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Biomass and commercial catch estimates for abalone stocks in areas proposed as sanctuary zones for the Capes Marine Park

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Contents

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Executive Summary

This study was undertaken to estimate the biomasses, biologically sustainable catches and current average annual commercial catches of three fished species of abalone, *Haliotis roei* (Roei), *Haliotis laevigata* (Greenlip) and *Haliotis conicopora* (Brownlip) in the proposed sanctuaries of the Capes Marine Park, south-western Australia. The current annual, catch estimates represent the catches that would be foregone by commercial fishers if the sanctuaries are implemented and will be used to evaluate the potential compensation to fishers (not part of this study). The biomass and catch estimates for each species in the proposed sanctuaries were estimated from a combination of scientific survey data and commercial catch information (provided by fishers) for the proposed sanctuaries. It should be noted that the design, field surveys, analyses of data and writing of this report had to be completed in less than a year, which limited the scope of this study.

Commercial abalone fishers who operate in the Capes area were consulted to identify areas where commercial quantities of abalone were known to occur within the proposed sanctuaries. Of the 12 proposed sanctuaries, three were identified as containing commercial stocks of Roei, with one of those zones, *i.e.* Cape Naturaliste, having two optional configurations. Four sanctuaries were identified with commercial stocks of both Greenlip and Brownlip. Roei, which occur over intertidal and shallow, subtidal reefs, were sampled using 0.5 m^2 quadrats along 34 transect lines (136 quadrats) set perpendicular to the shore. Greenlip and Brownlip, which are found in deeper waters over reefs, were sampled using 30 m^2 transects (2 transects per site) at 116 randomly selected sites (232 transects) within the areas identified by commercial fishers. The numbers and shell lengths of all abalone were recorded, and length-weight (total and bled meat weight) relationships were determined for each species from sub-samples taken from a range of sites, which thereby enabled estimation of the weights of all individual abalone recorded in the surveys.

For all three abalone species of abalone, industry harvests abalone at lengths above the minimum legal length (MLL) for capture. The minimum size at which Roei is harvested commercially in the Capes region is 70 or 75 mm, depending on location within the region (*cf.* 60 mm MLL); minimum sizes for Greenlip and Brownlip in the region range from 150 to 153 mm (*cf.* 140 mm MLL for Greenlip and Brownlip). Between 15 and 39% of Roei measured in the proposed sanctuaries surveyed were above the respective minimum size at which it is harvested commercially in those areas. In comparison, nearly half of the Greenlip and Brownlip in the proposed sanctuaries were above the minimum size at which these species are harvested in those areas.

Biomass and catch

The data from the surveys were used to produce biomass estimates for each species which were subsequently adjusted for the catches reported by fishers from the proposed sanctuaries during the 2006/07 fishing season. The point estimates of biomass for Roei above the minimum size at which it is harvested (harvest biomass, HB), *i.e.* > 70 at Cape Naturaliste options 1 and 2 and Wyadup, > 75 mm at Cape Leeuwin, adjusted for catches (kg, total body wt), in all sanctuaries surveyed were 17,777 kg, excluding Cape Naturaliste option 2, and 14,149 kg, excluding Cape Naturaliste option 1. The proposed sanctuaries with the highest estimated HB of Roei were Wyadup (9,881 kg – a relatively low density of animals above the minimum size it is commercially harvested, distributed over a large area) and Cape Naturaliste option 1 (7,186 kg – a high density population in a small area). The estimated HB of Roei for Cape Naturaliste option 1 was far greater than for Cape Naturaliste option 2 (3,558 kg).

The total estimated HB adjusted for catches for Greenlip and Brownlip abalone (kg, bled meat wt) in the proposed sanctuaries were 3,252 kg and 2,260 kg, respectively. The highest estimated HB were from Cape Leeuwin for both species (1,591 and 1,463 kg for Greenlip and Brownlip, respectively). The associated 95% confidence intervals for those estimates, determined through re-sampling, were relatively broad.

The current annual commercial catch for each species was estimated by applying values of fishing mortality, natural mortality to the estimates of HB. On the basis of the HB estimates which had been adjusted for catches, for Roei, the overall estimate was 5,579 kg for all sanctuaries excluding Cape Naturaliste option 2 and 4,470 kg for all sanctuaries excluding Cape Naturaliste option 1. The overall estimated annual commercial catches for Greenlip and Brownlip (kg, bled meat wt) were 993 and 557 kg, respectively.

The reference point analyses indicated that all three species in the Capes region are currently at, or close to full biological exploitation. We believe that the estimates of current annual catch in the proposed sanctuaries determined by applying values of fishing mortality to our estimates of harvest biomass, adjusted for commercial catches, provide the most appropriate estimation of annual catch foregone.

Acknowledgements

The authors are grateful to the commercial abalone industry, particularly, David Sutcliffe, Darren Adams, John Lashmar, Ian Taylor and Terry Adams and all commercial fishers who operate in the Capes region and willingly provided information on the locations of abalone stocks in the proposed sanctuaries and on the catches they had taken from these areas during the 2006/07 season. Many thanks to the sampling team of the Department of Fisheries, including Frank Fabris, Jamin Brown, Lachlan Strain, David Murphy, Fiona Parker and Mark Davidson, and to Peter Coulson of Murdoch University for their great dedication to the surveys undertaken in the study. Thanks to all staff at the Department of Environment and Conservation with whom we have had discussions regarding the project, and particularly to Peter Dans, Chris Simpson, John Lloyd, Judy Davidson and Fran Stanley. Thanks to Nick Caputi and Andrew Hill of the Department of Fisheries for discussions and advice. Thanks also to Jessica Meeuwig (University of WA) for her advice on sampling design.

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1.0 Background

The Western Australian Government is committed to establishing a marine park in the Capes Region (*i.e.* Cape Naturaliste to Cape Leeuwin). The Department of Environment and Conservation (formerly, Department of Conservation and Land Management – CALM) undertook a community consultation process in 2003/2004 to develop a draft indicative management plan for the proposed park. This draft included a zoning plan, which consists of a number of sanctuaries where commercial fishing, including that for abalone, will be prohibited (Figures 1.1 to 1.3). Fishers are entitled to apply for compensation under the *Fisheries and Related Industries (Marine Sanctuaries) Compensation Act 1997* where they have been impacted by the creation of a marine park. Accordingly, it is likely that claims will be submitted following the creation of the proposed Geographe Bay/Leeuwin-Naturaliste/Hardy Inlet Marine Park ("the Capes Marine Park").

An external economist employed as a consultant by the Department of Fisheries (DoF) previously prepared estimates of the potential compensation to commercial abalone fishers for the potential loss of income resulting from the exclusion of commercial fishers from the proposed sanctuaries. Compensation was estimated from commercial abalone log book catch data (held by DoF), and from information supplied by the abalone industry. However, there was a large discrepancy between these estimates of compensation.

Monthly catch data for commercial abalone is typically reported in 60 x 60 nm (nautical mile) blocks, but finer scale data based on 10 by 10 nm blocks is also provided daily as part of a quota return. However, the latter data are still not precise enough to accurately determine the proportion of abalone taken from the proposed sanctuaries. To facilitate determination of fair and appropriate compensation payments when the marine park is established, information was required that could be used to estimate more reliably the likely loss of abalone product to commercial fishers as a result of implementing sanctuaries in the Capes region. Such data may also be used to amend the proposed zoning of the sanctuaries in the Capes Marine Park, to minimise the loss of product to industry and the compensation liability to Government. "Benchmark information" on abalone stocks located in the sanctuaries of the park would enable future assessments to be made of the changes in abalone populations as a result of the closures.

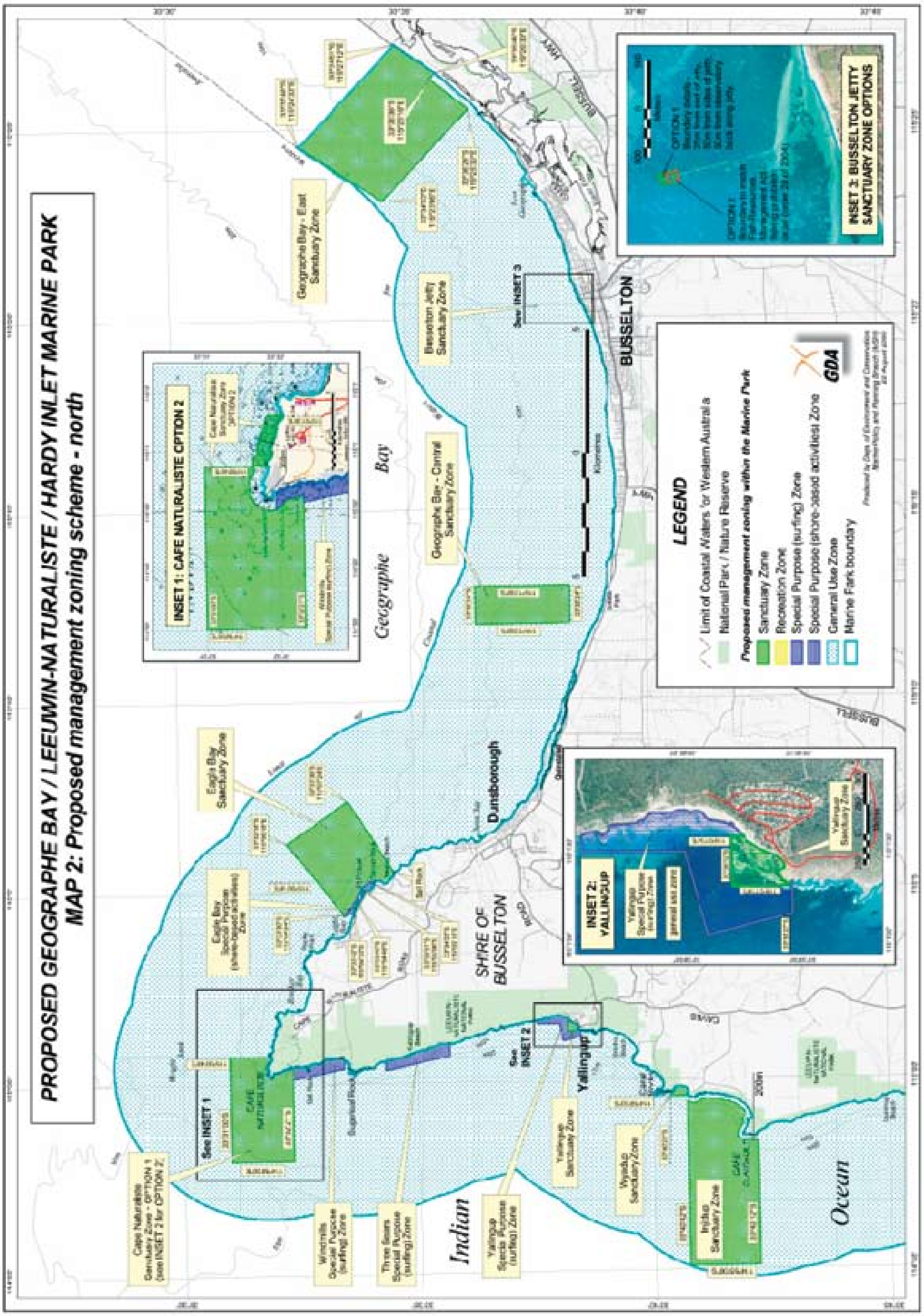

Figure 1.1 Map 2 of brochure entitled: "Proposed Geographe Bay/Leeuwin-Naturaliste/Hardy Inlet: have your say". Department of Environment and Conservation and Marine Parks and Reserves Authority.

