INTERNAL REPORT

SIZE LIMITS FOR GREENLIP ABALONE (*HALIOTIS LAEVIGATA*) IN PERKINS BAY, NORTH WEST TASMANIA

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Executive Summary

A fishery for greenlip abalone operates in regional North West Tasmania. Its annual production is relatively small; the highest annual catch was 125 t in 1984, and more than 50 t was consistently produced between 1983 and 1991. Much of this catch was taken from Perkins Bay, which is the large body of water between Smithton and Circular Head and includes reefs at Black Reef and North Point covered by catch-reporting Block 47 and Sub-block 48A.

Because of widespread concerns about the effects of overfishing in the State's abalone fishery in the mid-1980's, drastic management measures were implemented. Unlike the blacklip fishery which recovered, the greenlip fishery continued to decline, prompting a major study into sustainable management for the species in 1998. Recommendations from this study included both further reductions in annual catch and increases in size limits to 145 mm to raise egg production above levels that were found to be sustainable elsewhere. Despite the implementation of these recommendations, the catch from the reefs in Perkins Bay continued to fall, and in recent years was approximately 4 t p.a. It was assumed by managers that like many other greenlip fisheries, divers had serially depleted stocks on the productive reefs causing recruitment failure, and that management intervention had been insufficient and untimely to prevent a stock collapse. Meanwhile, divers complained that the size limit was now too high and that they could not find sufficient quantities of legal-sized abalone.

In 2004, researchers re-visited the region to assess the viability of fishing the depleted reefs, and find ways of restoring their productivity. It was immediately apparent that abalone were abundant at all sites, suggesting that the recent size limit increases in this region had contributed to its loss of productivity, and that a smaller size limit might restore annual catches to former levels while ensuring acceptable levels of protection to stocks.

Samples were collected from abalone populations at formerly productive sites. These samples were used to develop estimates of growth rates and median size at maturity. It was found that growth rates varied widely between sites, the largest and fastest growing abalone being found on the fringes of the reef, the smallest growing at sites on parts of the reef that had not been productive for many years. Immature abalone were almost entirely absent from the reef fringes, which led to the conclusion that when the population density increased in the slow growing sites, mature abalone moved to the reef fringes which were in some way unsuited to the earlier life stages. Estimates of median size at maturity were complicated by the absence of immature abalone from the

faster/larger growth sites, while those from the moderate and slow growth sites were consistent with estimates from the 1998 study.

Discussions with divers with a long history of fishing the region revealed that the size of abalone varied widely, and even at the smallest size limit under which stocks were fished (127 mm), some of the region's populations were never large enough to be taken. At the other extreme, abalone grew largest at the site used in the 1998 study. This information was particularly useful in developing estimates of growth rates that better represented the region's populations.

Estimates of egg production using the revised growth rates showed that a 132-mm size limit would preserve levels of egg production within the range of established threshold levels for areas with characteristics similar to Perkins Bay. Setting this 132-mm size limit assumed fishing mortality equivalent to an upper catch limit of 38 t p.a. However, considering the uncertainty involved with the estimate of this upper catch limit, and the history of collapse of greenlip populations exposed to overfishing, it would be prudent to cap the annual catch at approximately half the upper limit (20 t) until it could be demonstrated by fishery-independent abundance surveys that greater levels of catch may be sustainable. The existing Sub-block 48A annual catch (4 t) should be deducted from the North West regional catch (30 t) and the two regions managed separately.

There are alternative strategies for management of the fishery in this area that should also be considered. The first is that the size limit be left at 145 mm. Is the potential gain in catch at lower size limits worth the extra cost associated with managing this part of the fishery? The annual catch would continue to be approximately 4 t, which has been demonstrated sustainable. Other alternatives include translocation of abalone from slow-growth reef to faster growing reefs, and reef-scale micro-management by local diving communities. While these alternatives have merit, they would be difficult to implement under the existing management policies of the Tasmanian abalone fishery.

In summary, the conclusions of this report are as follows:

1. It is desirable to reduce the size limit sufficiently so that fishing effort may be spread over the many abalone populations within Perkins Bay (Sub-block 48A and Block 47), thus avoiding serial depletion among the few larger growing populations on Black Reef to which fishing is currently restricted. Therefore, it is recommended that size limits for taking greenlip abalone in Perkins Bay be reduced from 145 mm.

2. An appropriate size limit for Perkins Bay would be 132 mm. Provided that the annual catch is limited to the levels specified in conclusion 3 (below), egg production at a 132-mm size limit would be above minimum levels that have been found sustainable in greenlip populations elsewhere.

3. Initially, annual catches should be set at approximately half the estimated upper limit of acceptable fishing mortality i.e. 20 t. This annual catch is to be managed separately to the North West regional annual catch. The existing Sub-block 48A annual catch (4 t) should be deducted from the North West regional catch (30 t).

4. Fishery-independent estimates of abundance should be made at reefs in Perkins Bay prior to the start of the fishery at the reduced size limit, and from thereon abundance should be monitored at regular intervals (either six monthly or annually).

5. We recommend that all divers fishing in Perkins Bay participate in the GPS data logger scheme being developed at TAFI so as to monitor the spatial distribution of effort and thus provide a means to determine whether effort is evenly spread across populations.

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1. Introduction

This report was prepared at the request of the Tasmanian Abalone Fishery Advisory Council (AbFAC) to review size limits for greenlip abalone at the reef known as Black Reef in Perkins Bay, North West Tasmania. It had been widely reported that since size limits in the region were increased (from 127 mm to 132 mm in 1987, from 132 mm to 140 mm in 1999, and from 140 mm to 145 mm, 2002), it had become increasingly difficult to find economically viable quantities of legal-sized abalone, though abalone were apparently abundant. The most recent size-limit increase has coincided with a fall in the annual catch from reporting Sub-block 48A (which mostly comprises Black Reef catch) from 18 t in 2001 to 4 t in 2004. Local divers believe that while the size-limit increase was justified throughout most of the North West, at Black Reef, abalone grow more slowly and to a smaller size than elsewhere with few growing large enough to catch at the new size limit. This report reviews the suitability of size limits and proposes management options to make the fishery more productive whilst ensuring resource sustainability.

The scope of this review has been extended to cover reefs to the north of Circular Head (North Point) in reporting Block 47. These reefs were productive between 1983 and 1991, after which catches fell sharply. The fall is believed to be associated with widespread depletion and fishing at size limits too small to protect stocks. Since the 1999 increase in size limit (to 140 mm), no catch has been taken from Block 47, and it is reported that as at Black Reef, few abalone grow to legal size.

The size-limit increases in 1999 and 2002 were prompted by a TAFI report (Officer, 1999), also undertaken at the request of AbFAC, into size limits for greenlip abalone state-wide. During the 1990's, greenlip stocks in many areas were seen to be declining rapidly in the face of greater levels of effort caused by increased differences in the beach price between greenlip and blacklip abalone and inadequate management controls. It appeared that the Tasmanian greenlip fishery would follow the path of the other Australian greenlip fisheries, and abalone fisheries world-wide, and succumb to over-exploitation.

Concurrent studies of South Australian greenlip populations showed that they were able to survive high levels of fishing mortality provided that sufficient levels of egg production were maintained (Shepherd and Baker, 1998), and that the means to do this lay through manipulation of size limits. In 1998 TAFI commissioned an extensive field program in all productive greenlip waters, including Black Reef in North West Tasmania. Greenlip populations were sampled for fecundity, size at maturity and growth. Estimates were made of egg production across a range of fishing mortalities, for a range of potential size limits. The results were published (Officer, 1999) and the report's recommendations quickly adopted.

However, since then, the greenlip fishery has faced further size-limit related problems. On King Island many populations are severely depleted, yet there exist extensive areas of reef with populations of abundant small abalone, with few individuals reaching the size limit. In the North East and North West, stocks have continued to decline, prompting catch reductions. Only in the Furneaux Group are stock levels stable or increasing, and there the catch is mostly taken at 15 mm greater than the recommend legal size limit. This raises the questions: why did the report's recommended size limits fail to provide the measure of sustainability that it promised, and what can be learnt from the difficulties that have followed?

2. Methods

Per-recruit analyses, principally egg-per-recruit, but also yield-per-recruit were used to determine optimum size limits that met the requirements for threshold levels of egg production while maintaining acceptable levels of yield under a range of fishing mortalities (F) and natural mortalities (M). For the purposes of this study, the abalone of Perkins Bay were considered as a large metapopulation (cf. many isolated and small populations). This study mostly follows the methods used by Officer (1999) during his earlier study of greenlip populations in the region, and because he sampled populations across a greater geographic range, his estimates of the parameters for fecundity and length-weight relationship were used (Table 1). Fecundity was defined using the weight of gonad as a proxy for egg numbers.

Table 1. Parameters of length-weight and length-fecundity relationships for greenlip abalone in North West Tasmania, of the form a*length^{b} (Officer, 1999).

	a	b
Fecundity	0.0013619	2.322
Weight	0.0000604	3.146

Surveys were conducted in July and October, 2004 at a number of productive sites on Black Reef and offshore from North Point and Robbins Island. Study sites were chosen by local divers (Figure 1, Figure 2). Sampling involved collecting approximately 200 abalone per site. The samples were processed to obtain age and growth data, estimates of median size at maturity, and to characterise size distributions, although not all sites provided the same range of information.

