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BLACKLIP ABALONE (*HALIOTIS*
RUBRA) IN THE HOGAN AND KENT
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Summary

The growth and the size at onset of sexual maturity of blacklip abalone (*Haliotis rubra*) in the Bass Strait islands was studied prior to the commencement of a series of intensive fisheries. During the course of these fisheries, it became apparent that abalone were maturing at a larger size, and that the size-limit at which they were fished might no longer be appropriate. A research survey was conducted in the Kent and Hogan Groups in 1997 to recover tagged abalone and sample abalone populations with the objective of comparing various indicators of growth with those from a previous study. The samples were used to measure growth and size at onset of sexual maturity and to check assumptions predicated of the change-in-ratio analyses of the 1995 fishery.

It was found that there was a change in abundance of undersized abalone at the Kent Group indicating that the 1995 change-in-ratio analysis was invalid. Growth rates derived from a mark-recapture study were comparable with recorded growth rates of blacklip abalone from other areas of Bass Strait and South Australia. Comparison of growth rates derived from age-length data with pre-fisheries growth rates indicated faster growth, although the analysis was affected by size-selective removal of older abalone, spatial variation in growth and differences in techniques used to age shells. No change in growth could be detected using modal progression analysis of length-frequency distributions. An increase in size at 50 percent sexual maturity at the Kent Group was attributed to increased growth rates. Comparison of shell morphometrics showed some changes in shape that might be indicative of faster growth rates. It was concluded that the increased growth rates are attributable to reduced stock density caused by high fishing pressure.

It was also concluded that future fishing should be undertaken on a sustained basis (instead of fisheries of short duration), that the total allowable catch should be lower and the size-limit higher than in past fisheries.

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1. Introduction

Blacklip abalone are found on all Tasmanian coastlines. In the northern part of the State, blacklips are stunted (i.e. reduced in size compared with those from further south), and around many of the Bass Strait islands, do not normally reach the smaller of the Tasmanian legal size-limits (132 mm). Since the 1980's, it has been widely recognised that there were substantial stocks of stunted abalone, which, if harvested at a lower size-limit, would be of particular economic benefit to fishermen and to the State generally.

Individual quotas and a fixed total allowable catch (TAC) were introduced to the fishery in 1985. Progressive reductions of the TAC over the next three years caused some financial hardship within the industry, and in 1988 it was proposed that a special fishery take place around the Bass Strait islands and northern Tasmania to compensate divers for lost income. The stunted blacklip abalone populations would be fished at a reduced size-limit, and this extra catch would be in addition to the divers' annual quota.

That fishery took place in 1989. Since then, there have been four more stunted blacklip abalone fishing seasons (in 1991, 1993 and two in 1995), each of one month duration or less. The 1995 fisheries landed a total of 40.1 tonnes of abalone from the Kent Group and 37.3 tonnes from the Hogan Group. Historically, this combined catch from the Kent Group is nearly double the previous highest catch (in 1989), while the catch from the Hogan Group was within the range of past catches (Table 1).

Table 1. Catch (in tonnes) of blacklip abalone (*Haliotis rubra*) from the Hogan and Kent Groups
For clarity, the two fisheries of 1995 have been combined.

year	Hogan Group	Kent Group
1989	40.3	24.0
1991	27.6	13.8
1993	36.7	20.7
1995	37.3	40.1

After two weeks, the November 1995 fishery was abandoned because the divers reported unusually low catch rates, particularly from the Kent Group. Experienced abalone divers estimated that they had taken a very high proportion of the available stock, and that there were insufficient stocks to warrant further fishing. Estimates of rates of exploitation by the Tasmanian Department of Primary Industry and Fisheries (DPIF), using depletion and change-in-ratio methods were less than those of the divers, but still indicate a significant reduction in abundance of legal-size abalone (Table 2).

Table 2. Rates of exploitation of blacklip abalone

Exploitation rates of the November 1995 fishery, by number of abalone taken with 95 percent confidence limits, from Nash (1996).

Method of estimation	Hogan Group	Kent Group
Leslie Depletion	0.56 (0.44-0.65)	0.60 (0.48-0.70)
De Lury Depletion	0.58 (0.48-0.65)	0.58 (0.42-0.70)
Change-in-ratio	0.51	0.31

It is likely that there has been a marked reduction in the abundance of abalone since the start of the fisheries. Abalone have a tendency to occur in aggregations (Douros, 1987; Prince and Shepherd, 1992; Shepherd and Partington, 1995), which when targeted by divers at high levels of fishing pressure causes rapid depletion of stocks (Breen, 1992; Nash *et al.*, 1994). After each of the abalone seasons, the remaining abalone may have re-aggregated (Gorfine *et al.*, 1998; Nash *et al.*, 1994) and combined with new stocks from the recruitment process were subsequently fished in the following season.

In the earlier fisheries, there were sufficient abalone in the aggregations to maintain relatively high catch rates and satisfy divers. From the experience of divers during the November 1995 fishery, it appears that the recruitment process has not managed to keep apace with the cumulative depletion of successive fisheries and that stock reduction has been masked by the aggregating behaviour of abalone.

The Tasmanian Government has undertaken research into abalone stocks in the area and since 1988, fisheries researchers have completed nine cruises to the eastern islands of Bass Strait. Research has been conducted to ensure that the Bass Strait stunted fisheries are operated in a sustainable manner. The primary aims of the research have been to :

- estimate the size of the resource,
- determine the TAC for the stunted blacklip abalone fishery under different management regimes,
- determine an appropriate minimum size-limit, and
- assess the impact of each fishery.

The first research cruise was undertaken by Jeremy Prince in October 1985 (Prince *et al.*, 1987), who employed three licensed abalone divers from Flinders Island to collect samples from sites around the Kent and Hogan Groups. He concluded that the annual harvest from the Kent, Hogan and Curtis Groups combined would be about 25 to 30 tonnes, at a size-limit of about 110 mm.

A second cruise was undertaken prior to the first fishery of 1989, and background information about growth, size at maturity, mortality, fecundity and morphometrics was collected and egg- and yield-per-recruit analyses prepared (Nash *et al.*, 1994).

Since then, research cruises have been conducted in association with these fisheries (with the exception of the May 1995 fishery) to assess the impact of fishing on the stocks. Recommendations on TAC and minimum size-limit have been made on the basis of the research survey results. Methods to assess the Bass Strait fishery have yielded what are believed to be among the most detailed assessments of an abalone fishery yet carried out.

Following the 1995 fishery, there was evidence that the size at sexual maturity had increased at the Kent Group, indicating that abalone in these islands were now growing at a rate faster than that observed in 1988. It was considered that if this change in growth rate was real and not just a product of changes in sampling technique, then it might be an adaptive response by abalone to the depletion of stocks.

This report details the objectives and findings of a cruise by DPIF officers in January 1997 to conduct research into the status of blacklip abalone (*Haliotis rubra*) stocks in the Hogan and Kent Groups, Bass Strait. The objective of the trip was to improve knowledge of the biology of the stocks, as opposed to the quantitative assessments of earlier cruises. This is not to say that inferences cannot or should not be drawn about the relative abundances of abalone stocks compared with previous years, but that determining abundance was not an objective of this particular trip. Of particular interest was the recovery of abalone that had been tagged and released in the islands during the previous survey.

2. Objectives

The research program for this cruise was developed by Warwick Nash prior to his departure from DPIF in 1996. He was the program leader of abalone research during the course of the Bass Strait fisheries and developed research programs to assess the effect of fishing on abalone abundance.

The objectives of this survey are presented here with explanations detailing the circumstances under which they were developed:

2.1 Measurement of growth

There is evidence that abalone from these islands are growing at a faster rate. This evidence stems from earlier research work and from comments by participants of earlier fisheries concerning a higher proportion of cleaner, fast growing shells than seen in past years. The objective was to measure growth of blacklip abalone at the Kent and Hogan Groups in three ways:

2.1.1 Recapture of tagged abalone

By recapturing abalone tagged and released during the preceding survey of January 1996, it should be possible to obtain information about *annual* growth i.e. that was free of complicating factors such as the effects of seasonality, or that included an extra part of a growing season.

2.1.2 Modal progression analysis

Samples of abalone would be collected from a small number of representative sites in the island groups. Growth could be determined by comparing the movement of the modal size-class in length-frequency distributions of the samples with length-frequency distributions of samples obtained during the post-fishery (January 1996) survey. The 1995 fisheries removed a substantial proportion of abalone greater than 110 mm, and post-fishery length-frequency distributions show a corresponding peak at that size. Comparison of distributions from samples taken one year later should show movement of this peak, which would be attributable to growth of abalone of 110 mm shell-length.

2.1.3 Collection and analysis of age-length data

The third estimate of growth would be derived from the ring number (age)-length relationship, determined from population samples from selected sites around these islands.

In 1988, quantities of shells were collected, the number of rings in the spire of each shell was counted and the relationship between the numbers of rings and the length of the shells was determined. It would be useful to compare the relationship between shell length and ring-count from the respective years. It should be possible to determine whether the shells are larger for a given ring-count i.e. they are growing faster.

2.2 Size at onset of sexual maturity

Analysis of data collected during the post-fishing survey of 1996 showed that there was an increase in the size at which 50 percent of abalone become sexually mature (L_{50}) at the Kent Group. This change was unexpected and is most unusual. In contrast, there was no significant change in size at sexual maturity at the Hogan Group during that period. Given that evidence suggests that maturation is age-related rather than size-related (Nash, 1990), this increase in size is consistent with faster growth at the Kent Group since fishing commenced.

The size-at-maturity results imply, but do not prove, that growth rates were increasing. Changes in size at maturity may simply reflect subtle differences in sampling strategies on a population where growth rates are static. Given the unusual nature of the results from the size-at-maturity analysis, and to confirm that there had been a change in growth rate, it was deemed necessary to conduct further sampling and analyses in 1997.

2.3 Testing assumptions of the 1996 change-in-ratio analysis

The third objective was to reassess an assumption made about the samples collected for the change-in-ratio analysis of the November 1995 fishery. Change-in-ratio assessments compare the relative abundance of an unchanging reference part of the population (in this case, the under-sized portion), with the fished part of the population, both before and after the fishery. If the relative abundance of the undersized part of the population changed in the period between pre- and post-fishing surveys, then a basic assumption of change-in-ratio would be violated, and the assessment flawed.

It was therefore decided to look at the relative abundance of the undersized abalone during this survey. If they had undergone a temporary decline in catchability between the pre- and post-fishing surveys of the November 1995 fishery (presumably some sort of hide/escape response to the removal of the legal-sized abalone), then the proportion of under-size to size abalone should be higher in January 1997 than in the post-fishing survey of January 1996.

The samples collected as part of the growth measurement by modal progression analysis (above) could be used to provide data for this part of the work, providing that they were collected using the same length-frequency sampling procedures used with the 1995 fishery assessment.