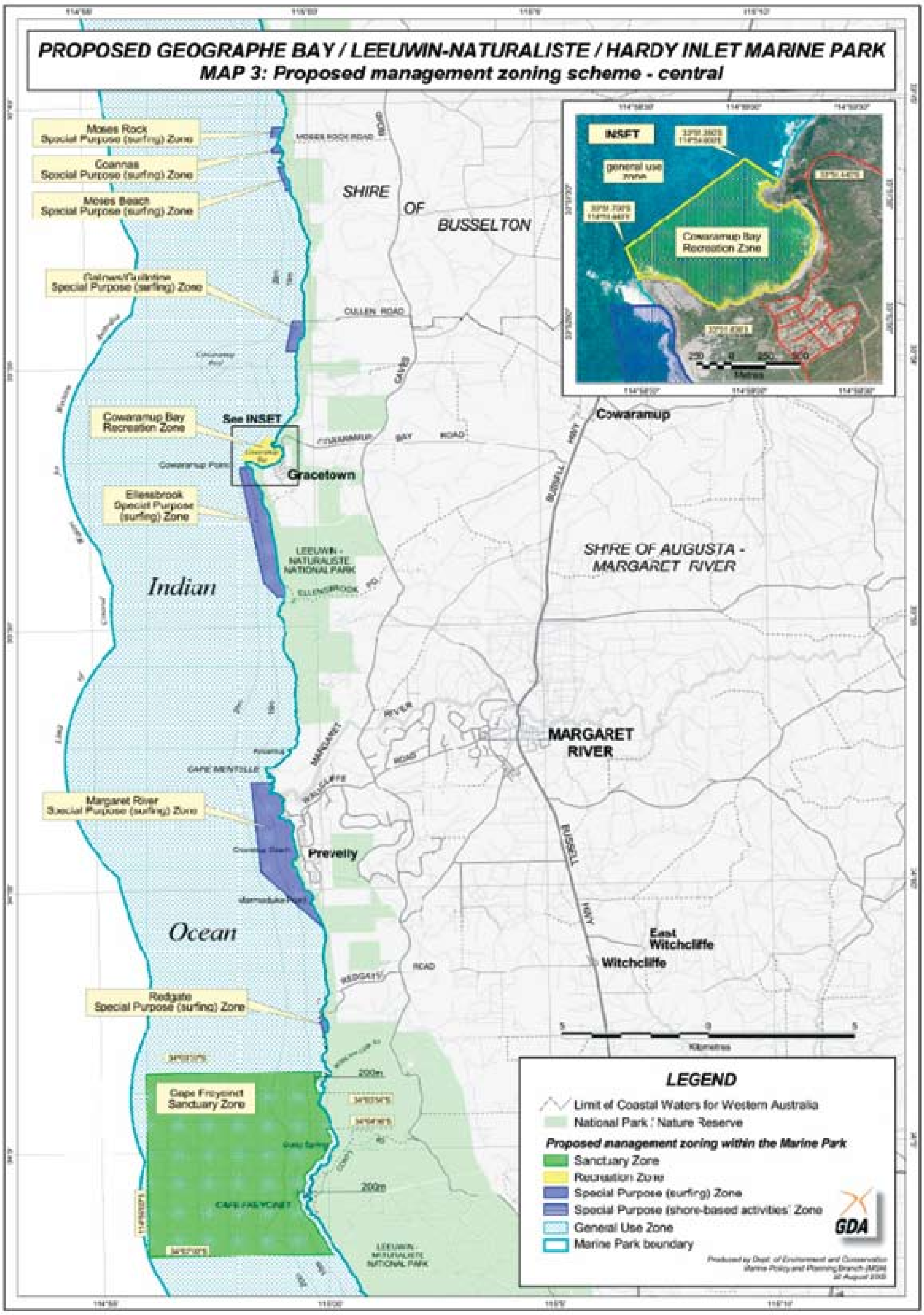

Figure 1.2 Map 3 of brochure entitled "Proposed Geographe Bay/Leeuwin-Naturaliste/Hardy Inlet: have your say". Department of Environment and Conservation and Marine Parks and Reserves Authority.

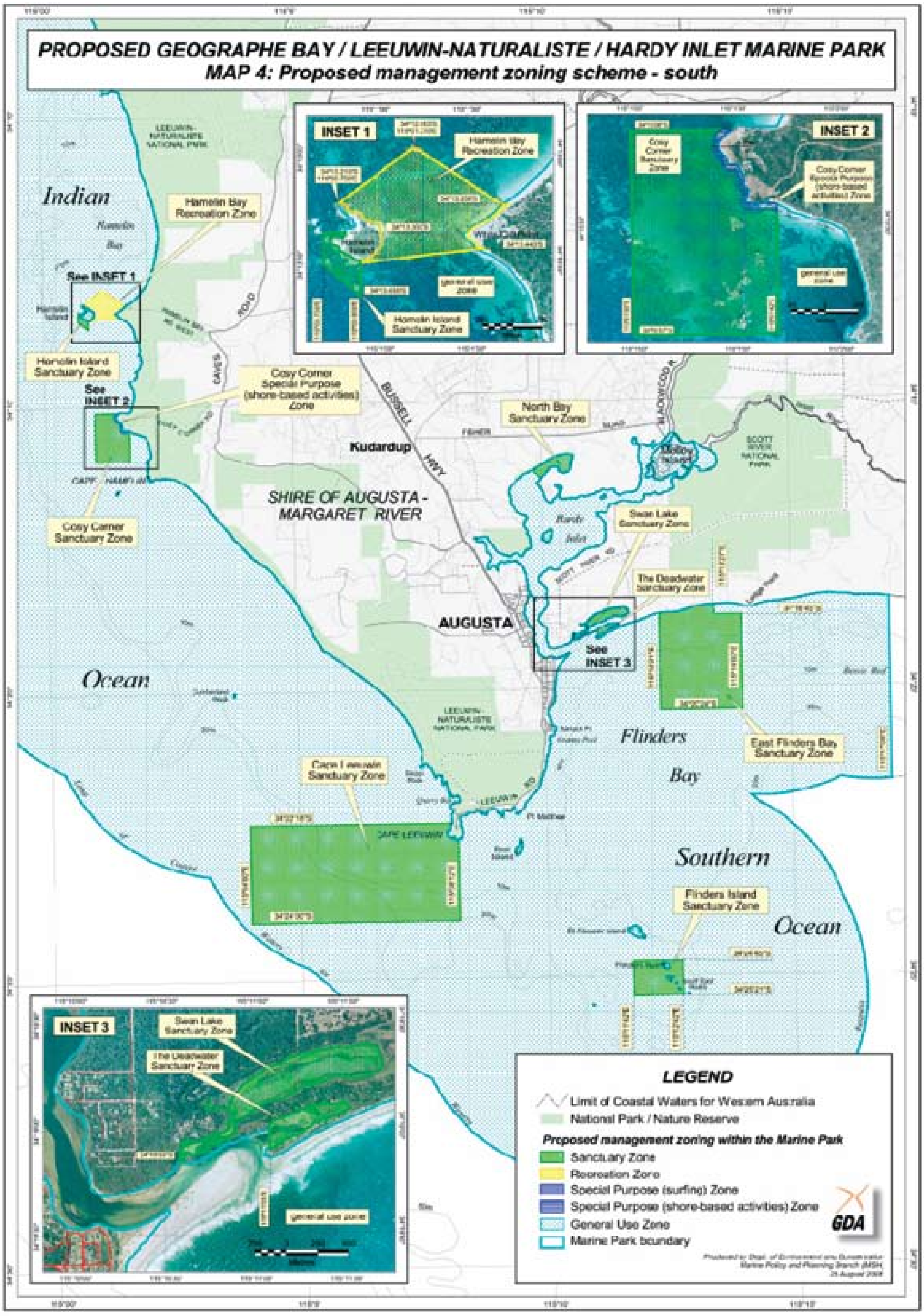

Figure 1.3 Map 4 of brochure entitled “Proposed Geographe Bay/Leeuwin-Naturaliste/Hardy Inlet: have your say”. Department of Environment and Conservation and Marine Parks and Reserves Authority.

The main aim of this study was to estimate the average, current annual commercial catch of each of the three abalone species within the proposed sanctuaries of the Capes Marine Park. The approach adopted was to determine those areas within the proposed sanctuaries that are currently commercially fished (through consulting commercial abalone fishers). The biomass of each commercially-harvested abalone species within the commercially-fished areas of the proposed sanctuaries was then estimated from scientific surveys and also taking into account data provided by commercial fishers on their catches from these zones in the 2006/2007 season (November to the end of the surveys in June). For each species in each proposed sanctuary in which commercially important stocks were identified, biomass estimates were made for abalone of all sizes, and above the size at which they attain maturity, legal size and commercial, harvest size (as, for all three species, the minimum size at which they are commercially harvested is greater than their respective minimum legal size). The calculation of appropriate levels of compensation for commercial abalone fishers was not part of this project.

