boundaries, using a size limit of 125 mm. The tonnages are summarised from Table 5 to Table 8. In this example, extreme catches have been removed. It also shows the percentage decrease in yield in the Eastern and Western zones, as a result of superimposing a new zone onto these existing zones. Note that the introduction of a 115-mm size limit at the Furneaux Group increases yield by only 30 tonnes.

Table 9. Example showing potential yield from a 125-mm size limit in northern Tasmania
The yield (tonnes) from the Northern Zone is shown for each of four boundary combinations. The tonnages for the existing Western and Eastern Zones are shown, together with percentage change to accommodate catch displaced by the Northern Zone.

	North	West	% Change	East	% Change
Arthur River to Eddystone Point	360	1245	-11.1	1109	-6.8
Green Point to Eddystone Point	330	1270	-9.3	1109	-6.8
Green Point to Musselroe Point	286	1270	-9.3	1145	-3.8
Arthur River to Eddystone Point, with 115-mm size-limit in Furneaux Group	390	1245	-11.1	1109	-6.8

4. Discussion

Reducing size limits and increasing yield from northern Tasmania is biologically justifiable. At reduced size limits, abalone in the north of Tasmania maintain at least two years egg-production before they are recruited to the fishery. Historical catches were substantial and were sustained at a lower size limit. Nevertheless, the uncertainties in this assessment mean that setting a size limit and yield for blacklip abalone in the north of the State must be done with some caution. The principal uncertainties discussed here include:

- the adequacy of the principle of size limit setting in Tasmania,
- the adequacy of our field sampling,
- inaccuracies in our estimates growth and age,
- potential variability in growth-rates and the size at sexual maturity, and,
- the historical basis for the estimation of annual yield.

4.1 The principle of size limit setting in Tasmania

We have reservations about the primary justification for setting size limits in Tasmania: that size limits be set to allow at least two years egg-production before abalone grow to a size at which they can be caught. The principle simplifies the concept of maintaining sufficient egg-production to ensure adequate levels of subsequent recruitment to the fishery. Unfortunately, this principle has never been rigorously tested and we have a poor understanding of the early life history of abalone. Natural mortality is highly variable when abalone are young (Shepherd and Godoy, 1989), and recruitment to juvenile stages is highly variable both spatially and temporally (McShane and Smith, 1991). Precise measurements of natural mortality are needed to obtain meaningful estimates of egg-production in blacklip abalone (Nash, 1992) but such estimates are impossible to attain. Whilst it is beyond doubt that egg production is necessary to produce abalone stocks, the premise that the abundance of abalone is directly related to levels of egg-production is dubious.

However, the simple rule of thumb of two years egg-production before capture appears to work in Tasmania. On the commercially fished reefs in the North West and King Island, where blacklip abalone are smaller than more southern stocks and most populations could spawn for at least two years prior to reaching legal size, there is little evidence for unsustainable fishing under the 127-mm size limit. This contrasts sharply with the East Coast, where catches of abalone from reefs off the beaches north of Bicheno, and between Binalong Bay and the Gardens declined during the mid 1980s, after years of heavy fishing. From crude estimates of biological parameters from the East Coast, it is likely that size at maturity plus two years growth exceeded the 127-mm size limit. It appears that populations of blacklip abalone at the Kent Group have also declined following years of high levels of fishing mortality. The size at maturity plus two years growth estimated from samples collected after the last (1995) fishery was larger than the 110-mm size limit.

4.2 Field sampling

A critical assumption of this study was that the abalone populations sampled were representative of the entire Northern region. Our sites were selected for a variety of reasons; some held good stocks of abalone, some held larger than usual abalone and other sites were selected because they held small abalone.

To satisfy each of the objectives of this study demands that sites be selected using different criteria. Estimation of the degree of protection afforded to stocks demands that offshore fast growing areas be sampled preferentially. This is because these areas will be most vulnerable to increased pressure at reduced size limits. Estimation of potential yields demands that inshore stocks holding smaller abalone be sampled to gauge the full extent of biomass in the region. In trying to satisfy both objectives our selection of sites may bias estimates of the degree of protection and potential yield. For example, the inshore area around Bluff Hill Point may be an inappropriate site to include in a broader estimate protection. Bluff Hill Point is an area that that would normally not be fished (the abalone are too small). If the inshore area around Bluff Hill Point had been excluded, then the average size calculated at which abalone mature in the region would increase, suggesting a reduced degree of protection in the region.