Samples were collected for ageing and growth determination from sites at Black Reef (BR1, BR3, BR7), Robbins Island (RI1) and North Point (NP3). The age data collected by Officer (1999) from Black Reef was combined with recent ageing samples to produce estimates of growth rates for the Perkins Bay metapopulation. Samples for size-at-maturity analysis were collected from Black Reef (BR4, BR8), while a sample for length analysis was collected from North Point (NP1). Other potential sampling sites were identified by local divers (NP2, BR2, BR5), but these sites were not sampled because of poor weather and lack of time. The ageing samples were also used for size-at-maturity analysis and both ageing and size-at-maturity samples were used for length-frequency distributions.

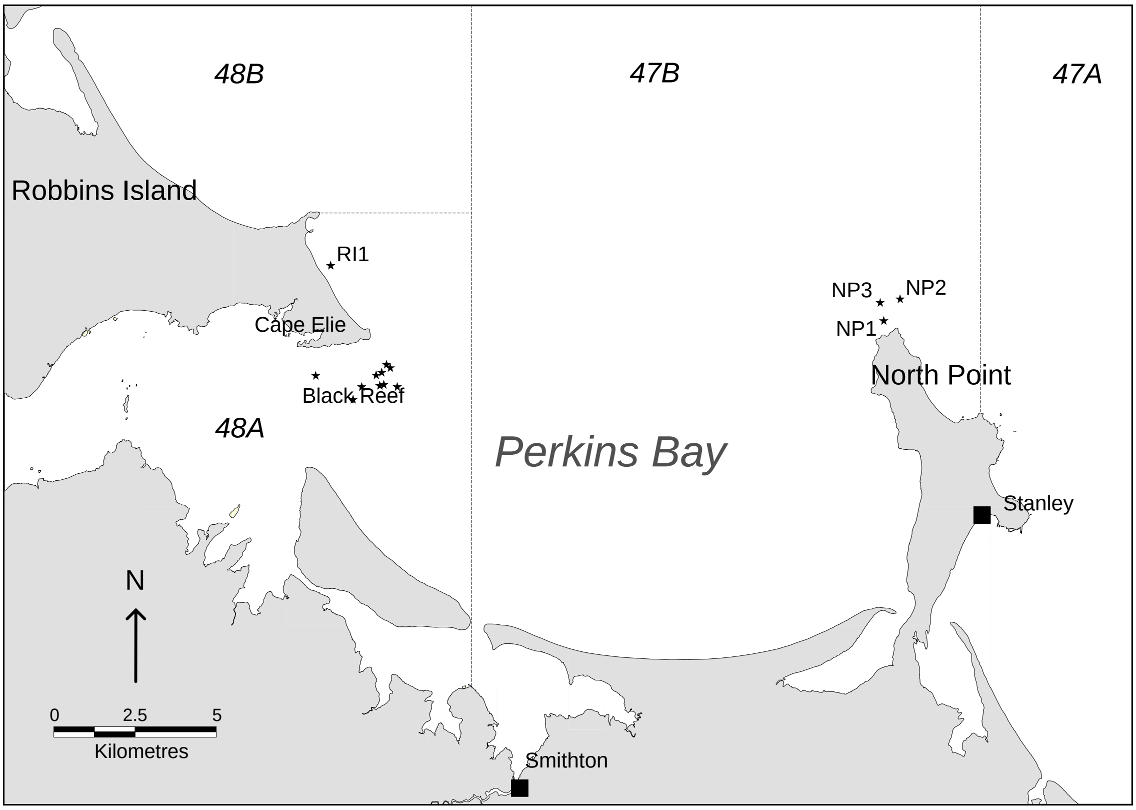


Figure 1. Perkins Bay, showing sampling sites at Black Reef and Robbins Island (see Figure 2 for more detail), and North Point (NP1 to NP3). The position of reporting blocks (e.g. *48A*) and their boundaries (dashed lines) are shown.

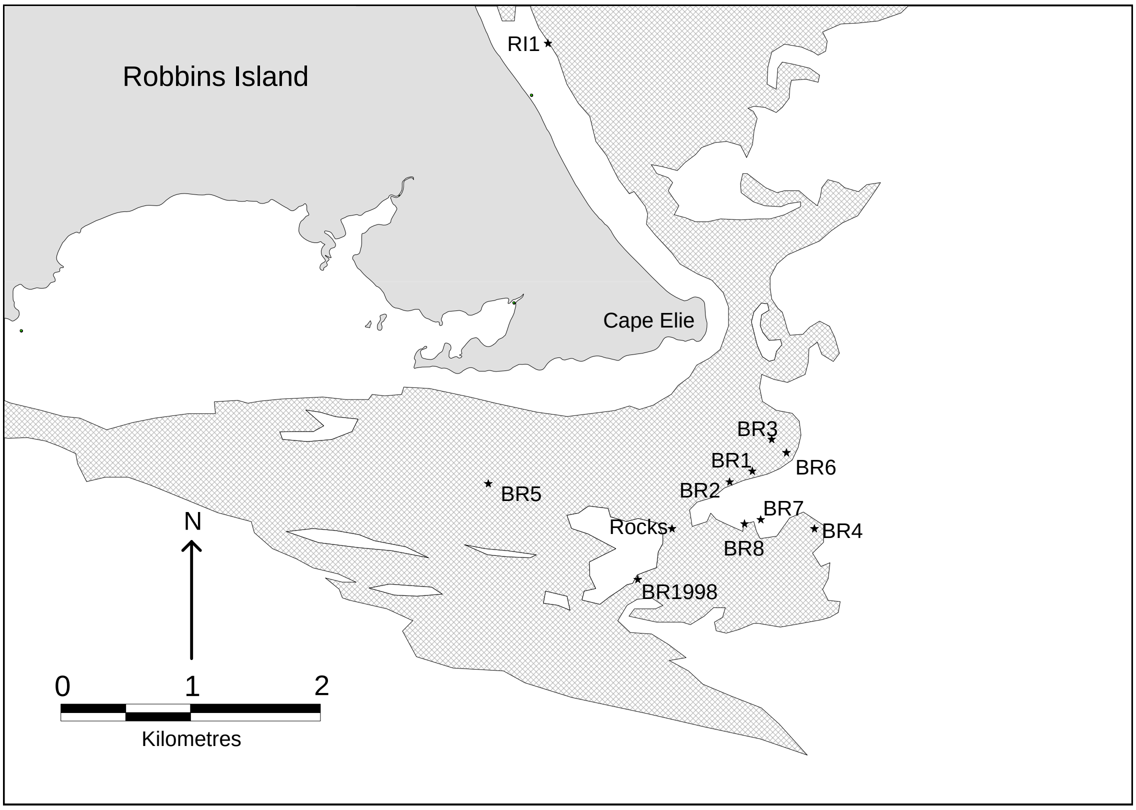


Figure 2. The position of the sites surveyed at Black Reef (BR1 to BR8) and Robbins Island (RI1) in 2004, and at Black Reef in 1998 (BR1998). The position of the Black Reef rocks exposed at low tide is also shown (Rocks). The hatched area shows the approximate position of the reef in 1992, determined from an aerial (satellite) photograph superimposed on the map.

Preparation of shells for ageing was undertaken using the documented standard spire-grinding method (Shepherd *et al.*, 1995; Shepherd and Turrubiates-Morales, 1997). Following the approach of Officer (1999), it was decided that age could be estimated from the number of rings counted in the spire of the shell divided by two (i.e. two rings per year). This assumption relied on verification from a study of greenlip abalone in the Furneaux Group, where individually marked abalone of known age were recovered and aged (Officer, 1999).

Age-length data were fitted by likelihood methods to the von Bertalanffy growth model:

$$L_t = L_\infty\left(1 - e^{-K(t-t_0)}\right) + N(0,\sigma)$$

where L_t is the length at time t, L_∞ is the asymptotic length , K the growth coefficient and t_0 the age when $L = 0$. The standard deviation (σ) of length was estimated assuming a normal distribution of lengths at age. Each likelihood was weighted with respect to the average length divided by the observed length. This has the effect of putting more weight on the smaller abalone, which means that the permitted variation about the fitted curve is less for smaller animals and larger for the larger abalone.

Sexual condition (mature, immature) was determined by visual inspection of the gonad. Low magnification was used to identify transitional stages following the onset of maturation. All abalone with gonads that were not fully developed were classified immature. Estimates of median size at maturity were developed from maturity data (mature/immature, length) fitted by likelihood methods to the logistic equation

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

where p is proportion mature, x is length, and c and d are parameters of the logistic function, by 1-mm size class. Each size class was weighted by the total number within that size class. The ratio of males to females was compared at sites where abalone were sexed, and the G-test used to detect significant differences from a one-to-one relationship.

Per-recruit analyses were performed using an unpublished Excel spreadsheet supplied by SARDI (S. Mayfield, pers. comm.) following the examples of Nash (Nash, 1992; Nash *et al.*, 1994). Egg production was expressed as a percentage of egg production in the absence of fishing (i.e. $F = 0$):

$$EPR = 100 \cdot \left[\sum_{t=t_r}^{t_\lambda} N_{t-1} \cdot e^{-(F+M)} \cdot E_t\right] \div \left[\sum_{t=t_r}^{t_\lambda} N_{t-1} \cdot e^{-M} \cdot E_t\right]$$

where N_t is the number of abalone surviving to age t and E_t the number of eggs produced by abalone at age t. F and M respectively refer to mortality due to fishing and natural causes.