1.1 Background on commercial abalone fisheries in the Capes region

The commercial fishery for abalone in Western Australia currently targets three species, namely Roe's abalone (*Haliotis roei*), Greenlip abalone (*Haliotis laevigata*) and Brownlip abalone (*Haliotis conicopora*) (Metzner *et al.* 2001). The management areas for the commercial fishery for Roei differ to those for Greenlip and Brownlip in Western Australia; there are six different management areas for Roei and three for Greenlip and Brownlip. The management of Roei in the Capes region falls within the Department of Fisheries' management area 6, which extends from Cape Bouvard to Cape Leeuwin (Augusta) and has 12 license holders (Mitchell and Baba, 2006). Data in log books for commercial catches of abalone show that, over the last 10 years, essentially all of the total allowable catch (TAC) of 12,000 kg whole weight (Mitchell and Baba, 2006) for Roei in management area 6 comes from the Capes region *i.e.* between Cape Leeuwin and Cape Naturaliste. The commercial log book data also show that most of the Roei catch in the Capes region is taken north of the Cape Freycinet proposed sanctuary (Figures 1.1 to 1.3).

The commercial fishery for Greenlip and Brownlip in the Capes region falls within management area 3 for these species, which extends between Busselton and Shoal Cape (east of Esperance), with 7 license holders (and 8 licences) (A. Hart, pers comm.). The commercial log book data show that approximately half of the annual Greenlip and Brownlip catch for management area 3 (TAC = about 32,000 kg for Greenlip and 7,500 kg for Brownlip, Hart and Fabris, 2005), comes from the Capes region, even though this region constitutes a relatively small proportion of the overall area of the zone. In contrast to Roei, most of the commercial Greenlip and Brownlip catch from the Capes region is taken south of the Cape Freycinet proposed sanctuary zone.

The minimum shell lengths at which, for management area 6, Roei are commercially harvested, are 70 or 75 mm, depending on the location within this management area, which are thus well above the minimum legal shell length of 60 mm for this species (Hart and Fabris, 2005; personal communication, Abalone Industry Meeting July 2007). Likewise, fishers in management area 3 for Greenlip and Brownlip harvest these species at lengths well above the minimum legal shell length of 140 mm, *i.e.* at 150 or 153 mm, depending on the growth rates of the abalone in the different fishing grounds (Hart and Fabris, 2005).

2.0 Methods

2.1 Identification of sampling areas within the proposed sanctuaries of the Capes region through fisher knowledge

The proposed sanctuaries in the Capes Marine Park cover a large area and, given the limited time and resources available for the project, it was not feasible to sample the sanctuaries systematically in their entirety. However, commercial fishers focus their fishing activities in areas where the quantities of abalone are large enough for commercial fishing to be viable. Therefore, the biomass of abalone that will no longer be accessible to fishers is that which lies in the areas of the sanctuaries that are currently fished. We thus focused on those areas within the proposed sanctuaries where commercially viable abundances of abalone are known to commercial fishers, who are currently fishing in the Capes region (these areas are referred to as strata throughout the report).

Commercial abalone fishers with key knowledge of locations of abalone stocks within the proposed sanctuaries of the Capes Marine Park were identified at an industry meeting in February 2007. Five of these fishers, who fish mainly for Roei, and three, who fish mainly for Greenlip and Brownlip (including one fisher who no longer currently fishes for abalone), were interviewed. During those interviews, fishers were asked to draw on the maps the areas where they know of significant numbers of abalone. Other information offered by fishers in those interviews, such as the depths and habitats at those locations, was also noted. In the case of Roei, one fisher kindly assisted DoF on a two day field trip to identify and map areas of significant Roei stocks within the sanctuaries. For Greenlip and Brownlip, two of the fishers acknowledged by other fishers as having the most current knowledge of these stocks, kindly provided GPS positions of their fishing locations (44 locations) for these species within the proposed sanctuaries.

Surveys for the three species were completed between the 4th March and 18th June 2007.

2.2 Sampling for Roei

The areas for Roei visited with the commercial fisher were marked using GPS. The GPS areas were then plotted in ArcMap 9.0 and overlaid on a 0.5 m aerial photo mosaic (taken in 2004) of each sanctuary. On the digital image, polygons were drawn around the recorded GPS positions to mark those areas containing significant abalone locations. The sketches and information provided by the other Roei fishers were cross-checked and, where necessary, some adjustments were made to the GIS coverage to accommodate the information provided by those other fishers. The surface area and perimeter of each polygon were extracted from ArcMap 9.0 and exported to Microsoft Excel^{TM} for use in other analyses. Twelve strata in the proposed sanctuaries were identified, based on the extent of the Roei populations (Table 2.1).

Roei were counted and measured in four quadrats (0.5 m^2 in area), 1.5 m apart (equally spaced), along a 6 m long transect line, laid perpendicular to the shore within each strata. Previous studies have shown that distance from shore is a major source of variability in Roei density (Hancock, 2004). A total of 34 transects and 136 quadrats were sampled in three proposed sanctuaries (including option 1 and 2 of Cape Naturaliste, Wyadup and Cape Leeuwin (Figs 1.1 to 1.3, Table 2.1). Both the total numbers of Roei and the maximum shell length (to the nearest 1 mm) of each individual were recorded for each quadrat.

Two strata at Cape Naturaliste Option 1 and one at Cape Leeuwin, which can only be sampled in very low swell conditions, were not sampled because of poor weather. As preliminary dives with a commercial Roei fisher in these strata indicated that they contained far higher numbers of abalone than in the other strata, existing data (for 15 quadrats) for similar habitat with high densities of Roei in the Perth metropolitan region (provided by DoF), were used as a surrogate for these three strata. Advice that, of the available data, the Perth data were likely to be most representative of Roei in those strata not able to be sampled was provided to us at a meeting with industry, Anthony Hart and Jeremy Prince in March, 2007.

Table 2.1 The area of the strata and number of transects and quadrats sampled to estimate the biomass of Roei within the proposed sanctuaries of the Capes Marine Park. Strata refer to those areas within the sanctuaries listed in the table that, through consultation with industry, were identified as containing commercially important stocks of abalone. * refers to strata that were not sampled and for which data from the Perth metropolitan region have been used.

Strata name	Area m^2 (GIS)	No. of transects	No. of quadrats
	Cape Naturaliste (Option 2)		
A	2,700	3	12
BA	4,200	3	12
BB	11,000	4	16
Sanctuary total	17,900	**10**	**40**
	Cape Naturaliste (Option 1)		
BC	3,100	3	12
C	5,000	4	16
D	320	1*	4*
E	2,000	2*	7*
Sanctuary total (excluding metropolitan data)	10,420	**7**	**28**
	Wyadup		
GA	33,000	8	32
GB	15,700	3	12
GC	160	1	4
Sanctuary total	48,860	**12**	**48**
	Cape Leeuwin		
HA	430	5	20
HB	320	1*	4*
Sanctuary total (excluding metropolitan data)	750	**5**	**20**
Total sampled (excluding Cape Naturaliste Option 1)	**50,030**	**30**	**108**
Total sampled (excluding Cape Naturaliste Option 2)	**57,510**	**27**	**96**

2.3 Sampling for Greenlip and Brownlip

The sampling areas (strata) for Greenlip and Brownlip were determined using a combination of the GPS locations and hand-drawn sketches on the aerial photographs of the sanctuaries that were provided by fishers and represented areas that they considered to contain significant abalone stocks. The GPS locations provided by fishers were plotted in ArcMap 9.0 and overlaid with a 0.5 m aerial photo mosaic (2004) of each sanctuary. Polygons encompassing areas within the sanctuaries identified by fishers as housing significant abalone stocks were created on digital aerial photographs by tracing an area around the digitally-transferred GPS points provided by fishers, and also by transferring onto the digital photographs polygons representing the areas sketched out by the fishers.

Sampling for Greenlip and Brownlip was completed in four of the proposed sanctuaries (Flinders Island, Cape Leeuwin, Cosy Corner and Cape Freycinet, Table 2.2). 40 GPS locations were assigned to each of the above sanctuaries using the Hawths GIS tool for stratified sampling (http://www.spatialecology.com/htools/tooldesc.php). For each sanctuary, the 40 GPS locations were distributed among the strata in that sanctuary according to an assigned priority level. Most of the computer generated sampling sites were assigned to those identified using fisher GPS points (termed "High priority strata"). Areas identified using sketches from fishers and no fisher GPS points ("Low priority strata") and presumed less likely to be currently fished, were allocated fewer sampling sites. The surface area and perimeter of each polygon and all GPS coordinates were extracted from ArcMap 9.0 and exported to Microsoft Excel™ for use in other analyses.

At each of 116 of the total of 160 computer-generated sampling locations (the maximum number of sites that could be sampled within the time available), two 30 x 1 m long transects were surveyed in opposite directions along bearings of 0° and 180°, without searching or movement away from the GPS location before the transects were laid (Table 2.2). This method is a modification of the method of McGarvey *et al.* (in press), as outlined in Carlson *et al.* (2006). The main modifications are that for the current study, the transect length was reduced from 100 to 30 m, the locations were randomly, not systematically selected and the divers swam in opposite directions, not in the same direction. For the analysis, the two 30 m transects at each site, (as they are not independent), were pooled.

2.4 Preliminary analyses for determining the required number of samples

Prior to sampling, preliminary analyses were completed using existing DoF data for other Roei (from near Perth) and Greenlip stocks (from Hopetoun), to explore the relationship between the number of samples and estimates of mean density and variation in the mean. The results of those preliminary analyses were used to determine the number of samples that would be allocated to each of the strata to obtain the required precision. See Appendix 1 for a detailed description of the data, their appropriateness, and for these preliminary analyses.

2.5 Length-weight relationships for the three abalone species

Subsamples of 80 Roei, 53 Greenlip and 50 Brownlip, and which covered essentially the full size ranges of each species recorded during the surveys, were taken from sites at two or more of the proposed sanctuaries. They were placed on ice before measuring their shell lengths, whole weights and bled meat weight. The data were used to determine length-weight relationships for each of the three species.