Because the sampling was not undertaken in a random manner, our estimates of size at maturity may not be representative of the entire northern region. However, random sampling of sites selected along the coastline would not be a workable solution to this problem. The patchy distribution of blacklip abalone limits populations to rocky substrate and concentrations of commercial importance occur only at infrequent intervals.

Ideally we would have collected information about the distribution of abalone along northern shores, and then selected randomly from a list of sites. Collecting such information would be a major task, and our approach sought to find a compromise solution. We obtained local knowledge about abalone stocks at some of the more popular sites, and then sampled those sites.

4.3 Growth, ageing and protection offered by size limits

The relationship between the age of blacklip abalone and the number of growth rings is a subject of much debate, and has not been confirmed for abalone living in northern Tasmania. McShane and Smith (1992) concluded that growth checks were unreliable indicators of age because blacklip abalone from Bass Strait waters in eastern Victoria did not always form annual growth checks. Shepherd and Huchette (1997) and Shepherd and Triantafillos (1997) have noted that the attack of muricid and polydorid borers causes the deposition of adventitious rings in both *H. scalaris* and *H. laevigata*.

In this study, we noticed that significant numbers of abalone had more than 20 growth rings (Figure 14 and Figure 15), whereas, in more southern waters, abalone generally had fewer than 20 growth rings (Nash, 1995; Tarbath, 1999a). While abalone from northern waters may live longer because of lower levels of fishing mortality, it is likely that the difference in numbers of growth rings is not due to age differences. As well as growth rings, abalone deposit extra layers of nacre (adventitious layers), perhaps in response to parasites boring through their shells. If this is the case, then the levels of protection suggested in this study (Table 2) may be exaggerated.

Incorrectly attributing rings in shells to growth has marked effects on estimates of the degree of protection offered by size limits. To project a worse-case scenario, we might assume that on average, two rings are laid down in blacklip abalone shells annually. This causes the growth rate parameter k to double. In a region such as the North West a doubling of k would substantially decrease the estimated degree of protection at a given size limit. However, values of k greater than 0.5 should be considered high, and possibly unrealistic, compared with values published by Day and Fleming (1992).

At two-growth rings/year, Eddystone Point in the North East and sites further south would receive less than two years protection, even at 132 mm. In the North West, most of the sites with size at maturity greater than 110 mm would also receive less than adequate protection at 132 mm. It is likely that abalone from these areas normally deposit one growth ring per annum. Within this area that seems vulnerable at two-growth rings/year the existing fishery at Couta Rocks is robust and appears to be maintained by adequate recruitment.

By assuming two growth rings per year, the age of abalone in the distribution of age-at-length data will halve (Figure 14 and Figure 15). At most sites, there will be no abalone older than 15 years (at some sites none older than 10). This is an unlikely result, given that we expect blacklip abalone to grow to 20 years. We do not expect fishing mortality to cull all the older abalone, because fishing pressure is at low levels in northern Tasmania. At most of the sites sampled, based on age-distribution and a maximum age of 20 years, it is likely that abalone lay down less than two rings per annum.

The assumption of annual growth rings has not been conclusively validated, but is based upon a growing body of observations, including those of Prince *et al* (1988) and Nash (1995). Between 1995 and 1998, tagging studies of blacklip abalone were conducted in parallel with age-length studies of growth, at Ironhouse Point, Magistrates Point and Couta Rocks (Tarbath, 1999a). There are two results from this work that have important implications for interpretation of the current growth analyses. Firstly, between-site differences in growth among tagged abalone corresponded with between site-differences in growth rate measured from aged shells. Secondly, among young abalone (less than 10 years old), growth increments observed in the tagging study corresponded with length-at-age at all three sites. It was concluded that there was strong evidence to support the assumption of annual growth rings at those three sites for young blacklip abalone.

The principal difficulty that we have with our ageing data is the number of old abalone, and the age that they reach. Older abalone may, under some conditions, lay down adventitious rings. In the above-mentioned tagging and age-based study at Couta Rocks, it was observed that abalone grew to a greater age than at the other two East Coast sites. It was also noted that abalone from Couta Rocks had a higher degree of shell damage from parasites, particularly among the mid- to large-sized shells, and among those with higher ring counts. A study of blacklip abalone at the Kent and Hogan Groups in Bass Strait (Tarbath, 1999b) observed that shells from younger and smaller abalone were generally free of parasites, while those shells with high ring counts were heavily bored. An unpublished study of the degree of infestation of abalone shells by mudworms found significantly higher damage in shells from Bass Strait waters than in those from other parts of the State (M. Lleonart, pers. comm.).