Yield per recruit was investigated as a precautionary measure to check that potential size limits would not significantly reduce yield. Yield per recruit was expressed as a percentage of the maximum biomass of a cohort (B_{max}):

$$YPR = \frac{1}{B_{\max}} \cdot 100 \cdot \sum_{t=t_R}^{t_\lambda} \frac{F}{(F+M)} \cdot N_t \cdot W_t (1 - e^{-(F+M)})$$

where B_{max} is the summed weights of the cohort, F and M respectively refer to mortality due to fishing and natural causes, t_R and t_λ respectively are age at recruitment and maximum age, N_t is the number of abalone surviving to age t, and W_t the weight of abalone at age t.

The per-recruit analyses assumed the following conditions:

1. A stock-recruitment relationship existed and for the purpose of this study, was confined to Perkins Bay.
2. The sampling adequately represented all populations contributing to egg production and yield in Perkins Bay.
3. The population structure existed in a steady state, with constant levels of recruitment.
4. Upon recruitment, abalone had an equal probability of capture.
5. A standard maximum age could be applied to cohorts.
6. All eggs had an equal likelihood of producing larvae, independent of the size of the abalone from which they were produced.

3. Results

Generally, it was noted that abalone were abundant at all sites sampled, including the Black Reef site sampled in 1998. Abalone were extraordinarily abundant at Black Reef 4, where separation between individuals over a wide area was frequently less than one shell diameter (Figure 3). At both the North Point sites and Black Reef 3, abundance, while not as high as at Black Reef 4, was sufficiently high to enable samples to be collected at very high rates. Shell scouring by sand among abalone of shell length 120 mm and greater appeared to be prevalent at all the sites visited in 2004. At the Black Reef sites, there were large populations of the pearl oyster *Electroma georgiana*, some of which were attached to abalone in sufficient numbers to completely obscure them.

Population size-structure

There were remarkable between-site differences in the proportion of juvenile abalone (<105 mm) to abalone of legal size (145 mm +), with some sites containing no juveniles, while several hundred metres distant, other sites contained no legal-sized abalone. Length-frequency distributions derived from randomly collected samples exhibited this variability between sites (Figure 4).

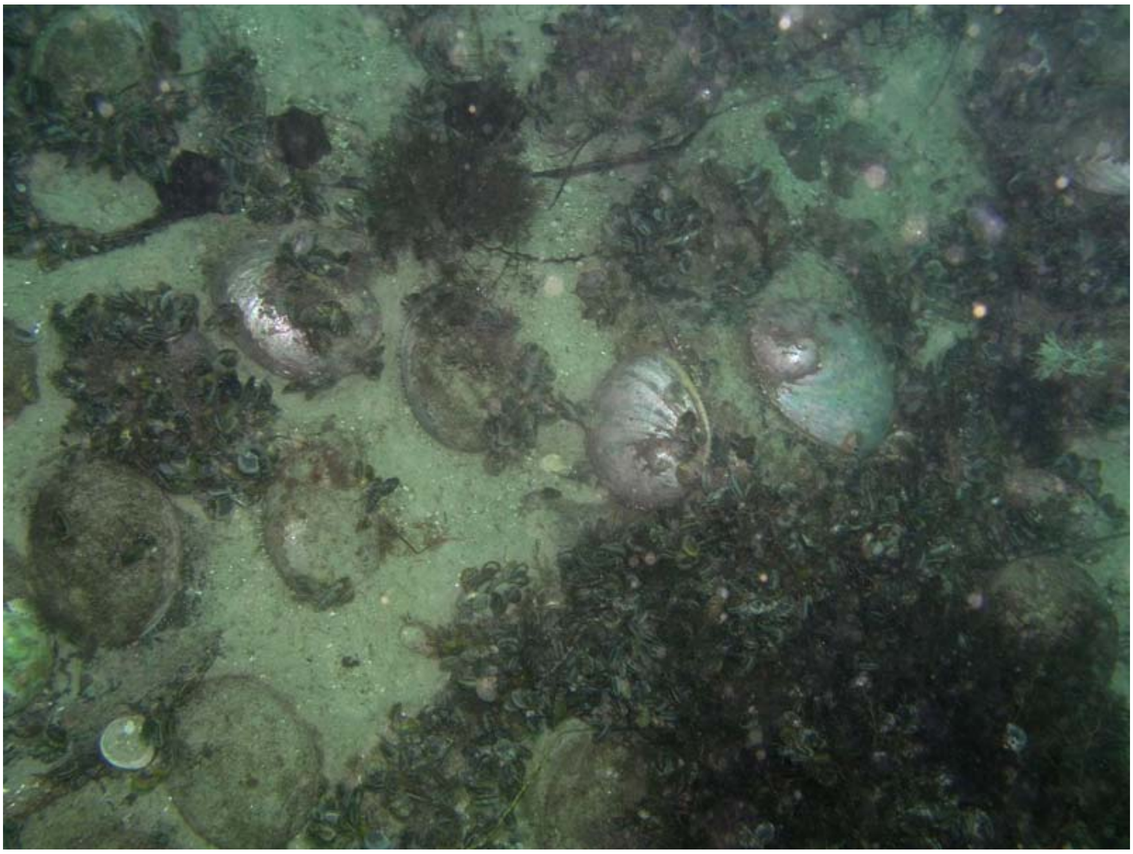
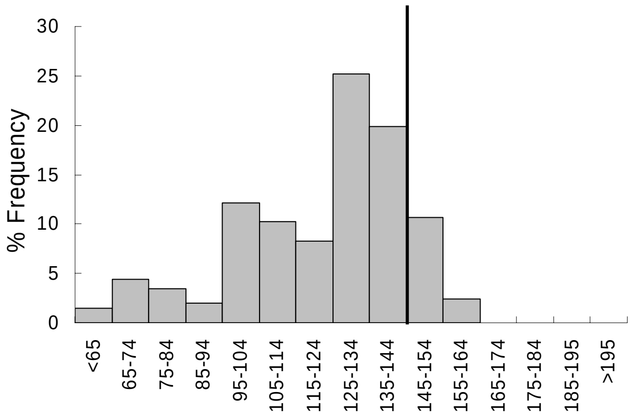


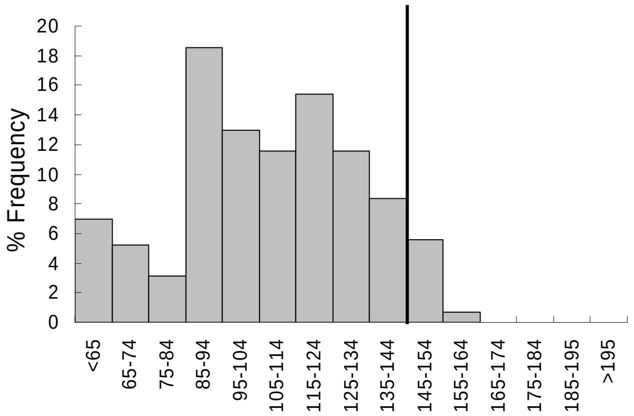
Figure 3. Greenlip abalone at Black Reef 4, showing the small distance separating individuals. Note sand-scoured shell of abalone in mid-picture, also dense clusters of the pearl oyster *Electroma georgiana*.

The first three Black Reef sites (Black Reef 1, Black Reef 3 and Black Reef 4) held much greater proportions of small abalone than the next three sites (Black Reef 7, Black Reef 8 and Black Reef 1998; Figure 4), although Black Reef 4 lacked the size range where transition to sexual maturity occurs (typically 65-95 mm). A feature common to the two groups of sites was that the Black Reef 7, Black Reef 8 and Black Reef 1998 sites were on the sand edge and typically covered in goose grass (*Amphibolis antarctica*), whereas Black Reef 1, Black Reef 3 and Black Reef 4 were distant (> 100 m) from the sand edge, and comprised mostly low relief rubble interspersed with silt or sand patches. Juveniles were almost entirely absent from the sand-edge site samples, but much better represented in the rubble reef samples (except Black Reef 4), perhaps because there was more cryptic habitat among the rubble. Conversely, abalone of legal size (145 mm) and greater were much more abundant at the sand-edge than further into the reef, and it seems logical to suggest that abalone recruit to the sand edge from mid-reef.