2.6 Analyses for determining abalone biomass within the proposed sanctuaries

Estimates of biomass and its precision were made for each species in the proposed sanctuaries using the following procedure:

1. estimating the weight of each abalone by converting its recorded length to a weight using the appropriate length-weight relationship (see above);
2. calculating the biomass of abalone in each quadrat for Roei and transect for Greenlip and Brownlip in the following categories:
    a. all visible (non-cryptic) abalone *i.e.* total biomass,
    b. all abalone above estimates of the size at maturity. Roei = 45 mm (Keesing, 1984), Greenlip = 95 mm (Hart *et al*., 2000), Brownlip = 125 mm (Wells and Mulvay, 1992).
    c. all legal sized abalone. Minimum Legal Lengths (MLL) are: Roei = 60 mm, Greenlip and Brownlip = 140 mm.
    d. all abalone above the size at which they are harvested in the proposed sanctuaries by commercial fishers (for Roei, 70 mm at Cape Naturaliste options 1 and 2 and Wyadup, 75 mm at Cape Leeuwin; for Greenlip and Brownlip, 150 mm).
3. for each strata in each sanctuary, calculating the mean biomass (of a-d above) per m^2 and then extrapolating to the biomass for the overall area of each strata;
4. summing the biomasses for all strata in each sanctuary;
5. estimating the variance for each strata and then calculating the overall variance in biomass for all strata in each sanctuary.

A more detailed description of the process for calculating the biomass estimates from the survey data is provided in Appendix 2.

Table 2.2 The area of strata and allocation of sites and transects to strata for estimating the biomass of Greenlip and Brownlip within the proposed sanctuaries of the Capes Marine Park. Strata refer to those areas within the sanctuaries listed in the table that were identified as being likely to contain commercially significant stocks of abalone.

Strata name	Fisher GPS points	Priority	Area m^2 (GIS)	No. of sites	No. of transects
		Flinders Island			
1	Yes	High	36,473	24	48
2	Yes	High	10,572	5	10
3	Yes	High	36,716	3	6
4	No	Low	21,107	2	4
5	No	Low	18,982	2	4
6	No	Low	157,720	2	4
Sanctuary total			281,570	**38**	**76**
		Cape Leeuwin			
7	Yes	High	157,720	30	60
8	No	Low	19,824	10	20
Sanctuary total			177,544	**40**	**80**
		Cosy Corner			
9	Yes	High	107,179	15	30
10	Yes	High	12,880	5	10
11	No	Low	22,295	0	0
12	No	Low	7,956	1	2
13	No	Low	17,961	1	2
Sanctuary total			168,271	**22**	**44**
		Cape Freycinet			
14	Yes	High	17,312	7	14
15	Yes	High	49,653	3	6
16	Yes	High	11,383	2	4
17	Low	Low	15,394	2	4
18	Low	Low	162,608	2	4
Sanctuary total			256,359	**16**	**32**
Overall total				**116**	**232**

2.6.1 Assumptions in the estimation of biomass in the proposed sanctuaries

1. Areas identified by fishers provide a good representation of all locations where commercial quantities of abalone are found, thereby enabling accurate estimates of the biomass of abalone in the areas that are currently fished by commercial fishers. If this assumption is not met, the biomass of abalone in sanctuaries will be underestimated. This is more likely to be an issue for Greenlip and Brownlip, which are found at lower densities and extend over far larger areas than Roei.

2. The counts of the scientific divers provide an accurate estimate of the abundance of abalone. The DoF divers have extensive experience in surveying abalone over a wide geographic area, and the initial field trip for Roei, undertaken with a commercial fisher, provided a level of confidence that this assumption is valid. The larger abalone, which are of most concern in this study, are less likely to be missed.
3. The method of taking into account the catch of abalone removed by fishing relies on the accuracy of information provided by fishers on their catches from the proposed sanctuaries during the 2006/07 fishing season. This assumption was verified partly by comparing reported catches with the logbook data, and through checking the consistency of the reported catches against the estimates of biomass determined from the survey data.
4. The estimate of natural mortality, M = 0.25 year^{-1}, is a good estimate for each species. Uncertainty in M was taken into account by re-sampling values of this parameter from a broad distribution, rather than using just the point estimate of 0.25 year^{-1}.
5. The biomass of abalone in sanctuaries in 2007 is representative of the average biomass over a number of years.
6. It is assumed, according to information provided by commercial fishers at an Abalone Industry Meeting held in July, 2007, that the harvest size for Roei is 70 mm at Cape Naturaliste options 1 and 2 and Wyadup, and 75 mm at Cape Leeuwin. Greenlip and Brownlip are assumed to be harvested commercially at 150 mm in the four sanctuaries surveyed.

2.7 Adjustment of biomass estimates for abalone removed by commercial fishing during the 2006/07 season

To adjust the estimates produced from the surveys for any commercial catches of abalone from the sanctuaries, fishers were contacted and asked to provide details of their catches taken during the 2006/07 fishing season, from 1/11/2006 to 18/6/2007. These dates were chosen to account for catches taken from the proposed sanctuaries in the period leading up to and during the surveys, and thus also account for impacts of commercial fishing for abalone on the survey biomass estimates. As the commencement date for the inclusion of catches was, to some extent, arbitrary, two catches reported for Roei taken at the end of October in 2006 were also included in the analyses. For each catch, the date, biomass (total weight for Roei and bled meat weight for Greenlip and Brownlip), species taken and name of proposed sanctuary were recorded. A detailed description of the methods used to adjust the survey biomass estimates for the catches reported by commercial fishers is provided in Appendix 2. The log book data held by DoF (10 x 10 nm blocks) were analysed to verify that the catches reported from the reserves were within the bounds that would be expected, based on those data.

Catches for Roei were reported between the end of October and the end of March. Greenlip and Brownlip catches were reported in January, February and June. Most catches reported by fishers were provided as a “beach weight” rather than “market weight”. Differences in beach and market weight of abalone were not accounted for in the biomass and catch estimates presented in this report. Data held by DoF indicate that the percentage weight reduction from beach to market weight of abalone is 3.6% for Roei, 5.8% for Greenlip and 7.5% for Brownlip.

2.8 Estimates of current catch based on estimates of fishing mortality

Estimates of the current annual commercial catch taken from the proposed sanctuaries of the Capes region were determined by applying estimates of fishing mortality provided by DoF to the biomass estimates for each of the three species above the respective minimum sizes at which they are commercially harvested. Fishing mortality was determined from using growth information for the three species and catch curve analysis. Catch was estimated using the Baranov catch equation (see Appendix 4 for details).

2.9 Estimates of biologically sustainable catch based on reference point analyses

A reference point analysis was employed to determine the biologically sustainable catch that could be taken annually from the proposed sanctuaries. This analysis could also provide an estimate of the current annual catch taken by commercial fishers from the proposed sanctuaries, provided the stock is fully exploited (biologically). Biologically sustainable levels of catch were determined from the level of fishing of the available biomass according to the limit reference point of $F = M$ (*e.g.* Thomson, 1993) and target reference points of either $F = 0.6F_{limit}$ (Perry *et al.*, 1999) or $F = 0.75F_{limit}$ (Restrepo *et al.*, 1998). Natural mortality was represented by a normal distribution with a mean of 0.25 $year^{-1}$ and standard deviation of 0.05, and thus was within the range of ~0.2-0.35 $year^{-1}$ reported in the literature for a number of abalone species (*e.g.* Shepherd *et al.*, 1982). The sustainable catch was calculated as that at which the probability of being within 10% of the target reference point was maximised, but the probability of exceeding the limit reference point was less than 20%. Full details of the methods for determining initial biomass, available biomass and sustainable levels of catch are provided in Appendix 3.

3.0 Results

3.1 Preliminary parametric sample size analysis

The preliminary sample size analyses for Roei indicated that the relative standard error (RSE) for the mean number of abalone per quadrat would decline substantially from ~50 to 30% as the number of quadrats increased from 4 to ~20 quadrats, but that the RSE would decline by only a further 5% if the number of quadrats were doubled from 20 to 40 (Figure 3.1). Likewise, for Greenlip, the preliminary sample size analyses indicated that the RSE would decline from ~40 to ~22% with an increase in the number of transects from 4 to 20, but decline only marginally with further increases in the number of transects sampled (Figure 3.1).

3.2 Length-weight relationships

The relationships between the natural logarithms (ln) of shell length (*L*) and total body weight (*W*) and bled meat weight (*MW*) were:

Roei

$\ln W = 3.048L - 8.905$ ($n = 80$, $R^2 = 0.99$, *mean square* = 0.019)

$\ln MW = 3.071L - 9.941$ ($n = 80$, $R^2 = 0.98$, *mean square* = 0.036)

Greenlip

$\ln W = 3.344L - 10.513$ ($n = 53$, $R^2 = 0.98$, *mean square* = 0.023)

$\ln MW = 3.363L - 11.590$ ($n = 53$, $R^2 = 0.97$, *mean square* = 0.035)

Brownlip

$\ln W = 2.922L - 8.311$ ($n = 50$, $R^2 = 0.77$, *mean square* = 0.017)

$\ln MW = 2.630L - 7.853$ ($n = 50$, $R^2 = 0.74$, *mean square* = 0.019).

The relationships between *L* and both *W* and *MW* were fitted well by power curves, which had been derived by back log-transforming the estimates of *W* and *MW* at each *L*, and correcting for bias (for equations, see Beauchamp and Olson, 1973) (Figure 3.2).

3.3 Length compositions of the three abalone species in the proposed sanctuaries

Between 15 and 39% of the individuals of Roei in the proposed sanctuaries surveyed were above the minimum size at which this species is currently commercially harvested in those areas (*i.e.* 70 mm at Cape Naturaliste options 1 and 2 and Wyadup, 75 mm at Cape Leeuwin) (Figure 3.3). The lowest proportion of harvest size animals was recorded at Wyadup (15%).