These results suggest that in northern waters, older abalone may deposit more than one growth ring per annum. This will effect determination of growth rates, but probably will not appreciably alter the degree of protection offered by size limits. The relatively low abundance of older abalone and their greater size will mean that these individuals will exert little leverage upon estimation of growth rates.

It should be noted that von Bertalanffy growth parameters are strongly correlated, so that by increasing average maximum length (L_∞) within a sample, the other two parameters k and t_0 become smaller. The converse also applies. Sampling, although undertaken within protocols, is not an exact procedure. By pure chance, sampling may collect abalone at either end of the size-range in disproportionate numbers with respect to the population from which the sample is taken. If sampling is undertaken after divers have removed quantities of legal-sized abalone, then our samples may be deficient in larger abalone, and L_∞ will be smaller and k larger. Consequently, the growth parameters of such a sample may differ markedly from general perceptions about growth in the area. For example, the difference between the rate of growth (*k*) and the average maximum size (L_∞) at George Rocks and Eddystone Point is remarkable, and is much more pronounced than we would expect from our observations. However, provided that younger abalone are represented in the sample so that the growth curve starts at a reasonable position (i.e. t_0 is a sensible size), then it matters little if L_∞ is large and *k* small or vice versa for the purposes for which growth is used in this study: the calculation of protection provided by size limits.

Prince *et al.* (1988), while working with blacklip abalone from south-east Tasmania found that three minor rings were laid down in the sixteen months following settlement, after which much more pronounced 'major rings' were laid down annually. Their method of ageing shells involved grinding the tip of the spire to expose a series of concentric rings, the first three of which were described as minor rings. Currently, researchers at TAFI cut transverse sections through shells to display growth rings. Minor rings are generally unrecognisable in the larger abalone (shell length greater than 70 mm) that make up the bulk of our samples. It is likely that the minor rings, and possibly some of the earlier growth rings become eroded in older abalone.

The use of growth rates derived from tagging studies may provide an alternative and possibly more robust estimate of the degree of protection offered by size limits. Unfortunately there have been no substantial tagging studies within the northern region and appropriate data only exists at Couta Rocks and Ironhouse Point (Table 10).

Table 10. Growth rates estimated by analysis of mark-recapture data

The von Bertalanffy parameters *k*, L_∞ and t_0, derived from growth increments of abalone measured at Ironhouse Point (East Coast) and Couta Rocks (West Coast) between 1994 and 1997. The parameters were derived from non-linear regressions of length against growth increment using Fabens' (1965) model. The number of increments measured at each site is shown in the right hand column (*n*), standard errors are given in brackets and t_0 was later calculated assuming that an abalone of age 0 was 1 mm long.

Site	L_∞	*k*	t_0	*n*
Ironhouse Point	152.6 (0.9)	0.52 (0.07)	-0.01	1153
Couta Rocks	147.4 (1.0)	0.27 (0.01)	-0.03	752

The growth rates for Ironhouse Point for both aged shells and tagging data suggest that growth rates in this area are higher than those found in northern Tasmania. It is inappropriate to assign high growth rates to slower growing areas to project future size-at-age. However, Couta Rocks was within the study area, and growth parameters from here can reasonably be applied to those sites on the West Coast south of Green Point with larger and faster growing abalone. The growth rate for tagged abalone from Couta Rocks matches that of the ageing study. The use of growth parameters derived from this tagging study increases the expected average size two years after maturation to 129 mm for abalone from the larger, faster growth sites between Green Point and the Arthur River (Nettley Bay, Black Rocks, Church Rock and Australia Point). The use growth parameters derived from tagging studies therefore suggests that these areas will be afforded less protection at lower size limits than they would had age-based growth parameters been used. However, the use of mark recapture derived growth parameters may not be legitimate when estimating length-at-age. Francis (1988) showed that the maximum possible length (L_∞ as estimated by mark-recapture studies) is larger than the average maximum length (L_∞ as estimated by length at-age-analysis).