Initial confirmation of the change-in-ratio result would be evident from a shift in the mode of length-frequency distributions i.e. an increase in growth. Because post fishery (1996) length-frequency distributions should be modal at the size-limit of 110 mm, it could be expected that one year later this mode should have shifted to the right.

By applying growth information from the mark-recapture study to the length data from the modal progression analysis, the 1997 length data could be back-calculated to provide an approximation of a 1996 length-frequency distribution. If the relative abundance of the size and under-size fractions of the modified 1997 sample was similar to that of 1996 post-fishery, it could be argued that the catchability of the undersized stock had been maintained throughout the course of the previous fishery, and that this would support the assessment.

2.4 Shell morphometry

Abalone shells from early Bass Strait fisheries were generally heavily bored by parasites, and were typically wide and high, reflecting slow growth rates. A frequent comment from participants of the most recent fishery was that the shells were cleaner and seemed to be more elongated. If abalone are now growing at a faster rate, then their shells might be expected to be flatter and narrower for their length than in 1988 (Worthington *et al.*, 1995). A comparison of shell morphometrics would determine whether there has been a change in the shape of shells since the 1988 surveys.

3. Methods

3.1 Field procedures

In January 1996, 500 abalone were tagged and released at each of the Hogan and Kent Groups of islands.

In January 1997, the research vessel *Challenger* returned to these islands to recover tagged abalone and to sample abalone populations for growth, maturity and morphometric assessment.

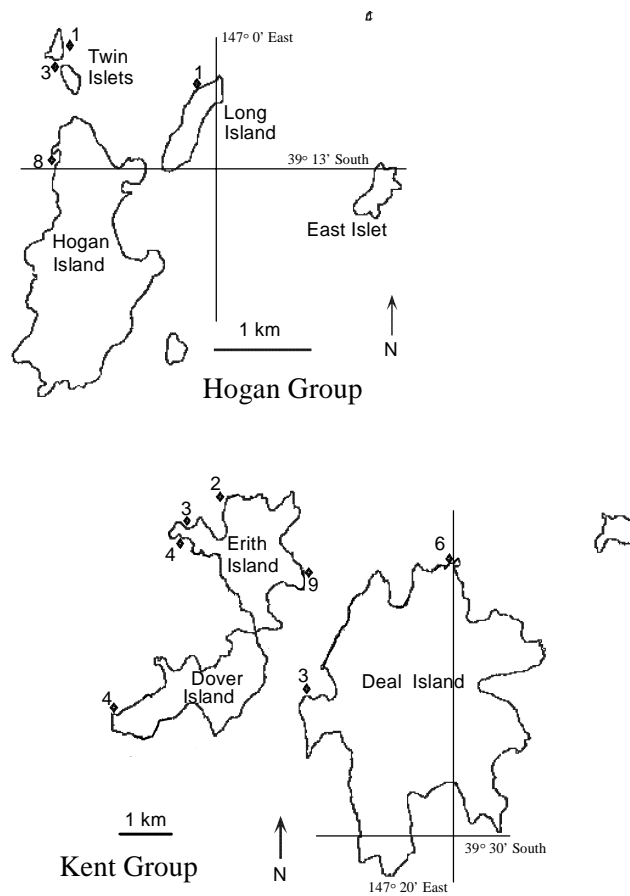


Fig. 1. Map of the Hogan and Kent Groups, Bass Strait, showing sites used during the 1997 research cruise.

Recovery of tagged abalone was first undertaken from site 3 at East Cove, Deal Island (Fig. 1). This site was on the southern edge of the cove on a narrow reef that extended from the shore to the sandy floor of the bay. Blacklip abalone were most common here in depths ranging from one to four metres, although searching was undertaken out to the sand edge at seven metres. Searching for the abalone was continued until recovery rates of tagged abalone per hour approached zero. The area searched extended up to 100 metres either side of the release site.

Searching activity was then switched to site 1 at Long Island in the Hogan Group. Once again, this site featured a narrow reef along the shore where abalone were again predominately found in the shallows. The searching strategy followed that used for Deal Island.

All abalone were measured immediately after capture, and those measurements recorded for entry onto a database at the Marine Research Laboratories, Taroom.

Samples of about 200 abalone of size greater than 80 mm were collected and measured for shell-length at each of three sites in the Hogan Group (Hogan Island site 8 and Twin Islets sites 1 and 3), and at two sites in the Kent Group (Dover Island site 4 and Erith Island site 4). After recording the measurements the abalone were returned to the water.

Further samples of up to 300 abalone were collected for ageing and morphometric studies. These were collected from the two tagging sites at Long Island site 1 and Deal Island site 3 and also from Erith Island site 3. These samples were retained and frozen to -18° C within several hours of capture. They were eventually processed at Taroom, several days after returning.

Sampling for size-at-maturity studies was completed at three sites in the Hogan Group (Hogan Island site 8, Twin Islet site 3 and Long Island site 1) and six sites in the Kent Group (Dover Island site 1, Erith Island sites 2, 4 and 9 and Deal Island sites 6 and 3). About 80 abalone between 60 and 110 mm were collected, measured and sexed at each site. The status of their sexual maturity was determined by gonad colour. Any green (female) or white (male) colouration of the gonad signified the onset of sexual maturity, and the animal was described as male, female or immature.

One female *laevigata* / *rubra* hybrid of shell-length 89 mm was found at Hogan Island site 8.

3.2 Laboratory and analytical procedures

3.2.1 Growth increment analysis

Growth increments were recorded against the length at which each abalone was released, and the data stored on a relational database developed under *OMNIS 7.0*.

Von Bertalanffy growth function (VBGF) parameters were derived for each area by linear regression of the increments against the size at which the abalone were released in 1996. From the equation of the regression,

$$y = b \cdot x + a \quad (1)$$

the coefficient of growth, K was calculated from

$$b = e^{-K} - 1 \quad (2)$$

which was subsequently transformed to

$$K = -\ln(b + 1) \quad (3)$$

and the maximum average length, L_∞ was calculated from

$$L_\infty = -\frac{a}{b} \quad (4)$$

Growth increments were also analysed using a non-linear regression of Fabens (1965) re-parameterisation of the von Bertalanffy growth function

$$\Delta L_i = (L_\infty - L_i)(1 - e^{-Kt_i}) \quad (5)$$

and the software package *Genstat 5, Release 3.2 for Windows, second edition*, where ΔL_i is the growth increment, L_i the release length and t_i the time at liberty of individual abalone.

3.2.2 Modal progression analysis

Length-frequency distributions were obtained from the shell measurements of samples of approximately 200 abalone obtained from four sites in each group of islands. The length data were then plotted against frequency. The resulting distributions, at a size-class of one millimetre were poly-modal, and comparison between successive years was inconclusive. It was not until the length data was grouped into 5-mm size-classes that a mode could be recognised.

The size-classes were then re-arranged to avoid overlapping size-limits, which for 1995 were 110 mm, with an upper limit at 132 mm. The frequency distributions accordingly were grouped by 5 mm increments to 105 mm, then 106-109, 110-114, 115-118, 119-122, 123-126, 127-131, 132-135 and from thereon by 5 mm increment.

Analysis of modal progression was done with the aid of *Microsoft Excel 7.0*. Because the 1995 fishery took abalone of shell-length between 110 and 131 mm, a distinctive peak should be apparent on length-frequency distributions at both of these points immediately after the fishery. The peak at the smaller size should be especially clear because there are many more abalone of 110 mm shell-length than there are the larger abalone. Displacement of those peaks to the right in successive samplings can be interpreted as growth.

3.2.3 Analysis of age-length data

Age of abalone shells was determined by counting rings laid down in the spire of the shell.

Shells were collected from Erith Island site 3 ($n = 116$) and Deal Island site 3 ($n = 188$), both in the Kent Group, and Long Island site 1 ($n = 323$) in the Hogan Group.

The physical measurements (length, width, height, whole-weight, meat weight, sex) of each abalone were recorded, and the shells then were prepared for ageing by a four part process, which involved:

- cutting a section through the spire to expose a cross section of the ring structure, and writing an identifying number on the shell,
- polishing with fine grit wet and dry paper using water as a lubricant/ washing medium,
- etching with weak hydrochloric acid, and finally,
- the rings were highlighted with a carbonate stain.

The shell sections were examined under a microscope, and the number of rings counted and clarity of reading for both sides of the section were recorded for each shell number. 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 differed from that of the right hand side. Ring-counts from the right hand side of shells with a clarity of three or greater were used in the analysis. Few shells were completely free of borers, but satisfactory readings could be made by following growth rings around badly bored sections.

The number of growth rings was considered to be indicative of the age (in years) of the abalone. The relationship between the age of blacklip abalone and the number of rings is a subject of much debate, and has not been confirmed for abalone living in these islands. Furthermore, McShane and Smith (1992) found that blacklip abalone from Bass Strait waters in eastern Victoria did not necessarily form annual growth checks, and that growth checks were therefore unreliable indicators of age. 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*. All this notwithstanding, it was decided to proceed with growth analysis using age-length data based upon these ring counts because the same analysis had been performed upon shells obtained prior to the commencement of fishing in the area (Nash *et al.*, 1994), and a comparison between the results of both analyses would provide information about growth rates. Any such comparison assumes that the causes of ring formation apply equally to both sets of shells.

Prince *et al.* (1988a), while working with blacklip abalone from south-east Tasmania found that three minor rings were laid down in the first sixteen months following settlement, after which much more pronounced 'major rings' were laid down in following years. His 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. Preparation of shell sections collected during the 1988 cruise followed this method, but for the purpose of comparison with the 1997 growth analysis, the minor rings were excluded.

The technique currently used to section abalone shells at the Marine Research Laboratories exposes only the major growth rings. Minor rings are not visible using the transverse sectioning method used with the 1997 samples because these rings only appear in the spire of the shell. To relate the age of the abalone in years to transverse section ring counts, it is necessary to add 1.5 years (sixteen months) to the count of major rings.

The von Bertalanffy growth function (VBGF) of the form

$$L_t = L_\infty \cdot [1 - e^{-K(t-t_0)}] \quad (6)$$

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. Growth curves were fitted by non-linear regression of age-length couplets using *Genstat*.

Growth curves were initially fitted to the 1997 age-length data from the three sites for the purpose of describing growth at each site.

A comparison was then made between the 1997 growth curves and those derived from samples obtained prior to fishing activity in 1988.

The 1997 growth curves were obtained using the age-length data from Deal and Erith Islands which were pooled to represent the Kent Group. The Hogan Group was represented by the Long Island site.

Growth curves were then fitted to the 1988 data from the Hogan and Kent Groups. Three data-points with high residual values were excluded from the 1988 Kent Group analysis on the basis that the abalone were several times heavier for their age than other abalone in their age-class, which was thought to imply that they were older than the ring-count suggested. The results are therefore marginally different than those published by Nash *et al.* (1994).