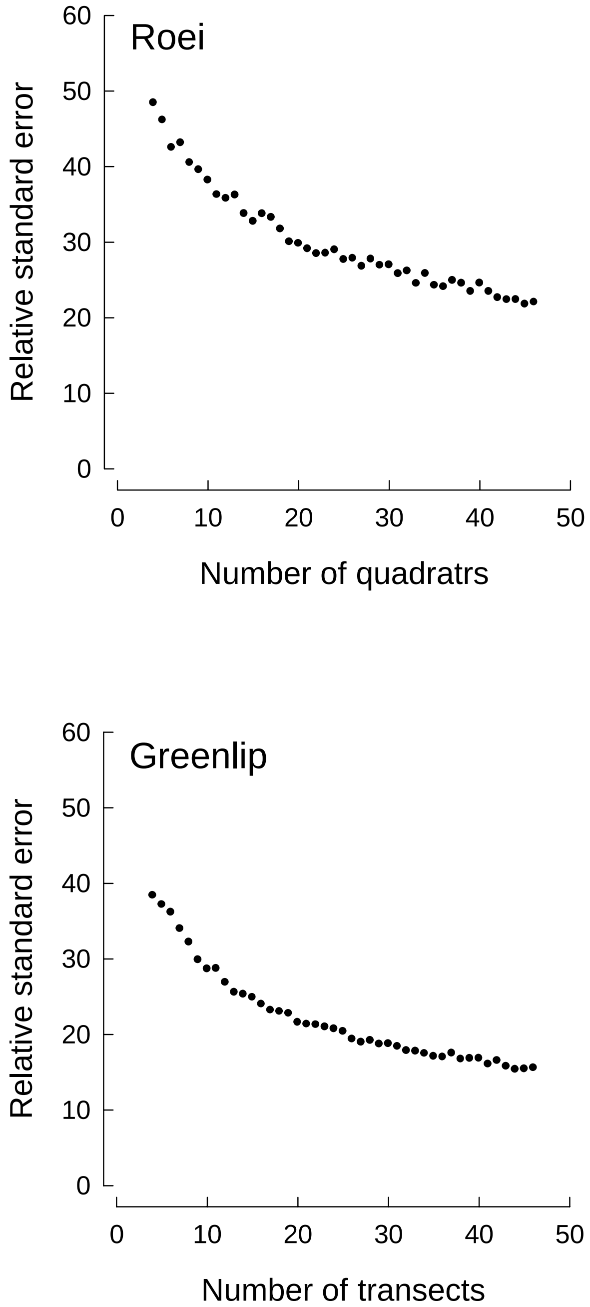

Figure 3.1 Preliminary analysis showing the relationship between relative standard error and sample size for densities of Roei and Greenlip, derived using data that existed for other stocks of these species, provided by the Department of Fisheries, Western Australia.

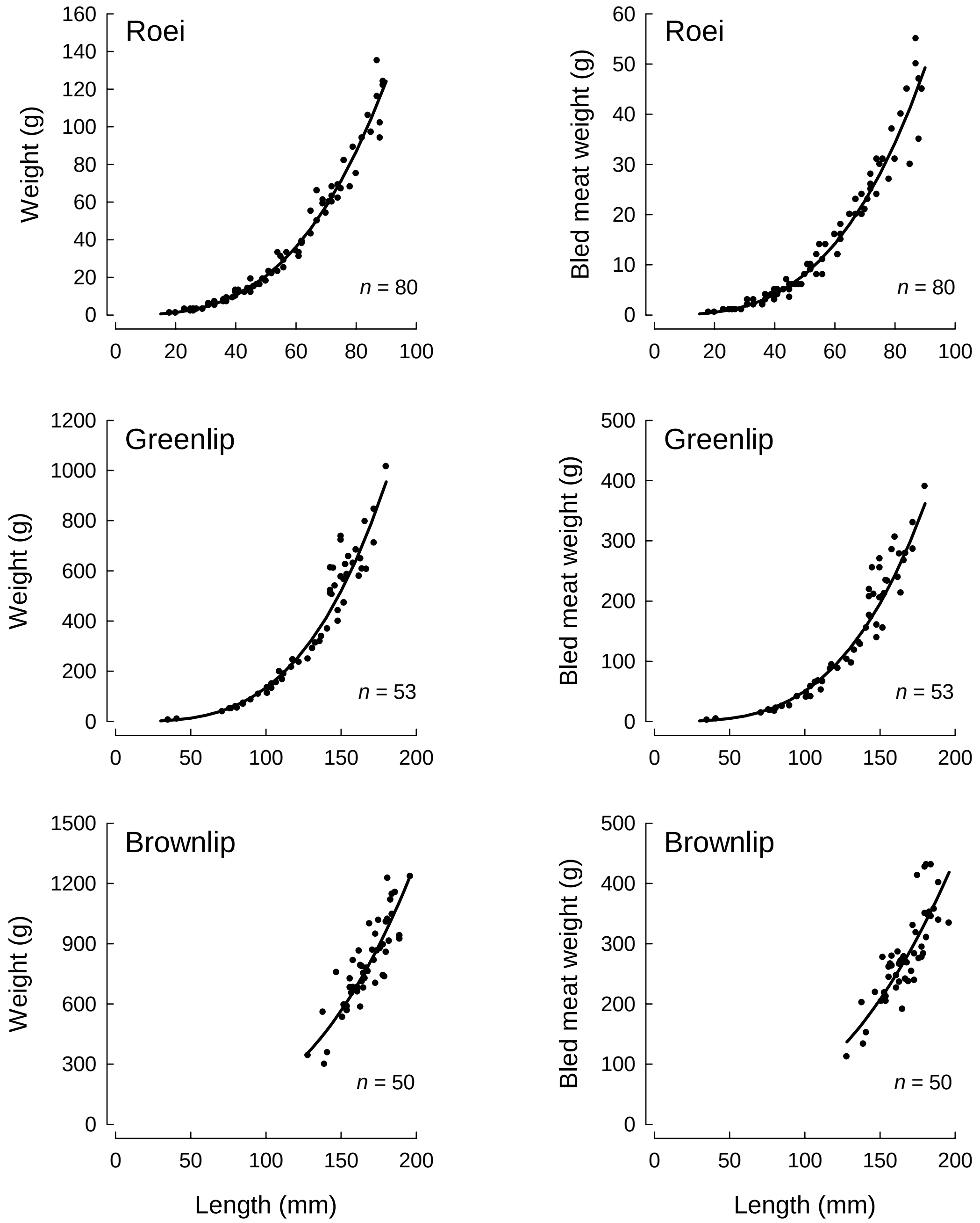

Figure 3.2 Relationships between length and the total wet weight and bled meat weight for the three species of abalone. The curves were produced by fitting linear regressions to the natural logarithms of the individual shell lengths and weights, back-transforming the weights predicted by the linear regression equations and a bias correction. n = number of abalone.

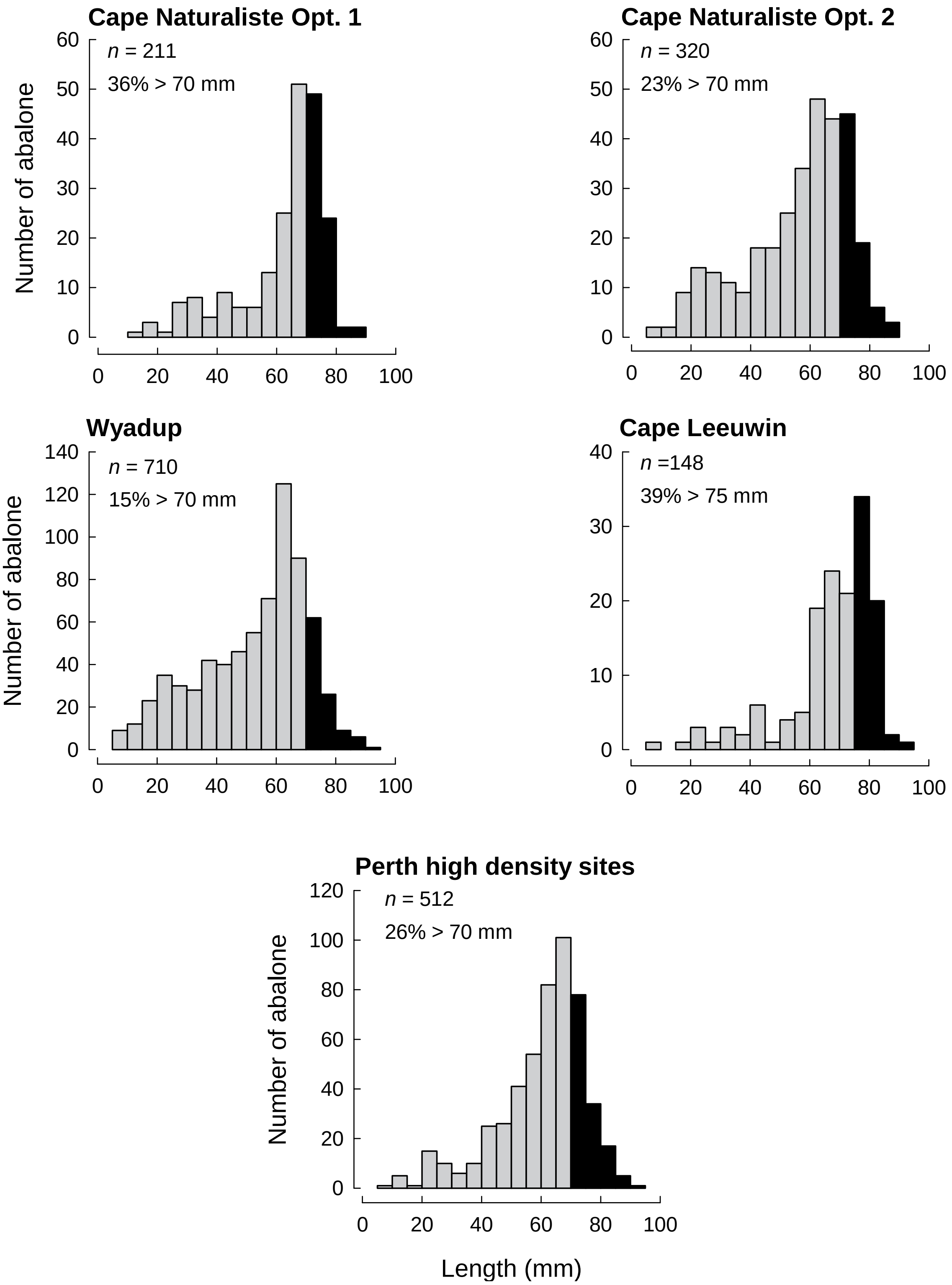

Figure 3.3 Length-frequency histograms for Roei measured during the surveys in the proposed sanctuaries of the Capes region for which significant, currently commercially fished stocks were identified, and for Roei in high density areas near Perth, which were used to represent two strata for Cape Naturaliste Option 1 and one strata for Cape Leeuwin that could not be sampled. Roei above 75 mm (harvest size) are highlighted in black. n refers to sample size.