Black Reef, Site 1



Black Reef, Site 3



Black Reef, Site 4

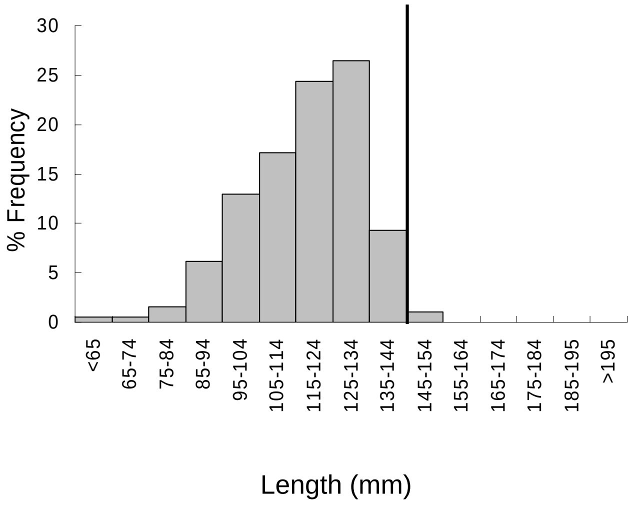
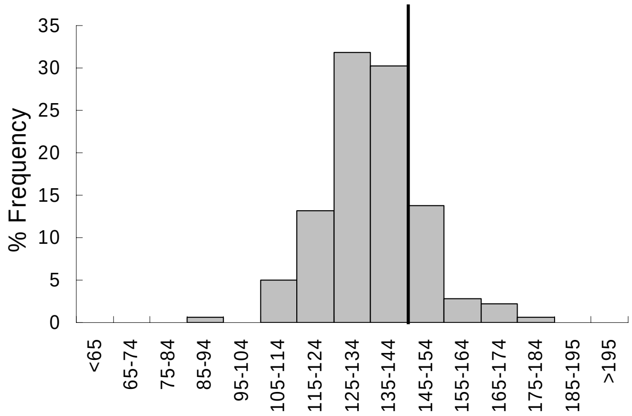
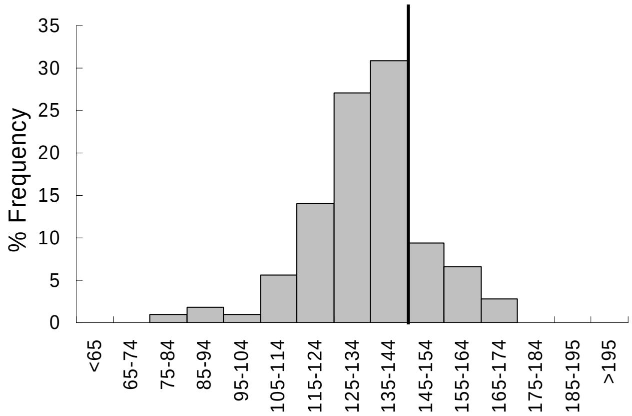


Figure 4. Length-frequency distributions of abalone from sampled sites. The vertical line shows the relative position of the current 145-mm size limit.

Black Reef, Site 7



Black Reef, Site 8



Black Reef, 1998 sample

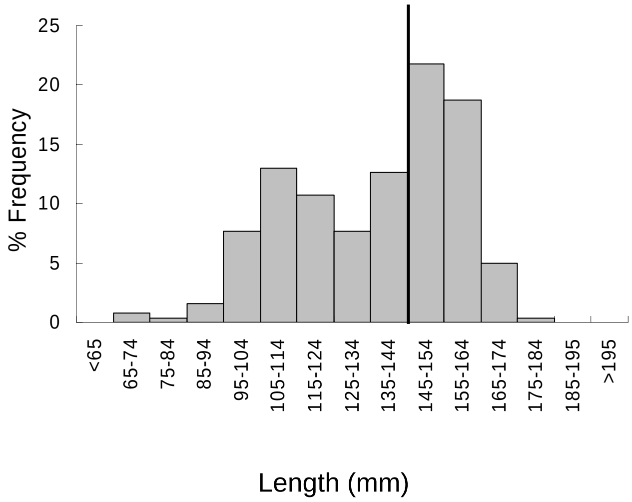
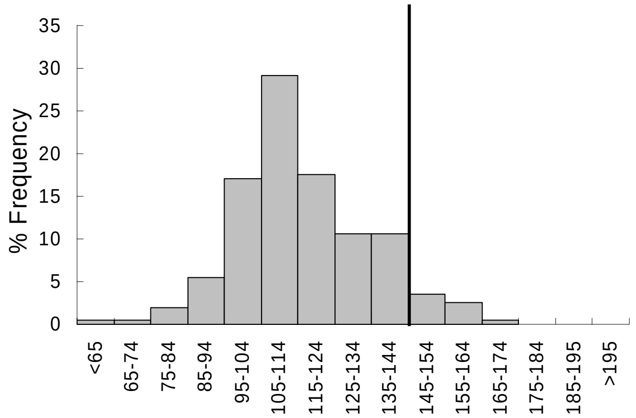
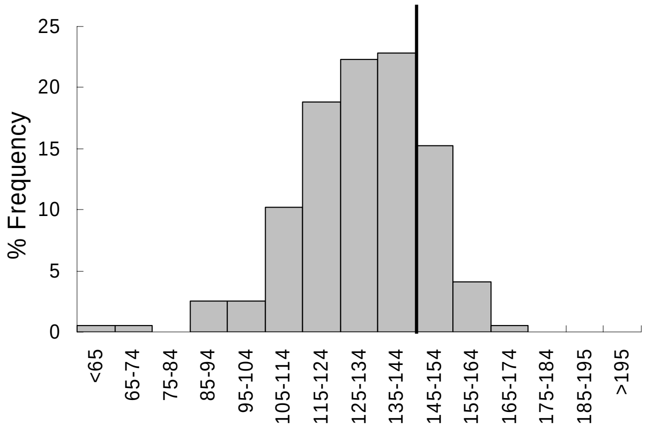


Fig. 4 [cont.]. Length-frequency distributions of abalone from sampled sites. The vertical line shows the relative position of the current 145-mm size limit.

Robbins Island



North Point, Site 1



North Point, Site 3

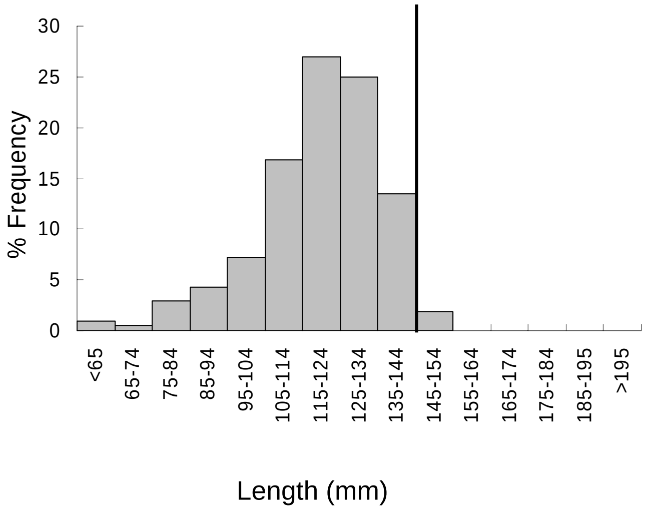


Fig. 4 [cont.]. Length-frequency distributions of abalone from sampled sites. The vertical line shows the relative position of the current 145-mm size limit.

Similar patterns in spatial distribution between immature and legal sized abalone at the other sites in Perkins Bay were not observed. Only one sample was collected at the Robbins Island site, which was also on the sand edge and like Black Reef, had few immature abalone. However, while the site was recommended to TAFI because it was commercially productive (P. Maguire, pers. comm.), there were fewer legal sized abalone than at the Black Reef sand-edge sites. At North Point, sites 1 and 3 were located on narrow fingers of reef among the sand, and lacked sand-edge / mid-reef contrast.

The percentage of legal-sized abalone reflects the economic potential of the sites from where samples were collected. Apart from the sand-edge / mid-reef effect on size distribution, the percentage of legal-sized abalone might be influenced by other factors, such as reef structure, algal cover or even variation in catching technique among divers. The percentage of legal-sized abalone varied from 45.8% (Black Reef, 1998 sample) to 1.0% (Black Reef site 4) (Table 2).

Table 2. Percentage of legal-sized abalone, by sample, 1998 to 2004

Site	% legal-sized	Sample Size
Black Reef 1998	45.8	262
Black Reef 1	13.1	206
Black Reef 3	6.3	285
Black Reef 4	1	193
Black Reef 7	19.2	182
Black Reef 8	18.7	214
Robbins Island	6.5	199
North Point 1	19.8	197
North Point 3	1.9	208

Growth and ageing

Shell age estimates were obtained from a total of 1008 abalone from six sites (Black Reef 1998, Black Reef 1, Black Reef 3, Black Reef 7, Robbins Island and North Point 3). Ages ranged between 1 and 31 years. At ages 1, and 16.5 years and older, there were only one individual per age class. The oldest abalone was 31.5 years, the next oldest 22.5 years.

$A_{99\%}$, the 99th percentile in the range of ages, was estimated at 16.5 years. However, considering that fishing mortality in the region has occasionally been high, and that per-recruit analysis is very sensitive to maximum age, this value was rejected as too low. After reviewing Officer's (1999) range of values of $A_{99\%}$ for Tasmanian greenlip populations, the more conservative value of 20 years as the maximum age for the per-recruit analyses was chosen.

The quality of fit to the age-length data by the von Bertalanffy model was apparent graphically (Figure 5). At ages less than 2 years, differences between the model and the observations became apparent, either because the number of individuals in each age class was too small or the model was a poor fit to the data. The parameters of the growth curve fitted to the combined data from Perkins Bay are show in Table 3.