3.3 Determination of size at sexual maturity

Size at sexual maturity was determined for each island group. Maturity data from each site were combined with those from other sites within the same group, and the proportion mature for each size-class (class width = 1 millimetre) was calculated.

The rate of maturation by size was determined by fitting the proportion mature for each size-class to the logistic equation using a generalised linear regression in *Genstat*

$$p = \frac{e^{a+b \cdot x}}{1 + e^{a+b \cdot x}} \quad (7)$$

where p is the proportion mature, x is the size-class, and a and b are parameters of the logistic function. L_{50} , the size at 50 percent maturity was determined using the procedure FIELLER, located in the *Genstat* library and described in the Procedure Library Manual (Payne and Arnold, 1995).

Subsequently, the maturity data from the 1988 and the 1996 surveys were re-analysed using the same methods that were applied to the 1997 data. This was done to remove any lingering doubts that a change in size at maturity may have been a product of the analysis technique, perhaps caused by different grouping methods.

3.4 Conditions of 1996 change-in-ratio analysis

A change-in-ratio analysis of the November 1995 fishery was completed by the Department of Primary Industry and Fisheries as an unpublished review of that fishery (Nash, 1996). This method of abundance estimation compares the ratio of the quantity of legal-sized abalone with the quantity of undersized abalone both before and after the fishery. It is essential that the undersized fraction of the population remains equally catchable over the duration of the comparison. An objective of this cruise was to check that the assumptions of constant catchability in the undersized fraction of the population had been met.

It was proposed that length data from the immediate post-fishery cruise in January 1996 be compared with modified length data from the most recent cruise, one year later. This modification involved a process of back-calculating each length datum by the amount of growth expected of it in the period between surveys, using Fabens' parameterisation of the VBGF (equation 5) and parameters from the tagging study at the two island groups.

Since we have no knowledge of differential rates (by size- or age-class) of mortality or migration, the comparison was limited to superimposing the modified 1997 length ogive over its 1996 counterpart.

3.5 Shell morphology

The fourth objective was to compare shell measurements from recent samples with those of the 1988 survey.

A comparison of shell morphometry was made by superimposing regressions of shell length against shell height and width, and of log transformed shell length against log transformations of whole weight, meat weight and shell weight for each group of islands, from the 1988 and 1997 data. Differences between regressions were tested using the t test in *Genstat's* linear regression analysis at 0.05 level of significance.

Relationships between shell length (L) and whole weight, meat weight and shell weight (W) were determined using the power curve equation:

$$W = aL^b \quad (8)$$

The power curve was fitted to the data by transforming (8) to a linear form using natural logarithms:

$$\ln W = \ln a + b(\ln L) \quad (9)$$

and the parameters a and b were then derived by subsequent regressions of the length and weight data.

4. Results

4.1 Habitat observation

Divers from the 1997 research cruise to the Kent and Hogan Groups noticed changes to the areas where sampling had formerly been undertaken. Particularly at the Kent Group, divers observed a decrease in abalone abundance and a striking increase in kelp cover.

In earlier years, researchers found quantities of abalone extending from the surface to more than twenty metres and samples were collected in depths down to ten metres. In contrast, in 1997 abalone were concentrated around the margins in depths of less than four metres.

It was more difficult to collect abalone. Although no quantitative assessment was done, it was estimated that it took three times longer to collect a bag full of abalone than it took before the fishery in October 1995. Gutters that previously held large aggregations of abalone now held only one or two individuals.

The kelp canopy appeared to be much denser than during the summer of 1996. The coverage of *Macrocystis* particularly seemed to be much more extensive and made it more difficult to work in the shallows.

These habitat changes were not quantified, but are based upon the observations of divers who had spent sufficient time in the area to be able to remember and subsequently recognise topographical features peculiar to the area. Fundamentally, features of reef (e.g. the coralline encrusted tops of boulders) that were readily identifiable from previous surveys and that had previously yielded quantities of abalone, were covered in sponges and other sedentary organisms atypical of good abalone habitat.

4.2 Measurement of growth

4.2.1 Growth-increment analysis

A total of 79 tagged abalone were recovered at the Hogan Group after being tagged and released for 362 days, and 57 at the Kent Group after 365 days. Growth parameters were derived from regression of growth against the time that the abalone were released, using both linear and non-linear regressions. The results of the analyses (both linear and non-linear) were identical and are presented below (Table 3).

Table 3. Von Bertalanffy growth parameters derived from mark-recapture data

The parameters K and L_{∞} (with standard errors) were derived from both linear (as per Fig. 2) and non-linear (Fabien's) regressions of length against one year's growth increment (the two analyses generated the same results) measured from tagged abalone in the Kent (Deal Island site 3) and Hogan (Long Island site 1) Groups of islands, Bass Strait.

Location	K	L_{∞}
Deal Island site 3	0.40 (0.06)	131.8 (3.1)
Long Island site 1	0.23 (0.04)	146.4 (6.2)

It is immediately apparent that there is great variation in growth between abalone of similar initial size (Fig. 2). It is also evident that the smaller abalone from the Kent Group grew faster than those from the Hogan Group, yet grew to a smaller average maximum size. The combination of using only a small number of abalone to produce the results, and the great individual variation in growth produces relatively large standard errors (Table 3).

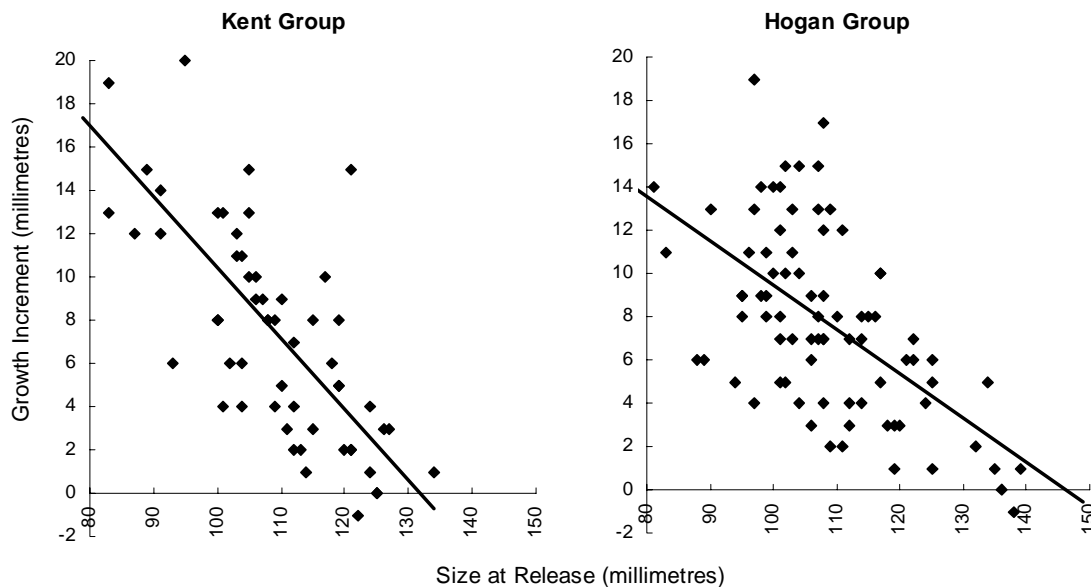


Fig. 2. Growth rates derived by a linear regression of growth increment against initial shell length for blacklip abalone (*Haliotis rubra*), at sites in the Kent Group (Deal Island site 3, $n = 57$) and Hogan Group (Long Island site 1, $n = 79$).

4.2.2 Modal progression analysis

It was anticipated that the displacement of the mode of the 1997 length-frequency distributions to the right of their 1996 counterparts would be indicative of growth (Fig. 3). However, the relative positions of the modes were variable and clearly indicate influences of factors additional to growth.

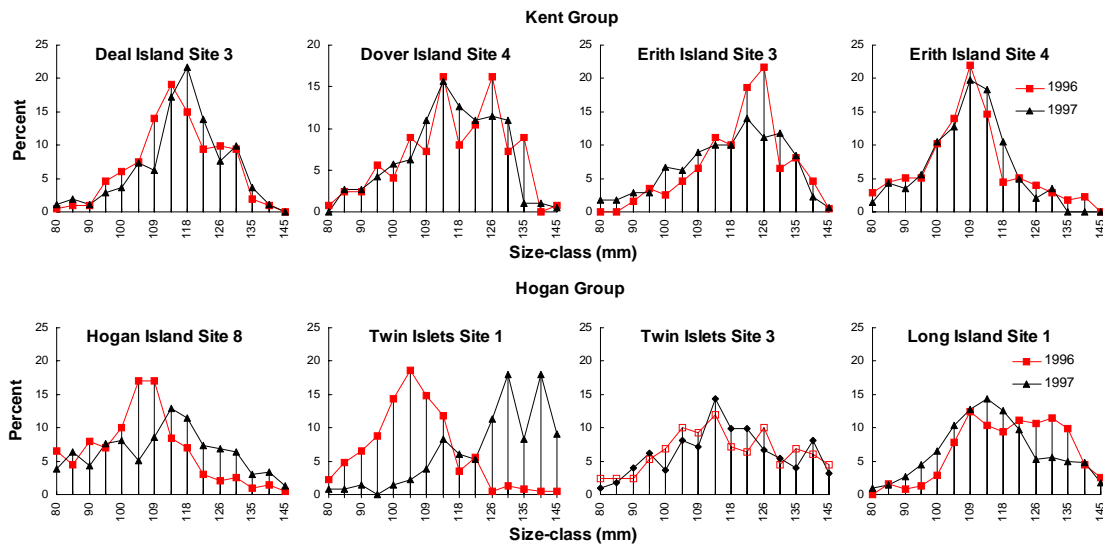


Fig. 3. Length-frequency distributions of samples of blacklip abalone (*Haliotis rubra*) comparing the change in relative percentage of size-classes over a twelve month period. Sample of approximately 200 abalone were collected in both 1996 and 1997 at four representative sites in each of the Kent and Hogan Groups.

4.2.3 Analysis of age-length data

Plots of the VBGF fitted to the age-length data are shown in Fig. 4. Abalone at the Long Island site ranged in age between 5 and 31 years, at Erith Island between 7 and 33 years and at Deal Island between 8 and 36 years, assuming one growth ring deposited per year.