4.4 Changes in sexual maturation and growth

Studies of blacklip abalone in Bass Strait have found that abalone respond to heavy fishing pressure by growing faster and larger (Tarbath, 1999b). After fishing, abalone populations were characterised by a higher size at maturity, and larger maximum size. Abalone shells became flatter, more elongated and lighter in weight. These results indicate that growth and size at sexual maturity are inversely related to abalone density (Tarbath, 1999b). A similar pattern of fast growth rates and increasing size at sexual maturity following heavy fishing pressure has recently been observed in southern Tasmania. It can be expected therefore, that changes in size at maturity and growth rates may occur in the more heavily fished areas of northern Tasmania as fishing pressure increases as a result of reduced size limits and increased yield. The likelihood of these changes in biology demands that size limits and catch limits are chosen in a conservative manner that allows for change.

4.5 The need to monitor performance of the fishery

The expectation of change in the parameters used to set size limits and yields demands that monitoring be established to ensure the future suitability of chosen size limits and yields. Knowledge of changes in growth rates and size at maturity, together with catch and catch-rates trends, and divers' perceptions of abundance provide the best means of monitoring the success of the fishery in the medium-term. Substantial localised decreases in abundance can be expected in the short-term as divers progressively fish down high levels of accumulated stocks. Changes in size at maturity will be easily and quickly detected by monitoring existing sites.

Unfortunately changes in growth rates and catch rates are usually less clearly defined and will be more difficult to detect. Two actions will improve our ability to identify fishery-induced change. Firstly, the closure of several sites within each region will allow a comparison of changes in biological parameters between fished and unfished sites. Ideal sites to protect from fishing might include Waterwitch Reef (King Island), Doughboys (North West), Passage Island (Furneaux Group) and one of the offshore reefs between Cape Naturaliste and Eddystone Point. The value of these sites to monitoring will depend upon the extent to which they remain unfished.

Secondly, tagging and releasing abalone will provide a better means of monitoring growth. We propose tagging and releasing 750 legal- and under-size abalone at up to two sites in each of the major regions. The abalone would remain at large for one year, after which research divers would catch them, possibly with the help of industry divers. Satisfactory growth information could be expected provided that tagging was undertaken prior to, or within the first year of a reduced-size fishery. Once again, the value of the exercise will depend upon the tagged abalone remaining uncaught. A similar tagging operation at Sterile Island in southern Tasmania was compromised because divers removed tagged legal-sized abalone.

There is a need to monitor distribution of catch and effort within the new zone. Divers may prefer to catch abalone in the southern part of the North East and North West, where there is better access, and King Island in particular may receive little attention. Estimates of potential yield for a Northern Zone were produced from the sum of contributions from each of the four regions from the period 1975 to 1986. We believed that these regional catches were sustainable. If catches from the Northern Zone are not distributed in accordance with the way in which projected yields were calculated, then fishing at locally unsustainable levels may occur. There is a requirement of fishery managers to monitor and manage distribution of effort.

4.6 Estimation of Annual Yield

Estimates of annual yield rely heavily upon size-composition data. Our use of size-composition data from samples collected by divers assumes that the size-range of abalone sampled from the population is representative of that population, and that abalone are equally catchable across their size-range. This is obviously untrue for abalone smaller than the mode. Small abalone, particularly those that are sexually immature, are cryptic and remain beyond the sight and reach of divers under rocks or in crevices. It is always difficult to take a comprehensive sample of the population at lower sizes, and size-classes smaller than the mode of size-compositions are under represented. This means that estimates of yield at size limits smaller than the mode will be unreliable. Conversely, samples of abalone larger than modal size are much more likely to be representative of the population.

The other major input to our method of yield estimation is the size of the catch at the 127-mm size limit. We have only limited knowledge of how the northern fishery performed whilst operating with a 127-mm size limit. Anecdotal evidence is mixed, and depends upon accurate recollections from over 15 years ago. The best information available is the catch data supplied on divers' logbooks. This provides a history of the annual catch from each region, including the period when the size limit was 127 mm. Catches and catch-rates indicate that the fishery was stable when abalone were caught above the 127-mm size limit.

Our approach was to use this data to estimate sustainable yields. Our preferred estimates of yield omit large catches in the North West between 1984 and 1986 because these catches were not sustained (Table 4). There is little doubt that poor access limited opportunities to maximise the historical catch in the North West. Nevertheless, the omitted catches are so much larger than the remaining catches of the period that inevitably, their ability to be sustained must be questioned.