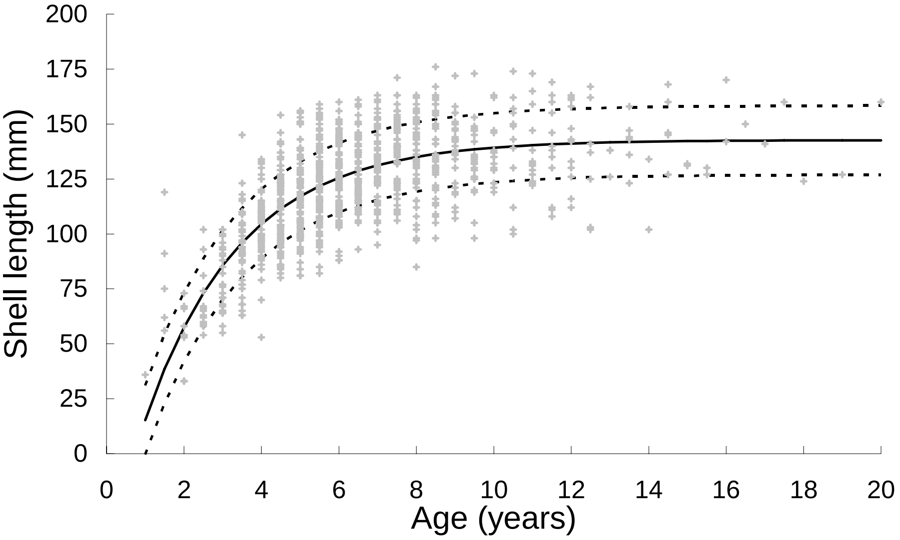


Figure 5. Age-length data from all sites in Perkins Bay (grey crosses), fitted to the von Bertalanffy model (solid line), with standard deviations from the model (dashed lines).

Table 3. Growth parameters from abalone collected at sites in Perkins Bay, 1998 and 2004

Age-length data from all sites sampled in Perkins Bay were combined. L_∞, K, and t_0 are parameters of the von Bertalanffy model, σ is the standard deviation of error about the model, and n the number of aged shells.

Site	L_∞	K	t_0	σ	n
Combined sites	143.6	0.37	0.48	16.81	1008

Abalone collected at the Black Reef site in 1998 clearly grew to a larger asymptotic length than those from the combined sites (Figure 6). Because of the simplistic nature of the per-recruit models used in this and Officer's (1999) study, and their capacity to accept only deterministic growth parameters, changes in asymptotic length have a profound effect on estimates of egg production and yield. The use of combined age-length data from all Perkins Bay sites 1998-2004 is an attempt to better represent the variable growth rates in the region and to moderate the effects of growth data from fast-growing sites applied to slower growing populations.

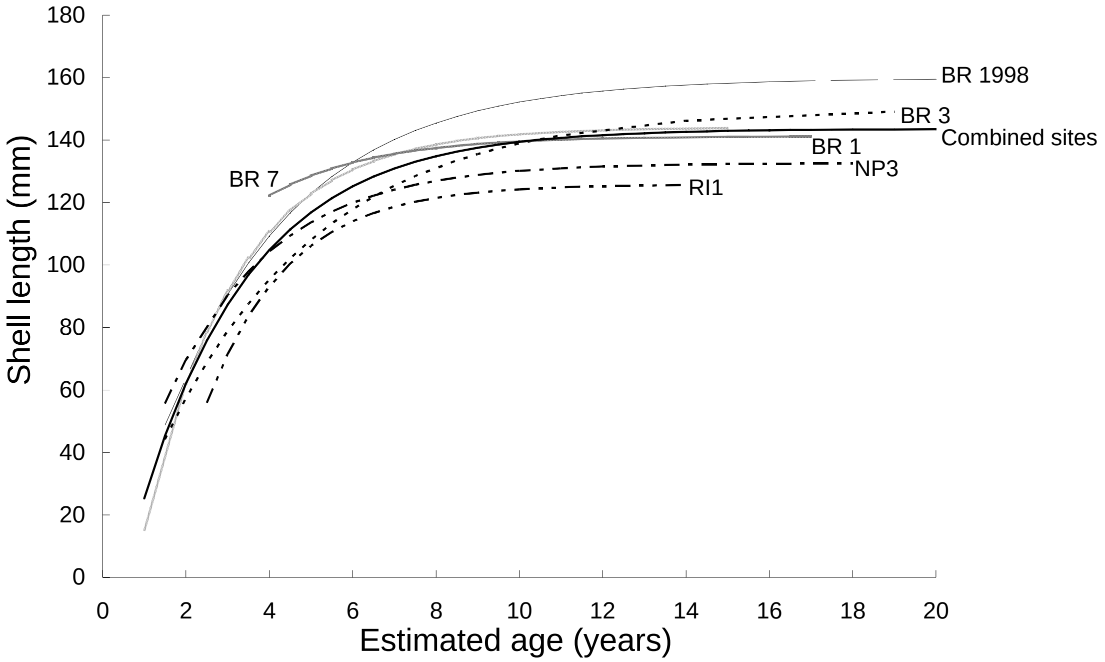


Figure 6. Comparison of Von Bertalanffy growth curves derived from age-length data from the Perkins Bay sites, 1998 to 2004. Abalone sampled from Black Reef in 1998 clearly grew to a greater average maximum length than those from the sites sampled in 2004. In the interests of clarity, the chart has been abbreviated to ages of 20 years and less.

Median size at maturity

At only one site (Black Reef 3) were sufficient immature abalone caught to produce robust estimates of size at maturity. Because of concern that this site might not adequately represent the Perkins Bay populations, the data set was extended to include samples from the 1998 survey work in North West Tasmania (Officer, 1999). The largest immature abalone was 91 mm, the smallest mature (female) was 68 mm. Size-at-maturity was estimated at 73.0 mm, which is similar to Officer's (1999) estimate of 71.7 mm.

Sex ratio

There were no consistent between-site differences in sex ratio (Table 4). Low *P*-values at Robbins Island and North Point 3 were probably due more to chance than reflective of their populations' sex ratio. Differences were statistically significant only at Black Reef Site 3 ($P<0.001$). For the purposes of estimating egg production from the region, an equal sex ratio was assumed.

Table 4. Sex ratio at sites sampled in Perkins Bay, 1998 to 2004

The numbers of males and females, the G-statistic used to determine differences from a 1:1 sex ratio, and *P*, the probability that those differences occurred by chance are shown.

Site	Males	Females	G statistic	*P*
Robbins Is, east	110	84	3.50	0.062
Black Reef 1998	137	124	0.65	0.421
Black Reef 1	64	72	0.47	0.493
Black Reef 3	35	73	13.66	<0.001
Black Reef 7	83	102	1.95	0.162
Black Reef 8	72	64	0.47	0.493
North Point 1	116	98	1.52	0.218
North Point 3	114	88	3.36	0.067
All sites (combined)	731	705	0.47	0.493

Mortality estimation

Estimates of rates of natural mortality (*M*) were derived from a combination of sources. For age-classes that were not fully recruited (i.e. juveniles and pre-recruits) estimates provided by SARDI were used. These ranged from $M = 4$ (age: 0 to 6 months), $M = 0.64$ (age: 6 months to 4 years), $M = 0.5$ (age: 4 years), $M = 0.3$ (age: 5 years).

For fully recruited age classes (6+ years), a range of potential values and their effects on yield and egg production were examined. At sites where shells were aged, estimates of the rate of instantaneous total mortality (*Z*) were derived from catch curves (Table 5), which in the absence of fishing could be attributed to natural mortality. Paradoxically *Z* was lowest where fishing mortality could be considered highest (Black Reef, 1998 sample) and highest at the site with little or no exposure to fishing in recent years (North Point 3). This was interpreted to mean that while the rate of natural mortality (*M*) could be as high as 0.4 for the fully recruited age classes, in all likelihood it was substantially less than this amount. Officer (1999) described a controlled experiment by Furneaux Aquaculture Pty Ltd where *M* was estimated at 0.11. For the purposes of per-recruit analysis, low values of *M* (e.g. $M = 0.1$) produce conservative (low) estimates of yield and egg production for a given size. Like Officer, values of $M = 0.1$ and 0.2 for per-recruit estimates were chosen.