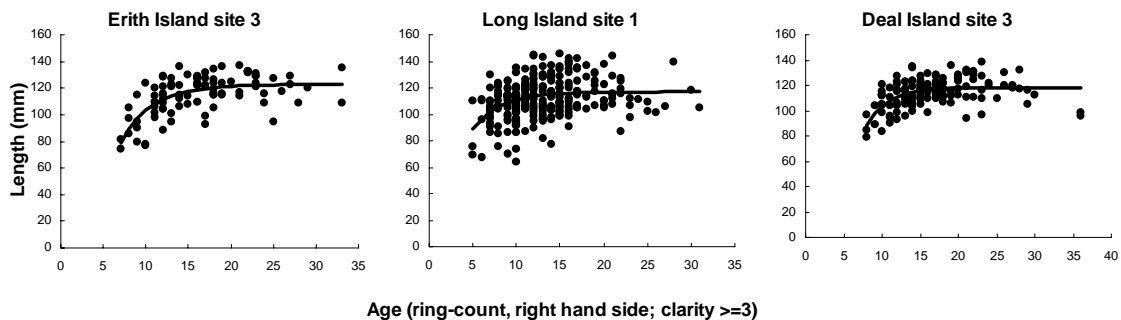


Fig. 4. Age-length couplets fitted to the von Bertalanffy growth function, using data collected from three sites in the Kent (Erith and Deal Island) and Hogan (Long Island) Groups, Bass Strait.

Derived by non-linear regression analysis, the values of the von Bertalanffy growth parameters are shown in Table 4:

Table 4. Von Bertalanffy growth parameters derived from age-length analyses

K , L_{∞} and t_0 are shown with standard errors, derived by non-linear regression analysis of age-length couplets of abalone collected at sites in the Kent and Hogan Groups, Bass Strait.

Location	K	L_{∞}	t_0
Erith Island site 3	0.27 (0.07)	122.8 (2.4)	3.1 (1.3)
Deal Island site 3	0.36 (0.09)	118.4 (1.4)	4.2 (1.2)
Long Island site 1	0.30 (0.09)	116.9 (1.8)	0.3 (1.9)

A comparison was made of the growth curves derived from age-length data collected from samples obtained in 1988 and 1997 by superimposing the earlier data onto the latest survey results (Fig. 5).

Differences in the size-range between the two samples become apparent. The youngest abalone from the 1997 sample are generally larger than their 1988 counterparts. The older abalone from 1997 are generally smaller than the younger abalone from that year (1997) and at the Hogan Group, are smaller than the same age abalone from 1988.

The 1988 survey also features younger abalone (down to two or three years old), which are absent from the 1997 data. Conversely, older abalone are not adequately represented in the 1988 survey, particularly at the Kent Group.

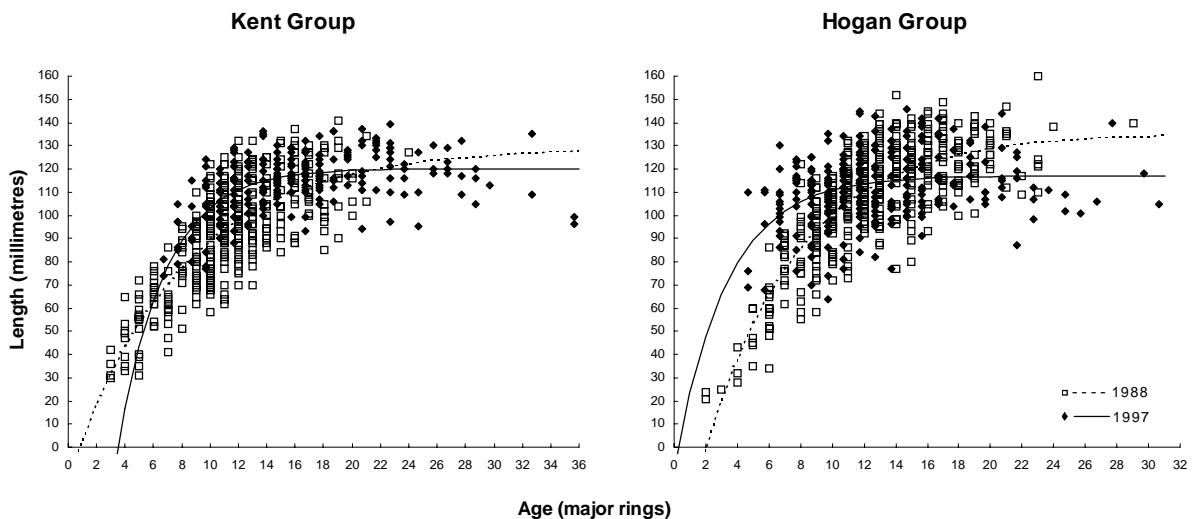


Fig. 5. A comparison between the VBGF derived from major ring count/length data from samples collected in the Kent and Hogan Groups, in 1988 and 1997.

Parameters of the VBGF derived from the 1988 and 1997 data are shown in Table 5.

Table 5. Comparison between VBGF parameters derived from age-length data, 1988 and 1997

The von Bertalanffy growth parameters K , L_{∞} and t_0 were derived by non-linear regression analysis of age-length couplets of abalone taken from sites in the Kent and Hogan Groups, Bass Strait. The ages of abalone from the 1988 data were derived from counts of major rings observed in ground spires, whilst in 1997, the age of the abalone was derived from the count of major rings on the right hand side of transverse shell sections. In 1988, prior to the commencement of a series of intensive fisheries, abalone were collected from five sites in the Hogan Group ($n=413$), and ten sites at the Kent Group ($n=350$) (Nash *et al.*, 1994). In 1997, abalone were collected from two sites in the Kent Group ($n=233$) and one site in the Hogan Group ($n=277$).

Location	K	L_{∞}	t_0
<i>1988</i>			
Kent Group	0.13 (0.02)	129.4 (5.9)	0.8 (0.5)
Hogan Group	0.17 (0.01)	135.7 (2.7)	2.0 (0.3)
<i>1997</i>			
Kent Group	0.30 (0.05)	120.1 (1.8)	3.5 (0.8)
Hogan Group	0.30 (0.09)	116.9 (1.8)	0.3 (1.9)

In 1997, abalone grew faster to a smaller average maximum size than they had prior to fishing.

4.3 Size at sexual maturity

Sizes at 50 percent sexual maturity from data for each of the three years sampled are presented in Table 6 and illustrated in Fig. 6:

Table 6. Size at sexual maturity

The size at 50 percent sexual maturity from samples of blacklip abalone from the Hogan and Kent Groups. 95 percent confidence limits are shown in brackets.

Year	Hogan Group (mm)	Kent Group (mm)
1988	82.5 (79.5-84.9)	74.9 (72.2-77.2)
1996	82.0 (78.4-84.8)	88.0 (86.4-89.4)
1997	84.8 (79.7-88.4)	94.6 (92.5-96.4)

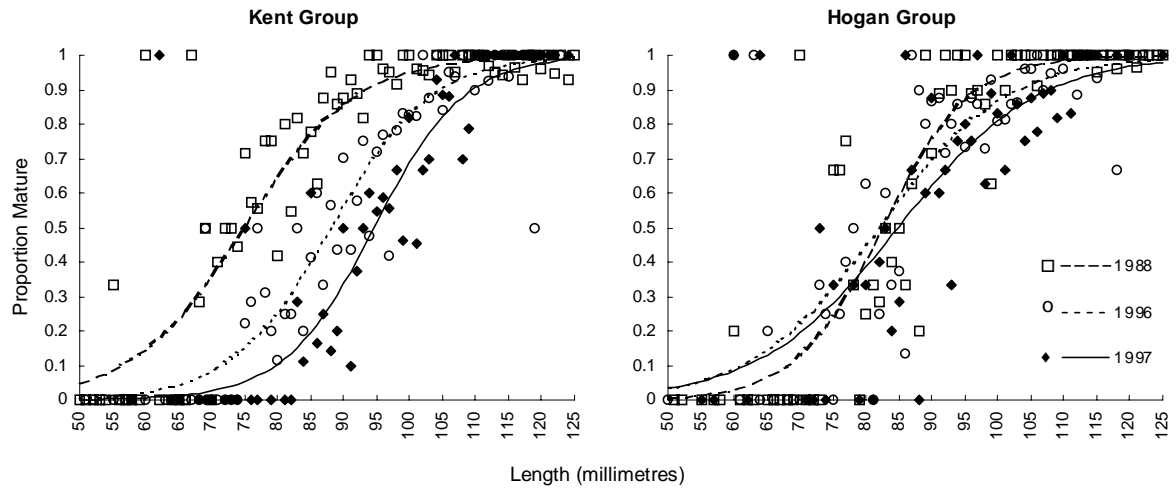


Fig. 6. Rates of maturation by length, from samples of blacklip abalone (*Haliotis rubra*) in the Kent and Hogan Groups, Bass Strait. The samples were obtained prior to the start of fishing (1988), immediately after the last fishery (1996) and then one year later.

At the Kent Group, the displacement of the fitted curve to the right shows that abalone are maturing at a larger size (Fig. 6). Table 6 shows that L_{50} is almost 20 mm greater over the period 1988 to 1997. At the Hogan Group, the situation is not quite so distinct. L_{50} is almost unchanged, but the slope of the line fitted to the maturity data has become progressively flatter as the proportion of large immature abalone has increased. This may reflect sampling error, but could indicate that some individuals are maturing at a larger size than previous years.

4.4 Conditions of 1996 change-in-ratio analysis

The predicted 1996 ogive derived from back-calculated 1997 length-frequency data was overlaid onto that from the 1996 post-fishing survey (Fig. 7).

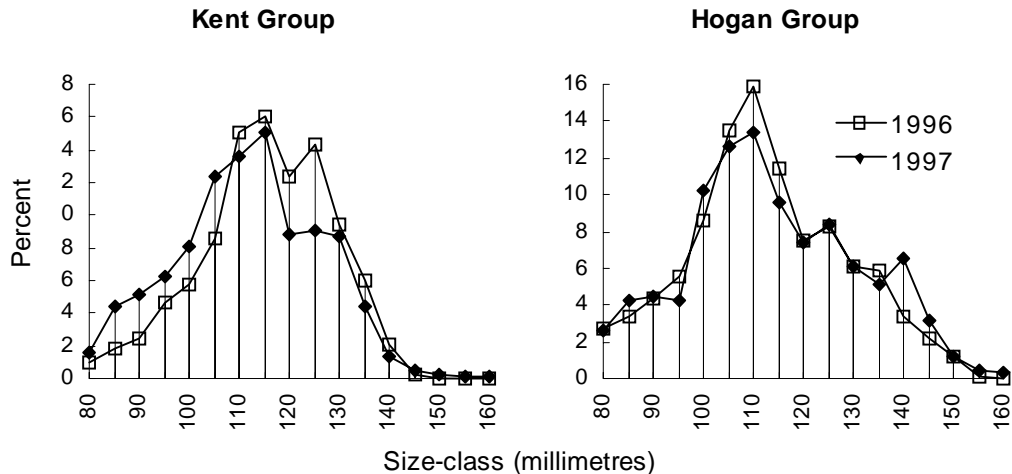


Fig. 7. A comparison of the percentage frequency of 5-mm size-classes from samples collected in 1996 (immediate post-fishery) and one year later (1997) from four sites in each of the Hogan and Kent Groups. Each year's sample size was between 800 and 1000. The 1997 data have been back-calculated one years growth, using Fabens' parameterisation of VBGF and the growth parameters derived from studies of tagged abalone at these islands during the period between sampling.