The length frequency data for the Perth metropolitan area for sites containing high Roei densities and which were used to represent the three strata in the proposed sanctuaries that could not be sampled, had a similar proportion (26%) of animals above the minimum size that is commercially-harvested (70 mm) to that for Roei at Cape Naturaliste Option 2.

Almost half of the Greenlip in the proposed sanctuaries at Flinders Island, Cape Leeuwin, and Cosy Corner and Cape Freycinet (data combined for the latter two areas due to low sample sizes) were above the minimum size at which this species is commercially harvested (150 mm) (44, 42 and 46%, respectively, Figure 3.4). A similar situation was recorded for Brownlip, with about half (49%) of the individuals being of harvestable size (Figure 3.4). Note that that no weighting has been applied for pooling of data.

3.4 Biomass per unit area of Roei, Greenlip and Brownlip in the proposed sanctuaries

The mean biomass (kg / 100 m^2) have been calculated for each species of abalone above their respective sizes at maturity and minimum sizes at which they are commercially harvested. The mean biomass (mean kg total body weight / 100 m^2) for mature (> 45 mm) Roei was highest at Cape Leeuwin (142), followed by Cape Naturaliste Option 1 (125), Wyadup (67) and Cape Naturaliste Option 2 (56) (Figure 3.5). The mean biomass for commercial harvest-sized Roei (> 70 mm at Cape Naturaliste options 1 and 2 and Wyadup, 75 mm at Cape Leeuwin) was substantially higher at Cape Leeuwin (95) than at all other sanctuaries and was far higher for Cape Naturaliste Option 1 (53) than for Cape Naturaliste Option 2 (18) and Wyadup (16). The relative difference between the estimates of mature and harvest biomass 100 m^2 of Roei was least at Cape Leeuwin and greatest at Wyadup. Note that the estimated densities for two strata at Cape Naturaliste Option 1 and one at Cape Leeuwin were taken from data for the Perth metropolitan region.

The mean biomasses (kg bled meat weight / 100 m^2) for mature Greenlip (> 95 mm) were far higher at Cape Leeuwin (1.6) and Flinders Island (1.4), than at Cape Freycinet (0.6) and Cosy Corner (0.3) (Figure 3.5). The biomasses of commercial harvest-sized Greenlip (> 150 mm) were also higher at Flinders Island (0.8) and Cape Leeuwin (0.7) than at Cape Freycinet (0.5) and Cosy Corner (0.2). The biomasses of mature and commercial harvest-sized Greenlip were very low and nil, respectively in the low priority strata.

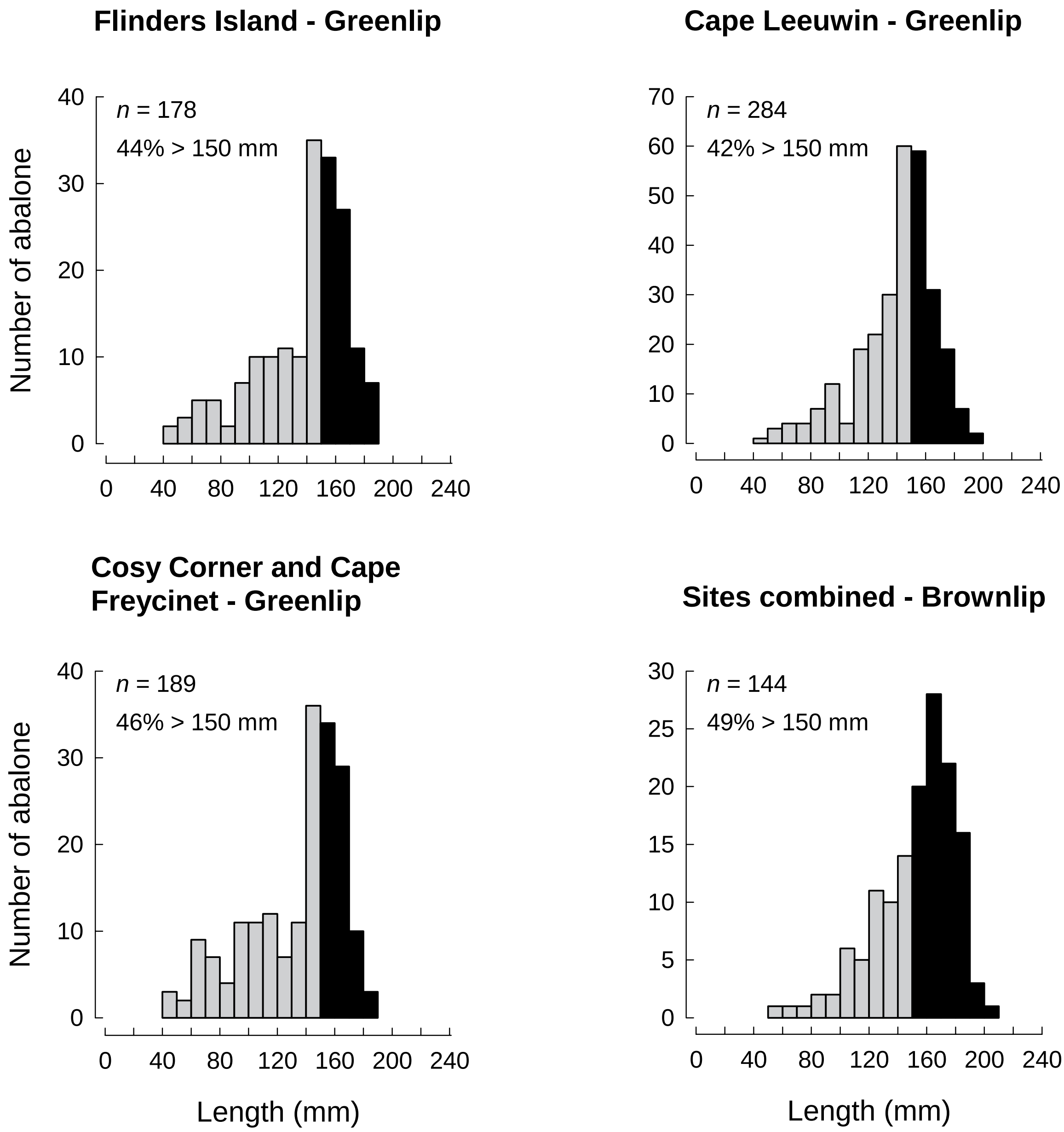

Figure 3.4 Length-frequency histograms for Greenlip and Brownlip measured during the surveys in the proposed sanctuaries of the Capes region for which currently fished, commercial stocks were identified. Data have been pooled for sanctuaries with low sample sizes of each species. Abalone above 150 mm (harvest size) are highlighted in black. n refers to sample size.

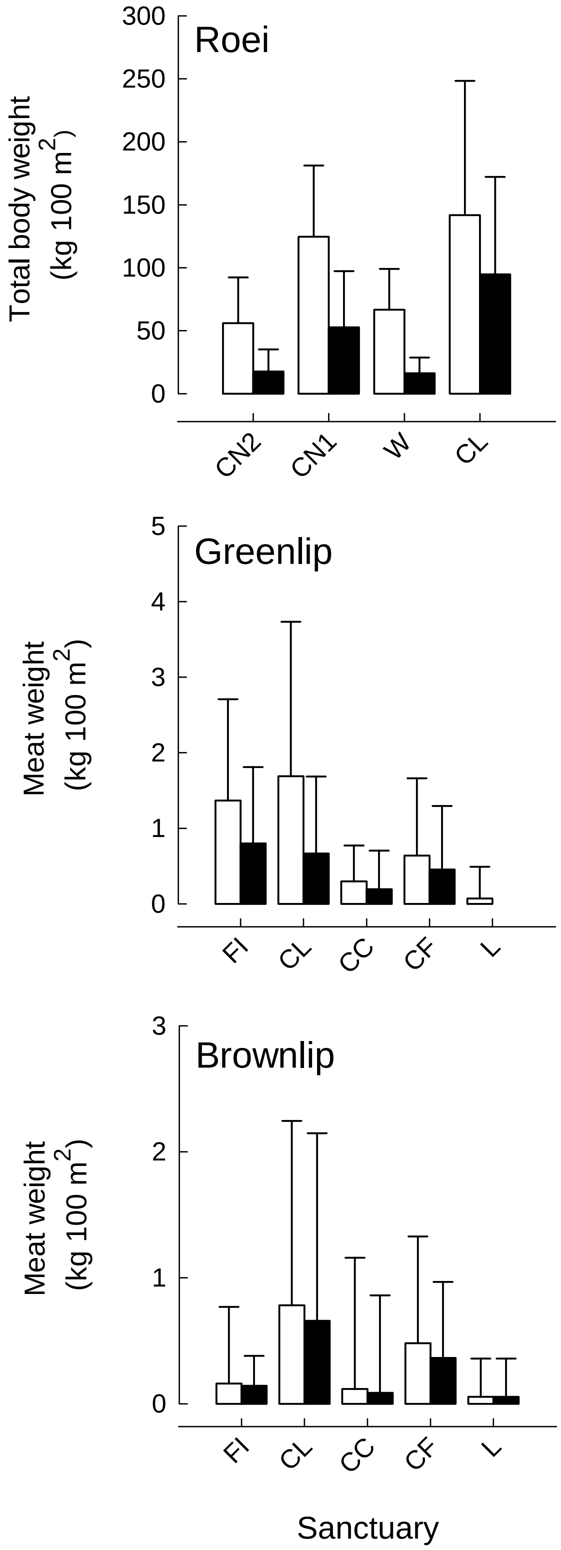

Figure 3.5 Mean biomass (kg 100 m^2) and upper 95% confidence intervals for mature (white bars) and harvest-sized (black bars) Roei, Greenlip and Brownlip, determined from the biomass estimates calculated using the survey data and applying a delta-log transformation. CN2, Cape Naturaliste Option 2; CN1, Cape Naturaliste Option 1; W, Wyadup; CL, Cape Leeuwin; CC, Cosy Corner; CF, Cape Freycinet; FI, Flinders Island; L, Low priority strata for Greenlip and Brownlip. Estimates for Roei in CN1 and CL have been adjusted using data for high Roei density sites near Perth.