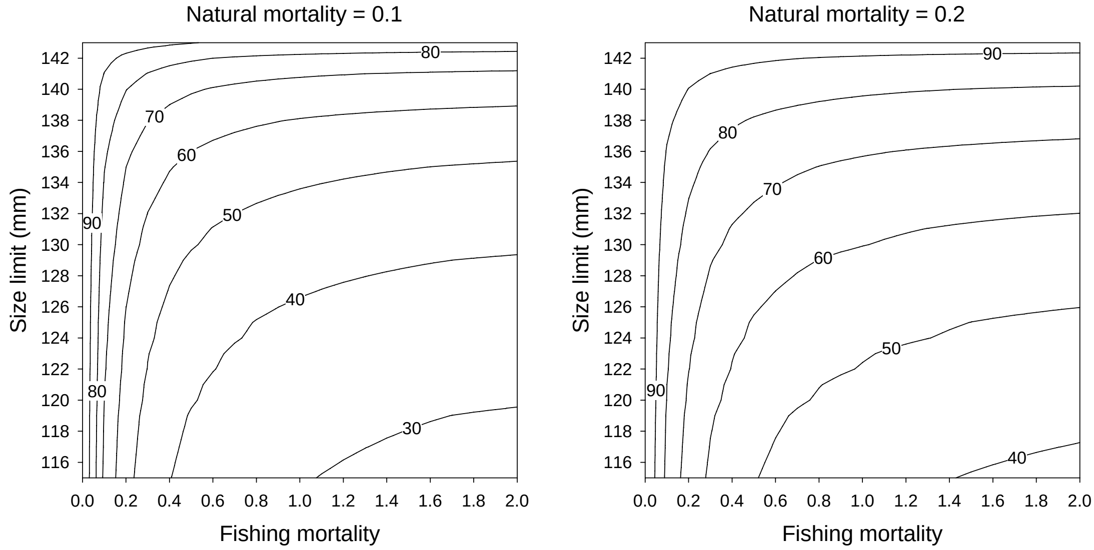
Table 5. Rates of mortality at sites sampled in Perkins Bay, 1998 to 2004

Estimates of instantaneous total mortality (*Z*), conversions to annual rates of mortality and survival, the number of aged shells per sample and the coefficient of determination are shown.

		Annual rate of:			
Site	*Z*	Mortality (%)	Survival (%)	*n*	r^2
Robbins Is, east	0.37	31	69	159	0.98
Black Reef 1998	0.25	22	78	235	0.94
Black Reef 1	0.32	28	72	152	0.87
Black Reef 3	0.32	27	73	149	0.89
Black Reef 7	0.31	27	73	136	0.83
North Point 3	0.40	33	67	177	0.83
All sites	0.36	30	70	1008	0.98

Egg conservation

Egg-per-recruit (EPR) was plotted for the Perkins Bay region, expressed as the percentage of total egg production in the absence of fishing**,** across a range of size limits and fishing mortalities (Figure 7). The sensitivity of per-recruit analysis to small changes in M is demonstrated, and EPR estimates for $M = 0.1$ (conservative) and $M = 0.2$ (less conservative) are shown. These contour diagrams are complex, containing much information. As an example of how they are intended to be interpreted, at $M = 0.1$, for fishing mortality (F) = 2.0, 50% of egg production would be conserved with a size limit of approximately 134 mm. Values of F greater than 1.0 progressively tend towards economic unfeasibility (low and falling catch rates encourage divers to seek better catch rates elsewhere).


Natural mortality = 0.1

Natural mortality = 0.2

Figure 7. Egg-per-recruit contour diagrams expressing egg production as a percentage of the total egg production in the absence of fishing, for two values of fully recruited natural mortality ($M = 0.1, 0.2$) across a range of fishing mortalities (F) and size limits.

Yield-per-recruit

Contour diagrams of yield-per-recruit (YPR) expressed as a percentage of the maximum potential biomass are provided for $M = 0.1$ and $M = 0.2$ (Figure 8). At the conservative value of $M = 0.1$, size limits of 134 mm or less ensure yields of at least 90% under a range of values of $F > 0.6$. Larger size limits imply that yield will increasingly be lost to natural mortality.

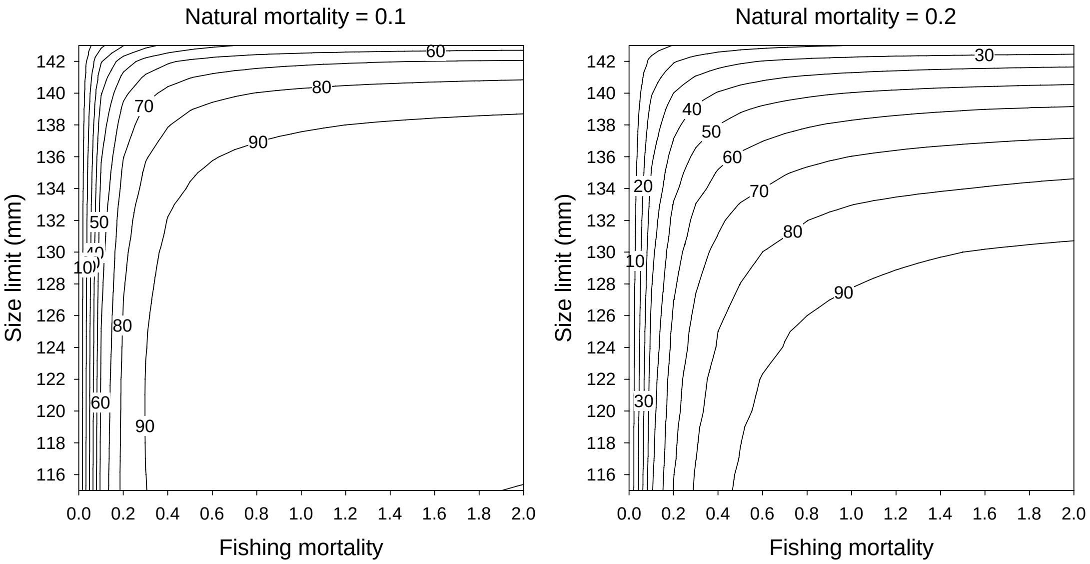


Figure 8. Yield-per-recruit contour diagrams expressing yield as a percentage of the maximum potential biomass, for two values of fully recruited natural mortality (*M* = 0.1, 0.2), across a range of fishing mortalities (*F*) and size limits.

4. Discussion

History of greenlip fishing in North West Tasmania

The principal purpose of this document has been to revise size limits in the Perkins Bay region, based upon a re-evaluation of estimates of egg-per-recruit in the light of revised information about abalone growth, and to estimate yields for the region that correspond with estimates for fishing mortality used in the EPR analysis.

The raising of greenlip size limits in North West Tasmania in recent years has been a contentious issue. While there has been unanimous support for ensuring that the fishery remains sustainable, the means for doing this have been subject to debate, most of which has been focussed on exactly what constitutes an appropriate size limit for the region. Managers have had to make decisions based upon scant biological information and the often conflicting advice from local divers.

In 1997, widespread concerns arose about overfishing and consequent recruitment failure in the Tasmanian greenlip fishery. The greenlip beach price had risen to a considerable premium over the blacklip price, which caused increased and largely unregulated catch and effort in the greenlip fishery. This prompted a review of the fishery, and in 1998, a series of population surveys were conducted at sites in Northern Tasmania that were chosen on the advice of local divers, including one site at Black Reef. Divers were asked to provide locations of sites significant to the industry that yielded good catches. Unfortunately, this was interpreted to mean “where are the best abalone found?”, which led to some sampling being done at sites with atypical abalone populations.

The review was completed in 1999 (Officer, 1999). It found that egg production was insufficient to maintain stock levels in most areas and called for substantial increases in size limit and regional catch limits. As a result, the size limit in the North West was raised from 132 mm to 140 mm in 1999, and then to 145 mm in 2002.

The site at Black Reef where 45% of abalone sampled were of legal size (145 mm +) appears to be in the atypical category (Table 2). At the sites sampled in 2004, less than 20% of abalone were of legal size, and in contrast, the 1998 site had unusually large abalone. This was the only site sampled in Perkins Bay in 1998, despite its history of large catches spanning many years, and it is likely that its potential contribution to the regional catch was underestimated.

The current 145-mm size limit seems appropriate for the North West greenlip populations sampled outside Perkins Bay, but it has proven too large for most populations within it. The result is that very little catch (~ 4 t p.a.) has been taken from Black Reef, and no catch has been taken at North Point in recent years. This has prompted a further review of greenlip populations in the region, with a view to setting more appropriate size limits and levels of catch.

The process of setting size limits

In recent years, Tasmanian abalone fishery managers have used the “two-year” rule of thumb when setting size limits (Anonymous, 2000), which in broad terms intends that abalone should breed for two years prior to recruitment to the fishery. The two-year rule makes use of the Tasmanian experience that blacklip populations survived heavy fishing if the gap between onset of maturity and recruitment was at least two years (Tarbath and Officer, 2003). Raising blacklip size limits to meet this guideline has apparently been successful, and divers now report higher levels of abundance among pre-recruits than they have seen previously (Tarbath *et al.*, 2005). However, while the two-year rule may be applicable to blacklip abalone in Tasmania, its use elsewhere in Australia and with other species has been criticised because it generates insufficient egg production (Preece *et al.*, 2004). This is probably because greenlip mature at a smaller size and younger age (Shepherd and Laws, 1974; Wells and Mulvay, 1995; Officer, 1999) than blacklip (Nash *et al.*, 1994; Tarbath *et al.*, 2001; Tarbath and Officer, 2003). Because fecundity of greenlip abalone is dependent on size (Shepherd *et al.*, 1992a; Nash *et al.*, 1994; Officer, 1999), the reproductive biomass conserved by the two-year rule may be insufficient to sustain the greenlip fishery, and although the two year period could be extended for greenlip, insufficient information can be gleaned from the history of the fishery to show how long that period should be.

One of the assumptions of the two-year rule applied to blacklip is that sufficient eggs are produced in the two year period so that populations will be sustained, even at high levels of fishing mortality. The relationship between egg production and recruitment is usually obscure (Sluczanowski, 1984), and particularly so among highly fecund invertebrates (Koslow, 1992) such as abalone, although Shepherd and Partington (1995) have demonstrated a stock-recruitment relationship in an isolated population. The two-year rule uses basic and readily obtainable biological information, and size limits are easily determined without the need for modelling egg production.