The comparison shows good correspondence between the position of modes in both island groups. However, while the Hogan Group shows that the proportion of undersize (80-110 mm) and legal-size (110-160 mm) fractions were comparable, there are more undersize and fewer legal-size abalone at the Kent Group.

The back-calculated sizes are approximate and a more rigorous approach would have used variance in growth rate as well as growth rate to estimate the previous year's length distribution.

4.5 Shell morphometry

There appears to be little change in the regressions shown in Fig. 8 and Fig. 9 over the course of the fishery. Tested at 0.05 level of significance, no change was detected in the relationships between shell length and (A) shell width, and (B) shell height between 1988 and 1997 (Fig. 8). Although there appear to be difference between regressions of shell height at the Hogan Group, the high degree of variance prevented separation.

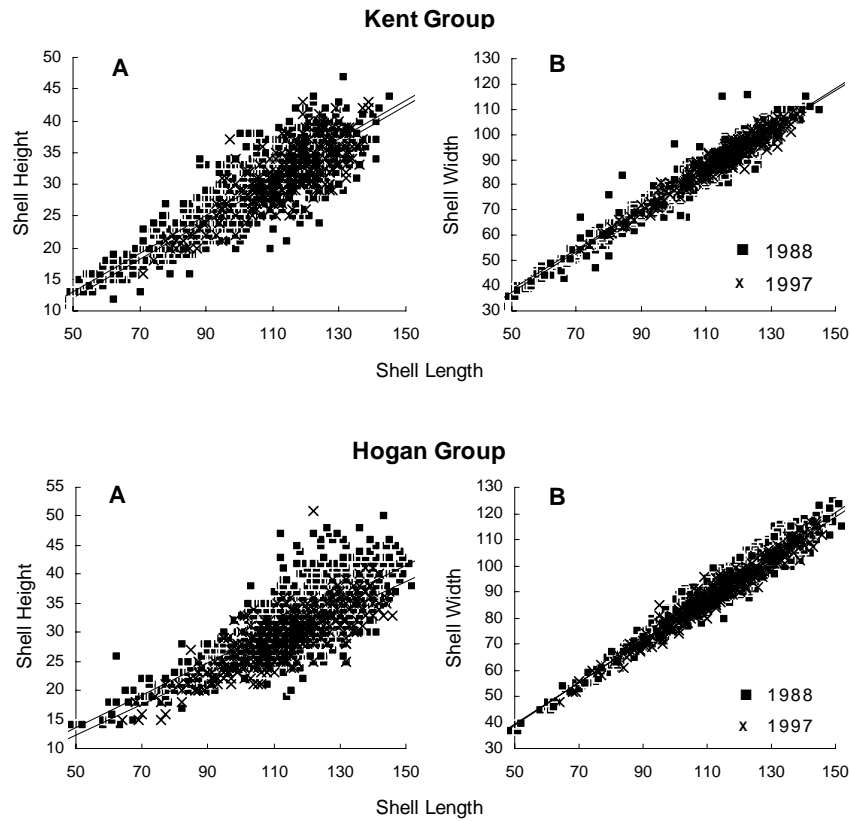


Fig. 8. A comparison of the relationship between shell length and (A) shell height and (B) shell width from samples collected in 1988 and 1997 from the Hogan and Kent Groups.

Differences were found in the weight of the shells (Fig. 9, C) between 1988 and 1997 in both Groups. Tested at 0.05 level of significance, shells from 1997 cruise were lighter than the 1988 sample, although those from the Kent Group were only marginally different.

The 1997 Hogan Group meat weights (Fig. 9, B) were also found to be marginally lighter than their 1988 counterparts.

No further differences were found between the Kent Group meat weights or the whole weights at either group.

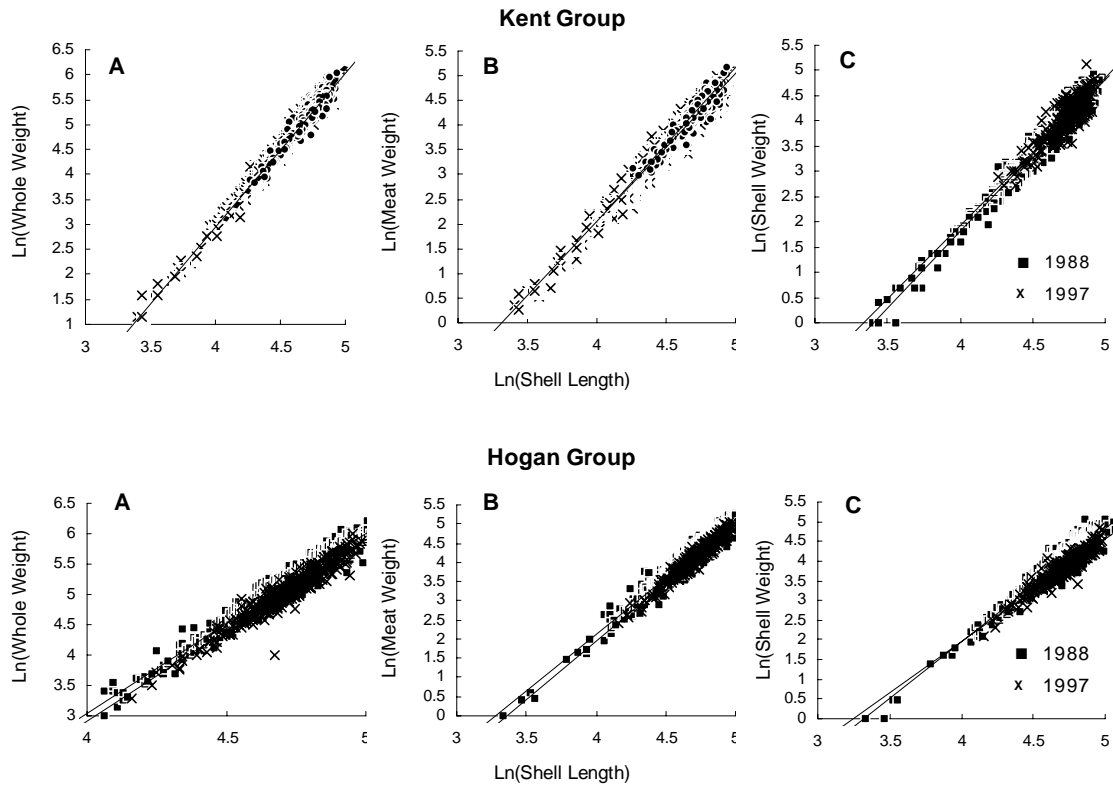


Fig. 9. A comparison of the relationship between the log transformations of shell length and (A) whole weight, (B) meat weight and (C) shell weight from samples collected in 1988 and 1997 from the Hogan and Kent Groups, Bass Strait.

The parameters of the relationships between shell length and whole weight, meat weight and shell weight are shown in Table 7.

Table 7. The relationships between shell length and whole weight, meat weight and shell weight of *Haliotis rubra* collected from the Kent and Hogan Groups in 1997

a and b are parameters of the equation: $\text{weight} = a \cdot (\text{shell length})^b$. r^2 is the coefficient of determination, and the 95% confidence limits of b are supplied in brackets. Sample size was 325 for the Kent Group and 391 for the Hogan Group.

	a	b	r^2
<i>Kent Group</i>			
Whole Weight	0.0000521	3.190 (3.076 - 3.305)	0.903
Meat Weight	0.0000316	3.103 (2.976 - 3.230)	0.877
Shell Weight	0.0000660	2.886 (2.703 - 3.068)	0.749
<i>Hogan Group</i>			
Whole Weight	0.0001216	2.980 (2.893-3.066)	0.922
Meat Weight	0.0000363	3.042 (2.954-3.129)	0.923
Shell Weight	0.0002176	2.598 (2.496-2.701)	0.864

5. Discussion

5.1 Observed changes in habitat

There are many possible explanations for the change in habitat observed by research divers in 1997. This change was characterised by both an increase in kelp cover and a reduction in cover by coralline algae. It could be a temporary aberration: a result of local weather events where still conditions have enabled unusually high growth of macro-phytes and a subsequent change in understory species. It could be part of an on-going process of change in relationship between the kelp canopy and the shaded understory (Dayton *et al.*, 1992), a part of which has been viewed in isolation. Of more concern, it may be attributable to the sudden removal of a high proportion of abalone over a short space of time, the effect of which has impacted upon the marine flora causing the observed change in habitat.

During the last fishery, divers tendered for access to a fixed quantity of abalone from the area. Several days after the season opened, harvesting of abalone became quite competitive amongst divers as they strove to catch the quantity for which they had paid. Experienced divers maintained fishing effort at unusually low catch rates that they would have long abandoned in Tasmania's mainland abalone fishery. Consequently, there was a high level of depletion over a short time interval.

It is considered that the removal of abalone at such high rates can cause changes to their habitat. While no work has been done to determine the effect of systemic disturbance caused by pulse fishing of abalone, Shepherd (1973a) has suggested that the over-fishing of *H. rubra* will cause an increase in growth of algae, resulting in a more favourable environment for sea urchins, particularly *Centrostephanus*. When present in large numbers, sea urchins are able to graze the substrate down to barren rock. This level of grazing prevents the regeneration of algae and the habitat becomes unsuitable for abalone. Furthermore, reduction of encrusting coralline algae by urchins diminishes the amount of habitat suited to settlement by abalone veligers (Shepherd and Turner, 1985). Tasmanian researchers have found that *Centrostephanus* abundance has increased in the eastern Bass Strait islands since 1982 (N. Barrett, pers. comm.).

Abalone, in contrast to urchins, are not destructive grazers, and do not remove the cover of coralline algae. In a recent study, Karlov (1998) reported a positive correlation between abalone density and encrusting coralline algae. Abalone larvae settle preferentially on crustose coralline algae (Morse and Morse, 1984; Prince and Shepherd, 1992; Shepherd and Daume, 1996). Boulder tops occupied by abalone have greater coverage of coralline algae than do boulder tops without abalone. While searching for abalone, commercial divers target purple boulders (those with coralline coverage) and leave brown boulders (those with sponge or other invertebrate coverage) because they know that the chances of finding abalone on the purple boulders is much higher.

It is not clear how the coralline algae cover is maintained. Abalone display quite distinct dietary preferences (Foale and Day, 1992), and while it is not suggested that abalone actively consume other encrusting invertebrates and plants, it is hypothesised that grazing and movement over the surface by abalone limit the establishment of organisms unfavourable to them, and maintain the coralline cover. Consequently, if abalone are removed from the boulder tops, this coralline cover is replaced by unfavoured plants and sponges and the abalone habitat becomes degraded.