The mean biomass (kg bled meat weight / 100 m^2) for mature (> 125 mm) and commercial harvest-sized (> 150 mm) Brownlip was greatest at Cape Leeuwin (0.8 and 0.7, respectively) and Cape Freycinet (0.5 and 0.4, respectively) and very low for the remaining sanctuaries and low priority strata (Figure 3.5).

3.5 Estimates of biomass of abalone in the proposed sanctuaries

For each species, estimates of total, mature, legal and commercial harvest biomass have been derived from (1) using the survey data alone and (2) using the survey data, and commercial catch data provided by fishers for the 2006/07 fishing season (Tables 3.1 to 3.3). The estimates of mature and harvest biomass are discussed below, as they provide the basis for calculating the biologically sustainable catch biomass and current annual catch.

3.5.1 Roei

The respective point estimates for mature and commercial harvest biomass of Roei in the proposed sanctuaries (in kg, total weight) from survey data alone were highest at Wyadup (32,574 and 7,965), followed by Cape Naturaliste Option 1 (12,975 and 5,490), Cape Naturaliste Option 2 (10,019 and 3,164) and Cape Leeuwin (1,064 and 710) (Table 3.1). The respective estimates were slightly higher for the combination of all sanctuaries surveyed excluding Cape Naturaliste Option 2, *i.e.* 46,613 and 14,165 than for all sanctuaries excluding Cape Naturaliste Option 1, *i.e.* 43,657 and 11,839 (Table 3.1). When catches were taken into account, the estimates of mature and commercial harvest biomass increased substantially for Cape Naturaliste Option 1 (15,458 and 7,186) and Wyadup (37,043 and 9,881) and slightly for Cape Naturaliste Option 2 (11,386 and 3,558). Overall, the estimates of mature and harvest biomass were 53,565 and 17,777, respectively, for all sanctuaries surveyed excluding Cape Naturaliste Option 2 and 49,493 and 14,149, respectively, for all sanctuaries excluding Cape Naturaliste Option 1 (Table 3.1). The 95% confidence intervals for biomass estimates were broad (Table 3.1).

3.5.2 Greenlip and Brownlip

From the survey data alone, the estimates of mature and commercial harvest biomass in the four sanctuaries surveyed for Greenlip and Brownlip (in kg, bled meat weight) were highest for Greenlip at Cape Leeuwin (3,000 and 1,181), followed by Flinders Island (983 and 574), Cape Freycinet (500 and 355) and Cosy Corner (355 and 232) (Table 3.2, 3.3). No commercial harvest

Table 3.1 Estimates, derived from the survey data, of total, mature (> 41 mm shell length, SL), legal (> 60 mm SL) and harvest (> 70 mm SL in all sanctuaries except 75 SL mm for Cape Leeuwin) biomass (in kg, total weight) for Roei in (i) each of the strata of the proposed Cape Naturaliste, Wyadup and Cape Leeuwin sanctuaries, (ii) for all strata (± 95% confidence intervals) in each of those sanctuaries, and (iii) sum of the point estimates for each sanctuary, excluding one of either of the two options for Cape Naturaliste. Biomass estimates adjusted for commercial catches taken from the proposed sanctuaries in the 2006/07 fishing season are provided for each sanctuary zone, and for all sanctuaries, excluding one of either of the two options for Cape Naturaliste. *** Denotes strata that could not be sampled and for which biomass estimates were produced using data from the Perth metropolitan region.

		Biomass estimates from survey data only				Biomass estimates from survey and catch data			
Strata	Strata area	Total	Mature	Legal	Harvest	Total	Mature	Legal	Harvest
Cape Naturalise Option 2									
A	2,700	3,139	3,038	2,219	1,007				
BA	4,200	2,017	1,931	1,237	537				
BB	11,000	5,052	4,927	3,546	1,375				
Totals	**17,900**	**10,390**	**10,019**	**7,253**	**3,164**	**11,776**	**11,386**	**8,130**	**3,558**
± 95% CIs		6,621-17,491	6,248-16,519	4,494-11,959	1,666-6,294	7,145-20,362	6,939-19,279	5,179-14,161	2,085-7,435
Cape Naturaliste Option 1									
BC	3100	7,581	2,142	2,135	561				
C	5000	19,186	3,307	3,528	1,953				
D***	320	918	881	657	297				
E***	2000	6,504	6,402	5,482	2,505				
Totals	**10,420**	**36,542**	**12,975**	**12,211**	**5,490**	**43,149**	**15,458**	**14,434**	**7,186**
± 95% CIs		16,967-126,497	9,984-18,869	8,779-19,831	3,704-10,141	18,891-123,689	11,779-21,703	10,777-24,600	5,123-13,203
Wyadup									
GA	33000	31,083	26,652	17,527	5,612				
GB	15700	6,788	4,912	4,185	2,205				
GC	160	640	683	558	64				
Totals	**48,860**	**38,478**	**32,574**	**22,402**	**7,965**	**45,051**	**37,043**	**26,202**	**9,881**
± 95% CIs		25,013-58,658	22,191-48,428	15,110-33,546	5,169-14,001	30,221-68,034	26,148-56,739	17,645-37,207	6,424-16,104
Cape Leeuwin									
HA	430	406	336	321	154				
HB***	320	748	718	617	521				
Totals	**750**	**1,152**	**1,064**	**944**	**710**	**1,152**	**1,064**	**944**	**710**
± 95% CIs		686-1,934	642-1,862	526-1,818	337-1,291	686-1,934	642-1,862	526-1,818	337-1,291
All sanctuaries excluding Cape Naturaliste Option 2									
Sum of sanctuary point estimates		**76,172**	**46,613**	**35,557**	**14,165**	**89,352**	**53,565**	**41,580**	**17,777**
All sanctuaries excluding Cape Naturaliste Option 1									
Sum of sanctuary point estimates		**50,020**	**43,657**	**30,599**	**11,839**	**57,979**	**49,493**	**35,276**	**14,149**

Table 3.2. Estimates (± 95% confidence intervals) of total, mature (> 95 mm shell length, SL), legal (> 140 mm SL) and harvest (> 150 mm SL) biomass (in kg, bled meat weight) for Greenlip, derived from (i) the survey data and (ii) survey data adjusted using information provided by commercial fishers on their catches taken from the proposed sanctuaries between January and June of 2007. For each sanctuary, biomass estimates have been pooled for all high priority strata (i.e. those determined using GPS locations provided by fishers). Low priority strata (i.e. those determined without GPS locations provided by fishers) have been pooled for all sanctuaries.

		Survey biomass estimates				Estimates adjusted for catch			
	Strata area	**Total**	**Mature**	**Legal**	**Harvest**	**Total**	**Mature**	**Legal**	**Harvest**
				Flinders Island - high priority strata					
Estimates	71,922	1,136	983	771	574	1,447	1,214	970	755
± 95% CIs		540-2,343	478-1,947	406-1,648	298-1,301	723-3,052	640-2,295	559-1,875	434-1,444
				Cape Leeuwin - high priority strata					
Estimates	177,545	3,558	3,000	1,876	1,181	4,277	3,604	2,380	1,591
± 95% CIs		1,574-7,757	1,516-6,624	1,046-4,299	612-2,989	2,227-10,158	1,852-7,810	1,342-4,776	970-3,159
				Cosy Corner - high priority strata					
Estimates	120,059	669	355	264	232	924	647	564	551
± 95% CIs		206-2,093	159-925	117-785	93-845	461-2,569	414-1,330	444-1,013	444-1,113
				Cape Freycinet - high priority strata					
Estimates	78,347	714	500	402	355	714	500	402	355
± 95% CIs		217-2,388	177-1,301	127-1,206	103-1,013	217-2,388	177-1,301	127-1,206	103-1,013
				Low priority strata - all sanctuaries					
Estimates	424,022	297	297	181	0	297	297	181	0
± 95% CIs		148-2,077	148-2,077	1,264	0-0	148-2,077	148-2,077	1,264	0-0
				All sanctuaries					
Sum of point estimates		**6,374**	**5,135**	**3,494**	**2,342**	**7,659**	**6,262**	**4,497**	**3,252**

Table 3.3 Estimates (± 95% confidence intervals) of total, mature (> 125 mm shell length, SL), legal (> 140 mm SL) and harvest (> 150 mm SL) biomass (in kg, bled meat weight) for Brownlip abalone, derived from (i) the survey data and (ii) survey data adjusted using information provided by commercial fishers on their catches taken from the proposed sanctuaries between January and June of 2007. For each sanctuary, biomass estimates have been pooled for all high priority strata (i.e. those determined using GPS locations provided by fishers). Low priority strata (i.e. those determined without GPS locations provided by fishers) have been pooled for all sanctuaries.

		Survey biomass estimates				Estimates adjusted for catch			
	Strata area	**Total**	**Mature**	**Legal**	**Harvest**	**Total**	**Mature**	**Legal**	**Harvest**
				Flinders Island - high priority strata					
Estimates	71,922	148	115	110	102	180	139	124	125
± 95% CIs		52-573	43-553	41-570	38-274	66-578	60-675	55-268	50-421
				Cape Leeuwin - high priority strata					
Estimates	177,545	1,431	1,386	1,253	1,168	1,799	1,719	1,639	1,463
± 95% CIs		653-4,003	590-3,986	556-3,418	485-3,813	883-5,007	813-3,920	849-4,308	767-4,133
				Cosy Corner - high priority strata					
Estimates	120,059	164	139	139	103	223	196	195	155
± 95% CIs		82-1,643	66-1,391	66-1,391	52-1,033	127-1,918	113-1647	114-1,649	97-1,228
				Cape Freycinet - high priority strata					
Estimates	78,347	395	377	289	285	395	377	289	285
± 95% CIs		147-1,068	138-1,041	117-749	105-757	147-1,068	138-1,041	117-749	105-757
				Low priority strata - all sanctuaries					
Estimates	424,022	278	232	232	232	278	232	232	232
± 95% CIs		97-1,515	97-1,515	97-1,515	97-1,515	97-1,515	97-1,515	97-1,515	97-1,515
				All sanctuaries					
Sum of point estimates		**2,416**	**2,249**	**2,023**	**1,890**	**2,875**	**2,663**	**2,479**	**2,260**

biomass was recorded for Greenlip in samples taken from the low priority areas. The mature and commercial harvest biomass of Brownlip were highest at Cape Leeuwin, *i.e.* 1,386 and 1,168, but low (< 400 total and harvest biomass) in all other sanctuaries surveyed. The overall estimates for mature and commercial harvest biomass, excluding catch, were 5,135 and 2,342, respectively, for Greenlip and 2,249 and 1,890, for Brownlip. When reported catches were taken into account, the respective estimates of mature and commercial harvest biomass for Greenlip had increased to 1,214 and 755 for Flinders Island, 3,604 and 1,591 for Cape Leeuwin and 647 and 551 for Cosy Corner. For Brownlip, these had increased to 139 and 125 for Flinders Island, 1,719 and 1,463 for Cape Leeuwin and 196 and 155 for Cosy Corner. The overall estimates of mature biomass, taking catch into account increased by about 1,000 kg for Greenlip (to 6,262 and 3,252 kg) and by about 400 kg for Brownlip (2,663 and 2,260 kg, Tables 3.2, 3.3).