We have purposely omitted potential catches from the Kent Group from the region of the North East and Furneaux Group. Studies of aged shells and growth increments from tagged abalone indicate that following rapid growth to a comparatively large size at maturity, the average maximum size of the abalone in these islands is as small as that found in other parts of the region. During the 1995 fishery, small quantities of abalone larger than 132 mm were landed from Judgement Rocks, Endeavour Reef and the Hogan Group. Apart from the Hogan and Curtis Groups, none of the remote islands can significantly contribute to yields from a northern abalone fishery. From size-composition information collected during the earlier fisheries, it is likely that abalone from these remote Bass Strait islands mature at a size comparable with those of the Furneaux Group.

Along the northern coastline of Tasmania, substantial quantities of abalone are found around headlands and on offshore reefs. Recent surveys have shown relatively high abundance of blacklip abalone on low relief reefs up to three kilometres offshore between Devonport and Penguin (Barrett and Willcox, 2000). Further east, reefs around the mouth of the Tamar produced about 40 tonnes of blacklip during the first stunted Bass Strait fishery of 1989. Abalone along this coast are noticeably smaller than their counterparts from elsewhere in the State, and it is unlikely that size at maturity in this area is larger than further east or in the Furneaux Group. Whether there are sufficient abalone here large enough to contribute significantly to yields from a northern blacklip fishery remains to be determined.

4.7 Recommendations for size limits and yield

The northern fishery was apparently sustainable at a size limit of 127 mm at higher catch levels than we have estimated (Tables 4 – 8). However, much of the area was unfished at this size limit, because the size limit prevented access to many areas. Our assessment suggests that the size limit could be reduced below 127 mm without threatening reproduction in the area. Unfortunately the choice of the most biologically appropriate size limits, yields and boundaries will sometimes conflict with practical issues such as diver access and policing.

The most sensible option from a biological perspective would be to establish a smaller size limit within the Furneaux Group than that used in the rest of the northern region (Table 8). This option would allow yields to be increased whilst still providing reproductive abalone with appropriate levels protection. However, catches of blacklip abalone in the Furneaux Group have always been low: if the size limit in the Furneaux Group were reduced to 115 mm, estimates of annual yield increase by only 30 tonnes (Table 9). It is questionable whether this relatively small increase in yield would justify the increased management and enforcement complexity required to police multiple size limits within the northern region.

At a uniform size limit of 120 mm across the entire region most sites would be afforded more than two years post-maturity protection (Table 2). This was particularly true in the area from Green Point (North West) to Musselroe Point (North East), including King Island and the Furneaux Group. Yield estimates suggest that a catch of 361 tonnes could be sustained at this size limit (Table 7). However, this size limit offers less protection to stock, and entails a higher degree of risk.

A more conservative approach would set a 125-mm limit between Green Point and Musselroe Point, with a yield of 286 tonnes (Table 7, Table 9). Unfortunately Musselroe Point is a poor geographical boundary, and launching trailer-borne craft in the North East would be difficult. A better boundary in the North East would be at Eddystone Point where there is an adequate launching facility for small craft and policing would be easier. At Green Point in the North West, launching facilities are also poor. Better access exists further south at Bluff Hill Point, although larger craft would face difficulties here.

To reduce policing and access difficulties it appears to be sensible to establish boundaries at the Arthur River and Eddystone Point. Conservative estimates suggest that a 125-mm limit would yield 360 tonnes per annum (Table 5, Table 9) and provide reproductive abalone with over 6 years of post-maturity protection in most of the region, and over 2 years at most sites in the North West. Potentially, this threatens some of the large fast-growing abalone populations between the Arthur River and Green Point. Moving this boundary north to Green Point may reduce the annual yield from the blacklip fishery by as little as 5 tonnes (because the Western Zone yield is reduced less, (Table 9)). This would provide greater protection to the Arthur River – Green Point stocks. However, the more southern boundary at the Arthur River is more enforceable, with improved small-boat access.

5. Implementation of the Northern Zone

After a series of discussions between industry, government and researchers following the release of a draft of this document, a new Northern Zone was established between the Arthur River in the west and Musselroe Point in the east. A size limit of 132 mm was adopted for the West Coast between Arthur River and Woolnorth Point, 127 mm for the remainder. The fishery opened on 1 January 2001 with a TAC of 280 tonnes. The Eastern Zone TAC was adjusted to 1120 tonnes and the Western Zone to 1260 tonnes, producing a net increase of 70 tonnes production over the previous year.

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