5.2 Measurement of growth

5.2.1 Growth increment analysis

Table 8 lists von Bertalanffy growth parameters from McShane, Smith and Beinssen (1988), derived from tag-recapture studies of blacklip abalone in Bass Strait (eastern Victoria) together with those from the current study. The parameters of the Hogan and Kent Groups (Table 3) fall within the range of those from Victoria. Tullaburga Island has long been regarded as supporting stunted abalone, while on the other hand, Sandpatch supports fast growth (H. Gorfine, pers. comm.).

The Victorian growth parameters are from studies that used tags applied by glue to the shell surface, whereas the Hogan and Kent Group studies used rivet tags applied to respiratory pores. The Victorian study compared growth rates between abalone with glued tags with abalone with tags fastened by stainless wire inserted into the respiratory pores, and at one site found a lesser rate of growth amongst abalone with wired tags. An earlier study in southern Tasmania also detected different rates of growth between abalone with and without wired tags (Harrison and Grant, 1971) and many researchers have subsequently avoided using any techniques that intrude into or cover the respiratory pores of the abalone (Tarr, 1995; Wells and Mulvay, 1995). While the rivet technique is mildly intrusive, it is widely used in Tasmania (Nash, 1995; Prince, 1989) and Prince has shown by comparing growth rates derived from rivet tagged abalone with those derived by direct ageing that he was unable to detect differences between growth rates of tagged and un-tagged abalone (Prince, 1991). For the purpose of this comparison, it is suggested that growth rates do not appreciably vary between rivet tagged abalone and those with glued tags.

Both the Victorian studies were of longer duration than this one - most of the abalone spent over 500 days at liberty. The Tullaburga Island growth parameters are derived from a study during the early 1970's, of 101 abalone, at large from 79 to 3980 days, size range approximately 60 to 130 mm. The Sandpatch parameters are from 75 abalone that were at large from 138 to 1119 days, size range approximately 20 to 130 mm.

Table 8. Von Bertalanffy growth parameters from abalone tagged at Tullaburga Island and Sandpatch, eastern Victoria

The growth coefficient K and the maximum observed length L_{∞} are shown with standard errors .

Location	K	L_{∞}
Tullaburga Island	0.35 (0.03)	121.0 (3.0)
Sandpatch	0.37 (0.01)	152.1 (1.0)

The current study enabled growth to be observed for exactly one year. While it may be subject to the effects of inter-annual variability in growth, it is free of the effects of seasonality (cf. a growth study that included two periods of high growth and one period of low growth) that might be reflected in growth parameters. Despite this, growth rates are highly variable across the size range, especially at the Hogan Group (Fig. 2).

5.2.2 Modal progression analysis

The 1996 sample was collected six weeks after the cessation of a fishery in which divers estimated that they had collected a very high proportion of abalone between 110 and 132 mm. It could be expected therefore that each of the 1996 ogives should show a knife-edge mode at 110 mm, followed by a sharp decline in frequency. This only happens at three sites (Hogan Island site 8, Twin Islets site 3 and Erith Island site 4). The other sites have strong modes at different size-classes: 15 mm above the 110-mm size-limit (Dover Island site 4, Erith Island site 3), 5 mm below the size-limit (Twin Islets site 1), or are distinctly multi-modal (Long Island site 1) (Fig. 3).

When compared with the sample obtained 12 months later, there appears to be a positive separation between the respective modes (i.e. growth) only from Hogan Island site 8, Deal Island site 3 and the two Twin Islets sites. In view of the way that length data have been grouped, there is no foundation for a quantitative assessment of growth. The modal shifts in the eight distributions are inconclusive, and may be induced by factors operating in addition to growth, and cause unpredictable variation between the numbers in each size-class.

Given the high degree of variability of growth increments from the mark-recapture study (Fig. 2), any subsequent sampling from these sites will display modes that are less well defined than that of the post-fishing survey of 1996. As the period between sampling increases and the effects of variability of growth become more pronounced, the modal size-class of the new sample is filled from size-classes other than the mode of the initial sample, and becomes increasingly less reflective of growth only from that mode.

Another cause of variation in modal progression may be due to sampling strategy. It was noticed during the post-fishing survey of January 1996 at several sites around Deal and Erith Islands that there were many more legal sized abalone remaining than the intensity of the fishery would suggest. At these sites, there seemed to be little appreciable reduction in numbers of legal sized abalone compared with the pre-fishing surveys, the cause of which may be attributed to either variable catchability within size-classes or variation in the level of fishing pressure (both of which are discussed in more detail in Section 5.3).

Some of these sites were selected again in 1997 because it was recognised that they had higher levels of abalone abundance and samples of abalone could be obtained quickly. This was a critical factor during the 1997 cruise because of the amount of field work that needed to be completed in just a few days. Abalone numbers seemed to be reduced compared with previous surveys and collecting samples occupied much more time than had been allocated. At the time, the peculiar nature of some of the sites and their effect upon any subsequent analysis was not appreciated. If time had allowed, a more considered approach might have chosen sites at random rather than selected for productivity, and much larger samples would have been collected.

5.2.3 Analysis of age-length data

Comparison of VBGF parameters from Erith Island site 3 and Deal Island site 3 (Table 4) highlights the spatial heterogeneity in growth of abalone over short distances (McShane, 1995b; Worthington *et al.*, 1995) and the difficulties with attributing growth rates to a region based upon sampling at a small number of sites.

Because of the intensity of fishing between 1988 and 1997, there was a paucity of large old abalone in 1997. Fig. 5 shows that newly recruited (and therefore unfished) age-classes have a much greater variance in length than do the older age-classes. Sainsbury (1980) has observed that if individuals have a common maximum average length but show individual variation in growth rates, then this will be manifested as a wide variation in length-at-age in middle-age which narrows and converges at maximum age.

However, in Fig. 5 the older abalone from 1988 are as large as the middle-aged abalone, while in 1997, the older abalone are generally smaller than the middle-aged abalone. It seems that the larger abalone from the older age-classes have been removed from the fishery, so the maximum average length has been reduced from what it would have been in an unfished population (e.g. 1988). Forcing the growth curve through these comparatively small old abalone produces distorted parameters. The higher value of K in the 1997 analyses is therefore attributable to both increased growth and removal of large abalone from the population. The removal of larger fish by size-selective fishing methods from age classes recruited to the fishery is well documented as “Lee’s phenomenon” (Lee, 1912), and its effect on the analysis of growth can be determined and subsequently treated (Ricker, 1975).

It was believed that because abalone abundance was much reduced in 1997 compared with the 1988 cruise (which took place before the advent of large-scale fisheries), that abalone growth rates should be higher now due to decreased competition between abalone for food and shelter. It was expected that this difference should be seen in comparisons between growth curves derived from age-length data from each cruise and would be manifested by steeper grow curves and higher average maximum sizes.

Using analysis of residual sum of squares (ARSS) after Chen (1992) with VBGF, no distinction could be made between growth rates of aged abalone from the two surveys. Fig. 5 shows that whilst the younger abalone of 1997 were distinctly larger than their 1988 counterparts, particularly at the Hogan Group, there was insufficient separation between the growth curves to be detected by ARSS. However, when mean lengths are plotted against age (Fig. 10), the difference between the samples becomes much more visible, and it is readily apparent that the younger abalone in 1997 are larger and growing faster than their 1988 counterparts.

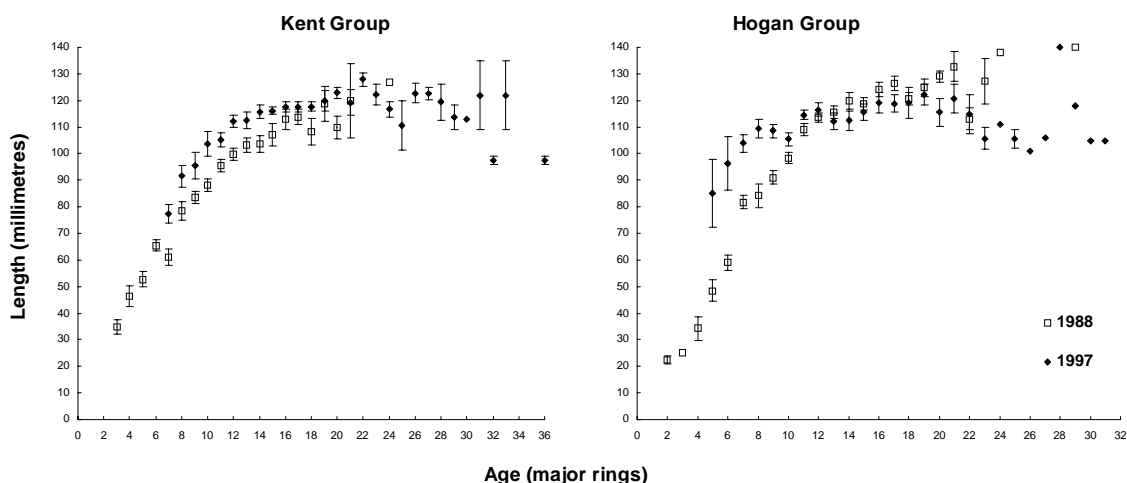


Fig. 10. A comparison showing the mean lengths at age, with standard errors, from samples collected in the Kent and Hogan Groups, in 1988 and 1997.

Abalone growth is typically rapid in the early years of life, but slows with age. Given the relatively small annual increment in growth of older abalone, differences in growth rate will be more visible among younger rather than older abalone. It would be unreasonable to expect to detect any differentiation in growth rate unless the comparison was limited to only abalone that undergo high growth rates between the years of 1988 and 1997. Due to an oversight, the smaller abalone collected in 1997 were not aged. A comparison between the youngest abalone would have made it easier to detect changes in growth.

Abalone growth from 1988 was compared with that from the latest survey (Table 5, Fig. 5). In 1997, the growth coefficient (K) was larger at the corresponding island groups than in 1988, implying that abalone now grow faster. However, the difference in the value of K between 1988 and 1997 may create an exaggerated impression of the increase in growth rate. Apart from Lee's phenomenon, there are other factors that may account for apparent changes in growth rate.

Spatial heterogeneity in growth rates, and the variation between the growth parameters from the two sites in the Kent Group were discussed above. Moreover, the two sites sampled at the Kent Group in 1997 are different from those of the 1988 cruise. The Long Island site sampled in 1997 is one of five sites at the Hogan Group sampled in 1988. Without any knowledge of how growth varies between any of these sites, intra-site comparison may not be valid.

Another problem with comparing these growth parameters lies in the methods used to age the abalone, and their comparative success. A much higher proportion of shells from the 1997 sample were aged, compared with 1988. This was because the shells from the 1997 cruise had less borer damage, and the ageing techniques used now are able to accommodate a higher degree of shell damage than earlier techniques.