The alternative method of setting size limits requires an egg-production model. Nash (1992) and Shepherd and Baker (1998) have proposed that size limits should be based directly on levels of egg production that were observed in both failed and sustained abalone fisheries. Like the two-year rule, the EPR approach to setting size limits has its limitations and is fallible. In particular, the assumptions made about the populations may be untenable. For example, it is unlikely that populations exist in a steady state with constant levels of recruitment. The sensitivity of EPR to a number of parameters which cannot be readily determined (e.g. *M*) is well documented (Annala and Breen, 1989; Nash, 1992). It is therefore stressed that size limits and yields proposed in this document should be applied in a conservative manner.

For greenlip abalone in South Australia, Shepherd and Baker (1998) have suggested threshold EPR levels appropriate to sustain fished populations, based upon the size of the population, its degree of isolation from other populations, and the likelihood of larval supply from adjacent populations. For intermediate-sized metapopulations, preserving 50% EPR would appear desirable, while for larger metapopulations, 40% EPR may be sufficient.

From their examples provided from the South Australian fishery, it appears that Perkins Bay falls into the latter category i.e. a large metapopulation. Perkins Bay has these characteristics:

1. There are numerous local populations throughout Perkins Bay, in sufficiently close proximity to suggest that larval intermixing occurs (Shepherd *et al.*, 1992b; Rodda *et al.*, 1997), and that might buffer declines in larval recruitment caused by localised depletion.

2. Perkins Bay is not isolated from other greenlip populations. While the nearest commercially significant population is at the Petrels (16 km north west of Guyton Point on Robbins Island), other populations exist close by but outside the bay. These are within a few kilometres west of Guyton Point, and on the eastern side of Perkins Bay, south-east of North Point. These populations were only infrequently fished even at the 127-mm size limit because they were too small. Similar stunted populations exist within Perkins Bay to the south of North Point, (P. Maguire, pers. comm.). These populations could be expected to supply eggs to the region even if the larger growing populations were heavily fished.

3. Tidal flows in Perkins Bay are commensurate with a tidal range of approximately 2.5 m. RAN Hydrographic Chart AUS 790 which covers the region shows strong westward tidal flows through the navigation channels. At other times, predominately westerly winds induce eastward flowing currents. Given this degree of flushing, larval dispersal appears likely throughout the bay and adjacent coast.

If larval dispersal is assumed to occur at scales of kilometres, then it can be concluded from the descriptions of the South Australian examples (Shepherd and Baker, 1998) that EPR in the range 40 to 50% would be sufficiently conservative to ensure a viable fishery in Perkins Bay.

Rates of natural mortality

Estimates for EPR and YPR for levels of $M = 0.1$ and $M = 0.2$ are provided (Figure 7, Figure 8). As previously mentioned, per-recruit analyses are acutely sensitive to small changes in M. Values of $M > 0.1$ would produce threshold levels of EPR at unrealistically small size limits. Unfortunately, accurately measuring natural mortality is notoriously difficult (Shepherd and Breen, 1992), and usually, estimates of M are gleaned from a combination of methods from a variety of sources.

The estimates of Z (fishing mortality plus natural mortality) at Perkins Bay ranged from 0.25 to 0.4. The highest value came from North Point in Block 47, from which no catch had been reported for many years, implying high values of M. Officer (1999) found similar levels of Z, even in unfished populations at the mouth of the Tamar River. Given the contrast in size composition between sites on Black Reef, it is possible that older abalone here migrate from mid-reef to the sand edge where they are fished. This would raise values of Z at both mid-reef and sand-edge sites. If low levels of F (0.1 – 0.2) are assumed, M would range up to 0.3 at the Perkins Bay sites. Shepherd and Baker (1998) list values of M for greenlip in South Australia ranging between 0.13 and 0.25. Whilst accepting that M is most likely to be nearer to 0.2, the safest approach would be to follow Officer’s (1999) example and set $M = 0.1$.

Rates of fishing mortality

The remaining requirement for setting size limits is to establish appropriate levels of F (fishing mortality). For this region, levels of F of 1.0 or more (i.e. more than 63% of the stock are removed each year) are possible. While this level of fishing mortality must be considered unusually high, it appears to be a regular feature of at least one part of the Tasmanian fishery under circumstances that are similar to Perkins Bay. Market samples taken from the Actaeons blacklip fishery frequently show knife-edge size composition consistent with levels of fishing mortality between 50% and 70% p.a. The Actaeons fishery is unusual, because there are a large group of divers living in towns close to the reefs at the Actaeons, and these reefs can be fished in most weather conditions. Divers tolerate lower catch rates at the near-by reefs because they can be readily accessed, and it costs less to fish there than more distant reefs. However, when catch rates get too low, they move to more productive regions, effectively reducing the rate of fishing mortality on the Actaeons abalone populations.

Similarly, the Perkins Bay reefs are close to the towns of Stanley and Smithton, which have launching ramps, processing facilities and accommodation for divers (Figure 1). It can therefore be expected that divers will prefer to fish in Perkins Bay rather than travel to the less sheltered and more distant reefs elsewhere in the North West greenlip fishery, and that the reefs there could be fished at low catch rates with rates of F of 1.0 or greater.

As a guide to estimating levels of annual catch equivalent to $F \geq 1.0$, it is proposed that the geometric mean of the tonnages taken during the most productive years of the fishery at lower size limits be used. Note that these catches were occasionally misreported, either in weight or attributed to the wrong reporting block.

Catches were reported from the wider area of Blocks 47 and 48, whereas the Perkins Bay region includes only Sub-block 48A and part of Block 47 (Figure 1). (Most of the Block 47 catch has been verbally reported as being taken from the area included in this study.) Because reporting of catch by sub-block started much later in 2000, the level of catch in Sub-block 48A prior to this is unavailable, and must be estimated based upon the spatial distribution of more recent catches. While this may under-represent catch because a high size limit could have reduced yields between 2000 and 2001, without specific knowledge of the distribution of Block 48 catches, this is the only method of apportioning catch. Table 6 shows the percentage of greenlip catch attributable to Sub-block 48A between 2000 and 2001 (the years 2002 to 2004 were not included because the size limit was too high). The percentage of catch from Sub-block 48A in the two-year period was 43.5%.

Table 6. Block 48 greenlip catch (kilograms) distributed by sub-block, 2000 - 2001

Sub-block	2000	2001	Total
48A	7952	17805	25757
48B	3930	4483	8413
48C	12322	12690	25012
Total	24204	34978	59182
48A %	33	51	43.5

Annual catches for Blocks 47, 48 and an estimate of the catch from Sub-block 48A are shown in Table 7. By applying the percentage contribution of Sub-block 48A catches (43.5%) to the Block 48 geometric mean catch for the period 1983 to 2001 (29 t), an estimate of the geometric mean catches for the years 1983 to 2001 can be made.

Note that before 1983, catches were either very low (Block 47) or varied greatly between years (Block 48) and hence the fishery was not fully exploited, so catches from both blocks were not included. The increase in size limit from 127 to 132 mm in 1987 was said to have reduced yields in Block 47 (because the abalone were too small), but this is not supported by subsequent levels of annual catch (Table 7) and it is more likely that the reductions in TAC in the late 1980's and the movement of divers out of the region during the early 1990's caused catch levels to fall. Catches from Block 47 taken after 1991 were consequently discarded. The catch in Sub-block 48A was affected by the 145-mm size limit from 2002, so Block 48 catches after 2001 were also discarded.

The sum of the geometric mean catch from Block 47 (24.8 t) and the estimated geometric mean catch from Sub-block 48A (12.8 t) is approximately 38 t (Table 7). For the purpose of estimating an appropriate yield from the region, it will be assumed that the sum of these means forms the upper limit of fully exploited catch levels for the EPR model, and that commensurate with this upper limit, fishing mortality was high, with values of *F* equal to or greater than 1.0.

Table 7. Annual catches, Blocks 47 and 48, 1975 – 2004

Catches used to calculate geometric means are in bold. The proportion of catch from Sub-block 48A was estimated from Table 6. The average was calculated from the arithmetic mean for the period 1975 to 2004.

Year	Block 47	Block 48	Sub-block 48A
1975	0	7	
1976	0	8	
1977	0	40	
1978	1	13	
1979	0	11	
1980	0	6	
1981	3	12	
1982	2	7	
1983	**14**	**40**	**17**
1984	**52**	**60**	**26**
1985	**12**	**36**	**16**
1986	**57**	**35**	**15**
1987	**37**	**33**	**14**
1988	**35**	**28**	**12**
1989	**20**	**27**	**12**
1990	**21**	**27**	**12**
1991	**13**	**32**	**14**
1992	4	**14**	**6**
1993	2	**26**	**11**
1994	3	**48**	**21**
1995	5	**23**	**10**
1996	1	**15**	**7**
1997	1	**28**	**12**
1998	2	**43**	**19**
1999	0	**18**	**8**
2000	0	**24**	**11**
2001	0	**35**	**15**
2002	0	27	
2003	0	14	
2004	0	14	
Geometric mean	**24.8**	**29.2**	**12.8**

Recommended size limits

At $F = 1.0$, a size limit of 132 mm would conserve approximately 47% EPR (Figure 7). YPR remained above 90% at this size (Figure 8). Higher size limits would enable conservation of greater levels of egg production, but at the risk of reducing the contribution from the smaller growing populations while imposing greater levels of fishing mortality on those that grow larger. A conservative approach to managing the fishery in this region would be to limit localised fishing mortality by distributing effort through the use of smaller size limits, while maintaining a low level of catch overall. However, size limits much lower than 132 mm would tend to fall below the EPR threshold, particularly if fishing mortality was locally high.