Abalone that are attacked by borers devote more shell growth to repairing damage and thickening the roof of the shell than do abalone that are unaffected by borers. This is usually at the expense of laying down new shell at the growing edge, so that parasitised shells appear to grow slowly (Shepherd and Breen, 1992). If heavily parasitised shells cannot be aged, then growth analyses will be biased by the faster growing non-parasitised ageable shells. Fig. 11 indicates that the potential for bias towards the faster growing shells is much higher in the 1988 sample than the 1997 sample.

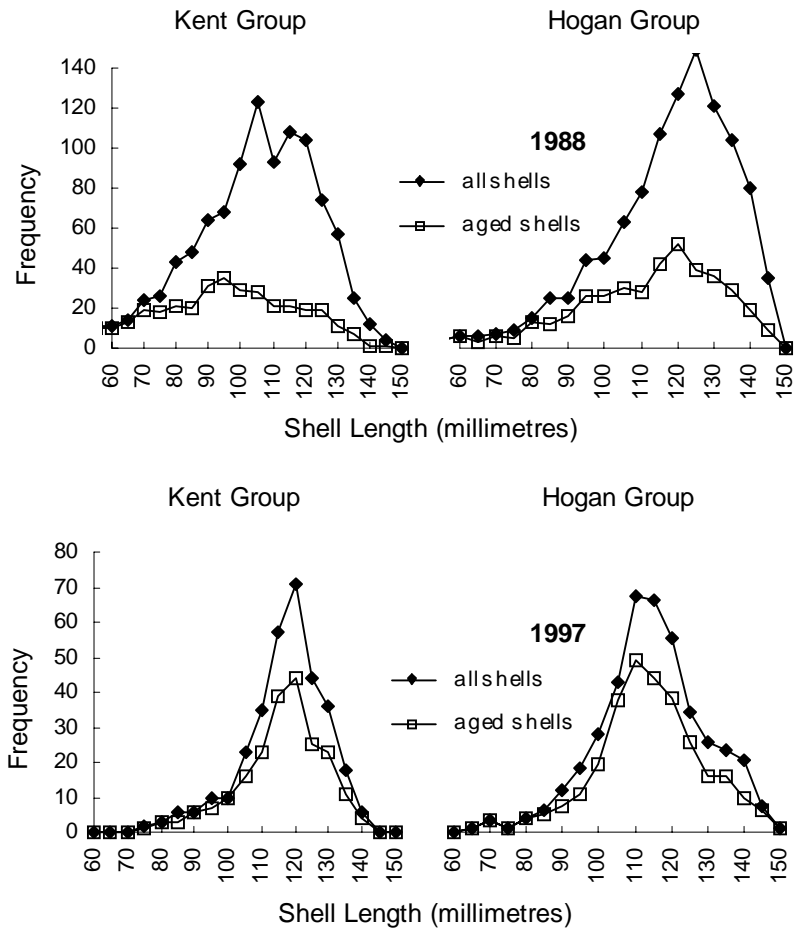


Fig. 11. Comparison between samples collected in 1988 and 1997 showing the proportion of ageable shells in each sample.

The thickening of shells as a response to boring parasites may involve the formation of adventitious rings (Shepherd and Huchette, 1997; Shepherd and Triantafillos, 1997). If the growth rings in bored shells can be successfully counted, there are problems determining which rings are annual rings and which rings are laid down as a response to boring. If adventitious rings cannot be recognised, their combination with annual rings will produce a higher estimate of age for length and cause growth rates of these individuals to be underestimated.

Another problem with ageing techniques which involves older shells particularly is the process of erosion of the outer rings by abrasion of the shell during the life of the abalone (Shepherd *et al.*, 1995; Shepherd and Triantafillos, 1997). If the first few rings are missing, this could cause an underestimate of age and consequent bias towards faster growth rates.

Even though growth parameters for the abalone collected during the 1988 cruise are low compared with other recorded values (Day and Fleming, 1992), because of the ageing technique and the comparatively high incidence of un-ageable shells, it is likely that they reflect growth only from the fastest growing abalone, and that average growth rates for the population overall are less than indicated.

A quantitative comparison of growth between 1988 and 1997 based upon these age-length data is therefore unreliable, and can only be used to indicate a general trend. Although VBGF parameters from mark-recapture studies and age-length analyses are not directly comparable (Francis, 1988), the results from the tagging study indicate relatively high rates of growth. Abalone stocks at these islands have always been considered stunted. This may now be considered a perception that has arisen from the inevitable comparison with abalone from more southern waters. Average growth rates in these Bass Strait islands are now comparable with those from populations studied in the Central and Eastern Zones of Victoria by McShane (1988) and from several sites in South Australia (Shepherd and Hearn, 1983).

5.3 Changes in size at sexual maturity

In 1985, Prince *et al.* found that all abalone greater than 95 mm were sexually mature at both the Kent and Hogan Groups, and this was supported by the 1988 survey (Nash *et al.*, 1994).

One of the more interesting findings of the post-fishing survey of 1996 was that the size at 50 percent maturity of abalone at the Kent Group had increased by a considerable amount since the previous determination of 1988, whereas the same analysis at the Hogan Group showed no change (Nash, 1996). Given that abalone mature at age, and not size (Nash, 1992), it provides strong evidence that the Kent Group abalone are now growing at a faster rate. Increase in L_{50} at the Hogan Group is restricted to larger abalone and is not spread across the entire size-range.

There are limitations about the accuracy of L_{50} and comparisons over a period of time may be confounded by other factors. One of the greatest difficulties in comparing analyses of historical data with those of more recently collected data lies in the dissimilarity of collection techniques. There are now more rigorous protocols in place for collecting size-at-maturity samples as distinct from ageing samples than existed previously. There is a greater awareness of the differences in behaviour of abalone, and the shortcomings of sampling techniques than existed in the past. The 1996 and 1997 surveys collected samples that were to be used primarily for size-at-maturity analysis by comprehensively searching a targeted area of reef, and taking all abalone (cryptic and emergent) within a certain size range.

If size-at-maturity samples are collected by a less than exhaustive searching technique, for example, by inability or disinclination to search all the cryptic habitat, then it is probable that the estimated L_{50} would be underestimated. Emergent abalone are usually mature, while cryptic abalone are usually immature (McShane, 1995b; Nash *et al.*, 1994). A sampling technique that does not or cannot search cryptic habitat will collect mainly emergent abalone. The small abalone thus collected will have a high probability of being mature and any subsequent analysis of size at sexual maturity will be disproportionately influenced by the degree of maturity of these small abalone. Conversely, a sampling technique that selected only from cryptic habitat may recover immature abalone that are larger than might otherwise be found, which will cause the size at maturity to be overestimated. Even with the best of intentions, it is extremely difficult to exhaustively search all cryptic habitat and inevitably small cryptic immature abalone will be under-represented.

The 1988 growth and size-at-maturity analyses were derived from common data. It is possible that the 1988 data is under-representative of cryptic habitat, and under-estimates size at maturity. The samples may have been taken from areas which had many inaccessible crevices, which would have reduced the ability of divers to collect cryptic abalone. This would cause the 1988 size at maturity to be smaller, and may partly explain the difference in L_{50} at the Kent Group, although it does not explain why the Hogan Group showed no change over the period.

In fished populations that are declining in abundance, the consequence of an increase in size at maturity without a corresponding increase in size-limit is that egg-production will be reduced. If we use growth increments observed in the mark-recapture study, Kent Group abalone in 1997 of size L_{50} (94.6 mm) have only one year's egg production before they become of legal size, at a size-limit of 110 mm (Table 9). However, there may be significant differences in growth rate between sites within the Kent Group and it has not been determined how well the site used for the mark-recapture study represents growth in other areas.

Table 9. Abalone size following the onset of sexual maturity

Estimates of shell length (mm) for five years at the anniversary of sexual maturity (L_{50}), using Fabens' parameterisation of VBGF, the growth parameters derived from the mark-recapture study and size at 50 percent maturity in 1997.

Years	Hogan Group (mm)	Kent Group (mm)
0	84.8	94.6
1	97.4	106.8
2	107.4	115.0
3	115.3	120.5
4	121.7	124.2
5	126.7	126.7

At the Hogan Group, the situation provides more protection for egg production than at the Kent Group. Using observations of growth from the tagging data, abalone of size L_{50} (84.8 mm) will be recruited to the fishery in slightly over two years.

The combination of faster growth rates, a higher size at maturity and declining abundance means that the 110 mm size-limit provides less protection for abalone stocks in these islands now than in 1988. The current size-limit may not provide for an adequate level of egg production at the Kent Group, particularly if exploitation rates of earlier years are to be maintained.

In 1988, it was estimated about 60 percent and 80 percent of virgin stock egg production from the Hogan and Kent Groups respectively would be maintained with a 110 mm size-limit, even at high levels of exploitation (Nash *et al.*, 1994). These estimates of egg production vary markedly with different values of natural mortality (Nash, 1992). The estimates of natural mortality used in the 1988 analysis were derived from catch-curve analyses of aged shells (Nash *et al.*, 1994) which are dependent on the success of age-ing techniques.

It has been noted that most of the 1988 samples could not be aged because they were extensively bored by parasites (Fig. 11), and consequently, the mortality estimates apply only to abalone with shells that were in good condition. Shepherd (1992) has described several means by which boring parasites and commensals cause harm to abalone and increase the likelihood of death. Consequently, the values of natural mortality used in Nash's egg-per-recruit analysis are probably under-estimated. Even though age-length keys might be constructed to include the parasitised shells, it is questionable whether age-length relationships from un-bored shells can be applied to abalone that devote energy to shell formation at the site of the parasitic attack, and probably to the detriment of growth at the leading edge of the shell. As a result, un-ageable shells are likely to be older than their length would indicate. If these shells are used in catch-curve analyses, then the slope of the regression line will be reduced and the mortality rate again under-estimated.

It is likely that with the combined effects of increases in growth, size at maturity and natural mortality, that egg production as a percentage of virgin stock is much lower in these islands than first thought.

Precisely what constitutes a sustainable level of egg production is yet to be determined. It is considered that at least 40 percent of virgin egg production should be conserved for large populations of *H. laevigata*, that smaller populations of this species may require greater levels of protection and that as productivity declines, even higher levels of egg production should be conserved (Shepherd and Baker, 1997). Nash considered that 50 percent conservation of egg production may be adequate for stocks of *H. rubra* with high recruitment rates, but much higher levels of protection may be needed in areas with low recruitment rates (Nash, 1992).

Very little is known of the relationship between the level of spawning stock and subsequent recruitment to abalone fisheries. There are cases of unfished abalone stocks declining because of natural recruitment failure (Shepherd, 1990; Sloan and Breen, 1988), and attempts to manage abalone fisheries by manipulating input controls with a view to maintaining egg production may fail (McShane, 1995a).

In the Tasmanian abalone fishery, it has been the practise to ensure that the size-limit is set at the size of two years growth above L_{50} . This is an arbitrary measure determined in the absence of specific levels of egg production, and while it appears to be successful, its effect has never been critically reviewed.

If the size-limit is increased at the Kent Group to L_{50} plus two years, stocks may be better protected but at the risk of reduced yield from the fishery. Where there are differences in growth rate, such as exist between the two sites studied in the Kent Group, an increase in size-limit may protect the faster growing stocks but waste yield in the slower growing stocks.

5.4 Conditions of 1996 change-in-ratio analysis

In his review of the 1995 fishery, Nash tested for variation in relative catchability between size-classes in the pre- and post-fishery data and concluded that there was no significant change (Nash, 1996). If there was a change in catchability of the undersized fraction as a group however, this change would remain undetected.

Comparison of the 1996 samples with the modified 1997 sample (Fig. 7) show that at the Kent Group, the proportion of size to undersize abalone has changed. It does not support the assumption that the undersize fraction of the population remained constant.

There are plausible reasons why there should be a difference in abundance between the two samples, particularly those involving movement and re-aggregation following the disturbance caused by fishing (Gorfine *et al.*, 1998) or variable rates of mortality (Prince *et al.*, 1988b; Shepherd and Breen, 1992), or variable rates of success of capture (catchability) between the emergent legal-size and more cryptic under-size abalone (Gorfine *et al.*, 1996). We have no specific information about movement or variable rates of mortality in these islands, but there is evidence for variable rates of catchability. This is based upon change in the size at maturity at the Kent Group, where there is only a small size difference between L_{50} and the 110 mm size-limit. It is likely that much of the undersized fraction of the population used in the CIR analysis is sexually immature.

It has previously been shown that abalone become emergent when they are sexually mature, and that immature abalone are usually cryptic (Nash, 1992; Nash *et al.*, 1994). The implications of this are that cryptic abalone are harder to find than emergent abalone. However there are times when cryptic abalone come out from under the rocks (Shepherd, 1973b) and consequently become easier to catch, or when emergent abalone hide and become less catchable. Both types of behaviour cause variable catchability of undersized abalone (Gorfine *et al.*, 1998).

Before any CIR assessment can be made, assumptions about constant catchability of both pre-recruits and legal-size stocks need to be reviewed (Chen *et al.*, 1995; Dawe *et al.*, 1993). With abalone, this could be done with area based surveys at several sites before and after fishing to detect any change in abundance, although the success of this technique will be limited by the degree to which the reef can be exhaustively searched. It is unlikely that such a search can ever be achieved (Gorfine *et al.*, 1998).

Alternatively, to reduce the risk of variable catchability of the undersized fraction, the CIR assessment could be done with the pre-recruits limited to what might be considered emergent abalone *i.e.* between a size approaching 100 percent maturity and the size-limit. It may be necessary to obtain a much greater sample size to ensure necessary precision of the estimate of exploitation, and if L_{50} is close to the size-limit, then this approach may not be feasible. There would be a much greater certainty that the requirements of equal catchability between various sections of the population are met.

5.5 Changes in shell morphometry

It is a common perception amongst fishers and processors that fast growing abalone have shells that are narrower, lighter and shallower for a given length than those of slow growing abalone and that meat weight yields from abalone at fast growing locations are less than those normally obtained.

This perception is supported by two studies. McShane *et al.* (1988) found that abalone from a site at Mallacoota (Tullaburga Island) had the highest growth rate of the sites studied. They also found that abalone from this site yielded a lower foot (meat) and total weight for a given length than the other sites, and that the shells were shallower.

The second study found that shells from blacklip abalone in New South Wales were heavier and wider at sites typified by slow growth rates than those from sites where they grew faster, and postulated how synthesis of new shell occurred at the growing edge when energy was plentiful, causing proportionally greater increases in length than other variables (Worthington *et al.*, 1995).

Participants of the 1995 fisheries commented that abalone shells, especially from the Kent Group, appeared to be shallower, more elongated and suffering from less borer damage than in past years. The higher proportion of ageable abalone shells (Figure 10) in 1997 also implies in part that borer damage is now not as extensive, and as a consequence of this, a higher proportion of shell growth should occur at the growing edge of shells rather than being diverted to shell repair.

Despite the perceptions of those involved with the fishery, difference between the shells from each year were slight, and could not be detected in comparisons of shell length against shell width, height, and whole weight.

However, a difference between meat weight and shell length between 1988 and 1997 was found at the Hogan Group, where the shucked meats from the 1997 sample were lighter. This difference could be attributed to faster growth following the onset of fishing.

It has been shown that abalone weight, particularly meat weight as a percentage of whole weight, varies seasonally (McShane *et al.*, 1988), and that this variation is closely tied to the annual reproductive cycle. It is also observed generally among processors in Tasmania that meat yields from abalone over summer months are less than those from the remainder of the year. Unless comparison of weights between abalone populations over a period of time are matched to a common stage of reproductive cycle, it would be difficult to determine whether a change in meat yield in a particular area was due to changes in growth rate or seasonal variation.

This study minimises the effects of seasonality by comparing meat weight to shell length rather than yield of total weight. However, it should be pointed out that processors have observed reduced summer yields in areas which are heavily fished such as the Actaeon Islands in south-east Tasmania, where abalone are caught close to the size-limit and catches display minimal size variation throughout the year. They describe the meats as being of inferior condition compared with the rest of the year.

The difference between meat weight regressions at the Hogan Group may be due to seasonal variation (the 1988 sample was caught in autumn, the 1997 in summer) rather than an increase in growth rate. If this was so, then there should be no difference between shell weight regressions from each year, which should be unaffected by seasonal variation and could not be expected to fluctuate in weight. However, the comparison between shell weights from each year shows that shells now weigh less for a given length and is evidence that growth rates are now faster.

A high degree of variability is evident with shell height samples (r^2 between 0.6 and 0.7, Fig. 8). This may be due to the method of measuring shell height at the Marine Research Laboratories. The technique used involves placing the shell on a flat surface, and measuring the height of the shell from that surface. If the shell is bent or bowed, the depth of the bow is added to the height of the shell, giving a false measure of height. It assumes that the degree of bowing of shells is constant. The depth of the bow was not measured in samples from either of the years. If this variation could be reduced, it is felt that a change in shell height would be more apparent.

6. Conclusions

The Kent Group may be particularly sensitive to heavy fishing pressure, which prevents it from recovering from fishing at high levels of exploitation in the way that other parts of the Tasmanian coastline are able to. Further south for example, the eastern shore of the Freycinet Peninsula and Schouten Island have produced a long term average of about 70 tonnes per annum live-weight of blacklip abalone over the last 20 years. Despite being in different bio-regions, the Kent Group and Freycinet/Schouten abalone habitats have many similarities. Physically, both have a relatively steep reef edge giving way to a sandy bottom between 25 and 40 metres depth. Both regions share the same geological structure of Lower Carboniferous granite. The total shoreline length of the Kent Group is about 60 kilometres, which is again comparable with the Freycinet Peninsula and Schouten Island.

Abalone grow at a faster rate and to larger sizes in the Freycinet/Schouten region than in Bass Strait. This accounts for some of the difference in production, although this difference cannot be attributed entirely to growth. Differences between the two areas concerning recruitment processes and levels of natural mortality that affect production are unknown and unquantifiable.

The Hogan Group has only a third of the coastline of the Kent Group, yet appears to be able to sustain higher levels of fishing pressure and is certainly more productive (Table 8). Divers have a perception of greater abundance of abalone at the Hogan Group, and recent cruises have found that abalone are distributed to much greater depths than at the Kent Group, particularly about the western shores of Hogan Island and around the Twin Islets. It was always believed that the difference in productivity between the two Groups was related to the inferior growth rate of the Kent Group. Estimates of natural mortality in the two Groups were similar (Nash *et al.*, 1994). It remains to be seen whether production will increase as a result of the recent increase in growth rates, or fall further as a result of depletion to stocks caused by the successive fisheries and their effect upon egg production and subsequent recruitment.

Changes in size at maturity and growth rate appear to be correlated with the heavy fishing pressure in these islands since 1988. The changes are more pronounced and easier to detect at the Kent Group than at the Hogan Group, which may be due to differences in the level of stock depletion and its subsequent ability to recover. When a fishery is heavily exploited, it is useful to note that there may be changes in biological parameters, and that these parameters may be used to substantiate estimates of exploitation rates.

Choosing a size-limit for future fisheries is complicated because growth rates and the size at sexual maturity are increasing. Determining a future size-limit demands that a further survey of growth and size at maturity be done prior to the commencement of the next fishery. Whatever size-limit is chosen, the window of opportunity to take abalone at the Kent Group is becoming progressively less because the size at maturity is increasing without any corresponding increase in average maximum size. The size-limit used in the 1991 fishery (118 mm) will provide a better level of protection if the current size at maturity prevails. Higher size-limits will provide greater protection but may unnecessarily limit the yield from the fishery.

Choosing a total allowable catch (TAC) for future fisheries that will maximise yield yet protect stocks is even more difficult. Past work by researchers has produced good estimates of the level of depletion by each fishery, but without information about recruitment, the level of cumulative depletion of successive fisheries is unknown and may only be detected when catch rates become uneconomical and abalone make adaptive responses to low stock densities. It is apparent that the previous TACs were too ambitious, and that a lower TAC must be considered, particularly at the Kent Group. It is likely that all the Bass Strait islands north and west of Craggy Island (but excluding King Island) may only sustain an annual harvest of 25 to 30 tonnes as Prince originally suggested (Prince *et al.*, 1987).

The effect of abrupt localised depletion of abalone from the ecosystem (pulse fishing) and its consequent effect upon abalone habitat has not been studied. For the benefit of future fishers, it would be prudent to harvest abalone at sustained low levels during the year rather than at high levels over a brief season.

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Appendix

The following details of the trip to the Bass Strait islands are given here for the benefit of those who organise future cruises.

On Monday, 6 January 1997, the research vessel *Challenger* left Hobart at 1:00 pm. It arrived at Deal Island at 7:00 pm the following evening (30 hours). The trip was undertaken in good weather and was uneventful.

The return trip left Deal Island for Hobart on the afternoon of Sunday 12 January at 1:00 pm, arriving at Hobart 45 hours later (10:00 am), after stopping over-night at Port Arthur. Once again weather conditions were favourable.

Challenger had a full complement. On board were Matthew Francis (skipper) and Andrew Alexander (mate), Stewart Dickson, James Bridley and David Tarbath, all from the Marine Research Laboratories, Taroona, and John Rudge, a commercial abalone diver from Mallacoota, Victoria.

Diving was undertaken from a fifteen foot aluminium dinghy. This dinghy carried four divers and their equipment. It was too small for the task, and the work was successfully completed only because of good weather conditions during the trip.