Recommended levels of annual catch

Historical catch levels have previously been used as a guide to setting levels of annual catch for other fisheries, including the four greenlip sub-regions (Officer, 1999), and the Northern Zone blacklip fishery (Tarbath and Officer, 2003). The problem with setting annual catches based on historical levels of fishing is (a) that it is not known if the historical catches were sustainable and (b) the quality of the early catch reporting, both spatially, and in terms of landed weight was often of a low standard, and some of the weights attributed to a specific block may be incorrect. Given this level of uncertainty, the upper catch limit of 38 t should be used as a guide only. Greenlip populations seldom recover following overfishing (Shepherd *et al.*, 2001).

Unlike the other Tasmanian greenlip regions in the late 1990's, there were no persistent indications that the North West fishery was being depleted. Prior to the size limit increases and the establishment of zoning in 2000, greenlip effort in the region was at low to moderate levels, with relatively high catch rates, which contrasted with the other three greenlip producing regions where catch rates had fallen (Officer and Tarbath, 2000). While catch rates in the Tasmanian greenlip fisheries are unreliable indicators of abundance (Tarbath *et al.*, 2004; Tarbath *et al.*, 2005), their continuance through many years at consistent levels of annual catch suggests that the North West regional catch was generally sustainable.

Considering the uncertainty with the estimated upper catch limit, it is suggested that the Perkins Bay annual catch be set at some fraction of the catch limit until it can be demonstrated by fishery independent means that higher levels of catch within the Bay are sustainable. For example, an annual catch of approximately half the estimated upper limit i.e. 20 t might be considered sufficiently conservative. This almost arbitrary level should be considered in the context of adaptive management. If the performance of the fishery in blocks 48A and 47 declines at this level of catch then moves would need to be made to reduce the cap. Ongoing monitoring would be required.

The Sub-block 48A annual catch (4 t) is currently included in the North West regional catch (30 t). It is recommended that the two regions be managed separately, each with its own size limit and annual catch cap. Consequently, the existing Sub-block 48A annual catch (4 t) should be deducted from the North West regional catch limit.

Officer (1999) noted that there were populations of smaller-growing greenlip distributed along the North West Coast between Perkins Bay and the mouth of the Tamar River (Blocks 43 to 46). When fished at the 127-mm size limit, these blocks occasionally produced up to nine tonnes of abalone in a year, although the mean annual catch for this region is approximately one tonne. Growth rates from abalone sampled from the mouth of the Tamar River confirm that these abalone grow to a small size, similar to the aggregate growth rates of abalone from Perkins Bay. It is suggested that the 132-mm size limit be adopted for greenlip in Blocks 43 to 46. Because of the limited extent of this part of the fishery, and the irregular nature of its landings, it may be best managed if catch from these blocks be included in the Perkins Bay annual catch.

Alternative strategies to manage the Perkins Bay fishery

There are alternatives to lowering size-limits and capping production in Perkins Bay. The first involves leaving the size limit at 145 mm which has been demonstrated sustainable. The catch could not be expected to increase, but there would be no increase in costs involved with managing the fishery as there would be with a reduced size limit and separate catch limit.

The second alternative also involves maintaining the existing size limit, but involves transferring abalone from slow growing to faster growing sites, or modifying product to suit market demands. There are expanding markets in South East Asia for premium quality live greenlip. The highest beach prices are paid for greenlip larger than 500g, or approximately 160 mm length (C. Mason, Furneaux Aquaculture Pty Ltd, pers. comm.). Most greenlip from Perkins Bay are too small, and are not suited to this market, and will probably be processed IQF, which sell for a lower price than live abalone. If the price difference between the premium market and the IQF market was sufficiently large to cover the costs associated with translocation and management, then this alternative could be justified. Modifying product through translocation has the potential to produce greater economic yields from an existing resource. However, there would be difficult fishery access issues to be negotiated between the wider group of stakeholders and those accessing the fishery.

A third alternative involves individual reef management, such as practised in Victoria's Western Zone blacklip abalone fishery. This is a small fishery, with relatively few participants. The divers assess the productivity of each reef in the Zone, in terms of potential annual catch and the minimum size at which abalone should be caught. Their annual catch recommendations are considered when setting the Zone's TAC, and size limits accepted provided that they meet the requirements for sustainable fishing. This approach could be successfully used in Perkins Bay, but again, would require an unprecedented level of cooperation between those accessing this part of the fishery and the remainder of the industry.

Management of greenlip fisheries in Tasmania

Since the early 1990's there has been increasing recognition of the difficulties faced in managing the Tasmanian greenlip fisheries. Much research and management effort has been devoted to ensuring that stocks remain at sustainable levels, but it seems that more work is required. In North West Tasmania and the Furneaux Group, populations are probably at stable or increasing levels, while at King Island and in the North East populations are likely to be declining (Tarbath *et al.*, 2004; Tarbath *et al.*, 2005).

Abalone abundance appears to be increasing in the Furneaux Group where the annual catch limit is 42 t, substantially lower than the long-term geometric mean of 70 t. Most of this catch is taken by one diver to supply a market paying a premium for large abalone, which means that they are caught at a much greater size than necessary to maintain threshold levels of EPR. The North West catch (currently 30 t) is also lower than the long-term geometric mean (40 t), although the 145-mm size limit is only marginally adequate to preserve sufficient egg production at high levels of fishing mortality. In the regions where stocks are falling (North East and King Island) the annual catch has been above the geometric mean catch for many years.

The difficulties of managing the fisheries stem from two closely-linked causes. The first is that there has been a failure to consider that fishing mortality on individual greenlip populations may often be higher than expected (S. Shepherd, pers. comm.). In contrast to blacklip abalone habitat, the reefs where greenlip are caught are usually low relief with sandy patches with little cryptic habitat. High proportions of the greenlip population are visible, and if of legal size, are vulnerable to capture. Some divers have reported that they take all the greenlip on a sand edge, which means that levels of F are probably much greater than 1.0 on some reefs. The only way that managers can control such high levels of fishing mortality is to ensure that annual regional catches are low relative to historical levels, and hope that when depletion becomes noticeable, divers choose to fish alternative reefs with better catch rates.

The second problem is caused by variation between growth rates within a region. Size limits that are too high lead to unequal levels of fishing mortality between smaller and larger growing populations. If it has been assumed that the smaller growing populations would provide eggs to sustain the larger growing populations but fail to do so, the larger growing populations become depleted, leaving populations of abalone too small to be fished. On King Island, abundant populations of abalone too small to be fished are reported in some areas, while elsewhere reefs have become depleted. Perhaps a division of the region into large- and small-growing areas, each with its own size limit and annual catch limit could reverse the stock decline. The logical extension of this approach is micro-management at the reef scale or smaller, but this approach would be difficult to implement under current Tasmanian management policies.

The simple solution to these problems appears to be to reduce annual catches to levels that are irrefutably sustainable, and maintain size limits sufficiently high to protect stocks. Greater levels of yield require an acceptance that populations are dynamic, and that information about population biology and abundance needs to be regularly updated. More specifically, a means of monitoring abundance that will detect depletion and knowledge of regional growth rates and the distribution of sources of egg production are required. Most importantly however, research and management are constrained by limited budgets, and it needs to be demonstrated that the benefits derived from the increased catches outweigh the costs associated with monitoring and management, which under the current management plan and associated Deed of Agreement, may prove difficult in small regional fisheries.

5. Conclusions

1. It is desirable to reduce the size limit sufficiently so that fishing effort may be spread over the many abalone populations within Perkins Bay (Sub-block 48A and Block 47), thus avoiding serial depletion among a few larger growing populations. Therefore, it is recommended that size limits for taking greenlip abalone in Perkins Bay be reduced from 145 mm.

2. An appropriate size limit for this region would be 132 mm. Provided that the annual catch is limited to levels specified below, egg production at a 132-mm size limit would be above minimum levels that have been found sustainable in greenlip populations elsewhere.
3. Initially, the Perkins Bay annual catch should be set at approximately half the estimated upper limit of acceptable fishing mortality i.e. 20 t. This annual catch is to be managed separately to the North West regional annual catch. The existing Sub-block 48A annual catch (4 t) should be deducted from the North West regional catch (30 t).
4. Fishery-independent estimates of abundance should be made at reefs in Perkins Bay prior to the start of the fishery at the reduced size limit, and from thereon abundance should be monitored at regular intervals.
5. We recommend that all divers fishing in Perkins Bay participate in the GPS data logger scheme being developed at TAFI so as to monitor the spatial distribution of effort and thus provide a means to determine whether effort is evenly spread across populations.

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