The proportion of commercial harvest biomass to mature biomass in the proposed sanctuaries was lower for Roei than for both Greenlip and Brownlip (Tables 3.1 to 3.3). Thus, for example, from the biomass estimates alone, the ratio of harvest biomass to mature biomass for Roei in all sanctuaries sampled excluding either Cape Naturaliste Option 1, or Cape Naturaliste Option 2 was 0.30 : 1, and 0.29 : 1, respectively, but was 0.46 : 1 for Greenlip and as high as 0.84 : 1 for Brownlip (for all sanctuaries sampled for Greenlip and Brownlip).

3.6 Estimates of biologically sustainable catch and current annual commercial catch

For each species, estimates are provided for the levels within the proposed sanctuaries of 1.) biologically sustainable catch, *i.e.* based on reference point analyses and 2.) average current annual catch, *i.e.* based on estimates of fishing mortality. The calculations for biologically sustainable catch and current catch estimates have been undertaken for both the survey biomass estimates alone, and these estimates, taking catch into account.

3.6.1 Roei

For Roei, the estimates of biologically sustainable catch were similar but mostly slightly higher than those of the current catch (Table 3.4). Thus, for example, if $F_{target} = 0.6F_{limit}$, and on the basis of the biomass estimates derived taking catch into account, the estimates of biologically sustainable catch and current catch were 6,590 and 5,579, respectively, for all sanctuaries combined, excluding Cape Naturaliste Option 2, and 5,770 and 4,770, respectively, for all sanctuaries combined, excluding Cape Naturaliste Option 1. The values determined for biologically sustainable

Table 3.4. Estimates (kg, total weight), for Roei in the proposed sanctuaries, of sustainable catch biomass, as derived from the reference point analyses, and average annual catch, as determined by applying an estimate of F on harvest biomass (estimate of F provided by DoF). Both analyses assume M = 0.25 $year^{-1}$ and were performed on both the biomass estimates derived from the survey data only, and on the biomass estimates adjusted for commercial catches reported from the proposed sanctuaries zones during the 2006/07 fishing season. Confidence intervals have been estimated using re-sampling to take into account uncertainty in the estimates of biomass, M and F. Note that the estimates of sustainable biomass do not take into account the economics of harvesting abalone of different sizes.

	Estimates derived using survey data only		**Estimates derived using survey data and information on commercial catches**	
	Estimates of biologically sustainable catch	Estimates of biomass of current catch	Estimates of biologically sustainable catch	Estimates of biomass of current catch
	$F_{target\ t}$ = 0.6 F_{limit} or = 0.75 F_{limit}	F = 0.34-0.54 $year^{-1}$	$F_{target\ t}$ = 0.6 or 0.75 F_{limit}	F = 0.34-0.54 $year^{-1}$
	Cape Naturalise Option 2			
Estimate	1,140 or 1,430	999	1,240 or 1,670	1,164
± 95% CIs		543-2,012		636-2,254
	Cape Naturaliste Option 1			
Estimate	1,650 or 2,040	1,774	2,060 or 2,360	2,273
± 95% CIs		1,123-3,453		1,523-4,145
	Wyadup			
Estimate	4,250 or 4,550	2,522	4,400 or 5,550	3,083
± 95% CIs		1,566-4,488		2,007-5,198
	Cape Leeuwin			
Estimate	130 or 150	223	130 or 150	223
± 95% CIs		123-440		123-440
	All sanctuaries excluding Cape Naturaliste Option 2			
Sum of estimates	**6,030 or 6,740**	**4,519**	**6,590 or 8,160**	**5,579**
	All sanctuaries excluding Cape Naturaliste Option 1			
Sum of estimates	**5,520 or 6,130**	**3,744**	**5,770 or 7,370**	**4,470**

catch and current catch were greatest when catch was taken into account, and were highest at Wyadup, followed by Cape Naturaliste Option 1, Cape Naturaliste Option 2 and Cape Leeuwin (Table 3.4; Figure 3.6).

3.6.2 Greenlip and Brownlip

As with Roei, the estimates of biologically sustainable catch were similar to those derived by applying fishing mortality for Greenlip, but the former was less for Brownlip (Tables 3.5, 3.6). For example, if $F_{target} = 0.6F_{limit}$, and on the basis of the biomass estimates (kg, bled meat weight) derived by taking catch into account, the estimates of biologically sustainable catch and current catch in all sanctuaries combined were 730 and 993, respectively, for Greenlip and 300 and 557, respectively, for Brownlip (Table 3.5,3.6). The values for biologically sustainable catch and current catch were slightly greater when catch was taken into account, and were greatest for both species in the proposed sanctuary at Cape Leeuwin.

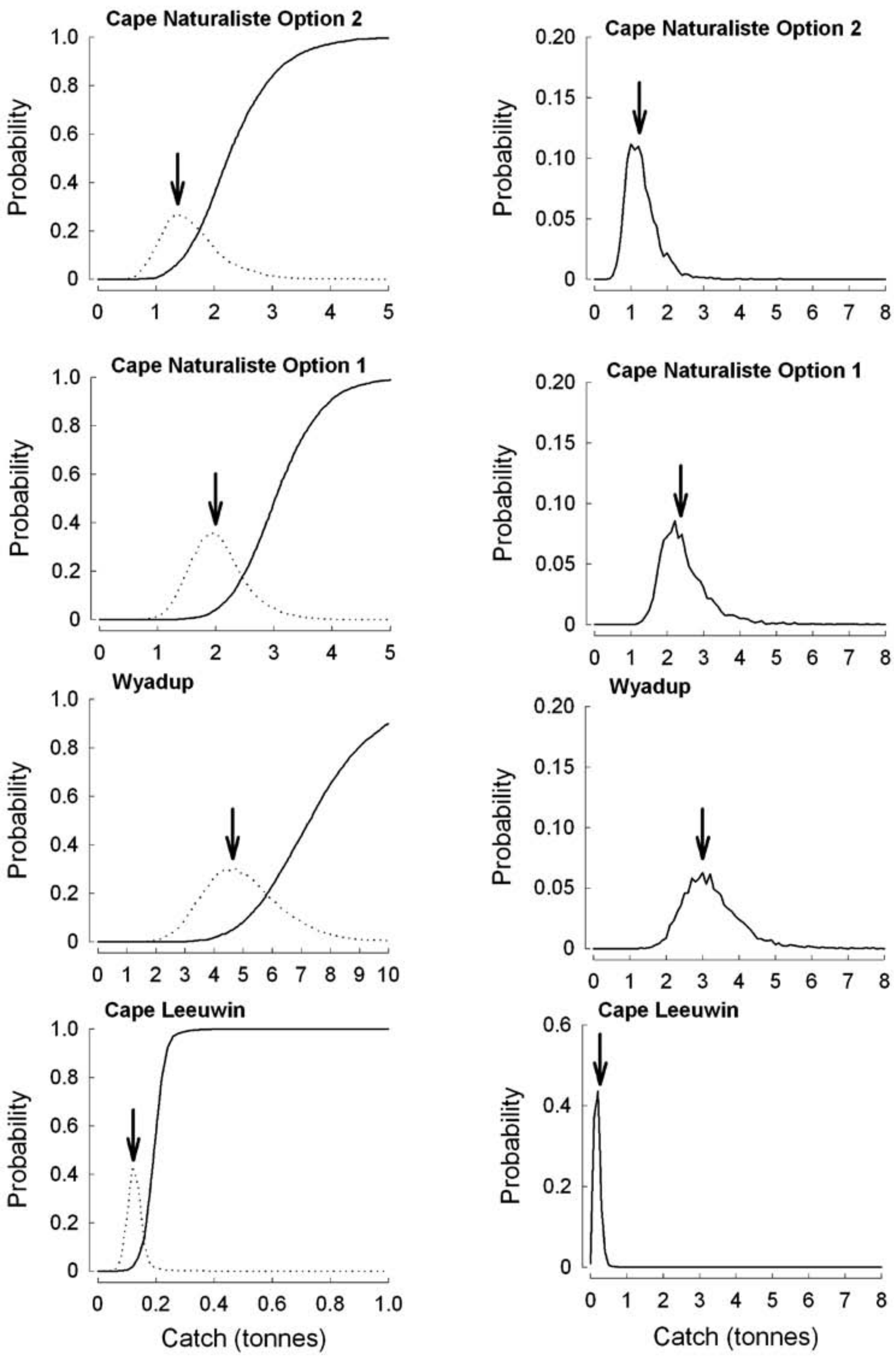

Figure 3.6 Sustainable biomass (figures on the left), calculated from reference point analyses, and estimated annual catch (figures on right), as determined from estimates of fishing mortality and biomass, for Roei (tones, total weight) in the proposed sanctuaries of the Capes region. Trends in this figure are based on the biomass estimates employing both survey and catch data. Solid and dotted lines refer to the probability (expressed as a percentage), respectively, of each level of catch exceeding the limit reference point (F=M) and falling with 10% of the target reference point (F=0.6*Limit reference point). Arrows are used to highlight point estimates of sustainable catches and estimated annual catches.

Table 3.5 Estimates (kg, bled meat weight), for Greenlip in the proposed sanctuaries, of sustainable catch biomass, as derived from the reference point analyses, and average annual catch, as determined by applying an estimate of F on harvest biomass (estimate of F provided by DoF). Both analyses assume M = 0.25 $year^{-1}$ and were performed on both the biomass estimates derived from the survey data, and biomass estimates adjusted for commercial catches reported from the proposed sanctuaries during the 2006/07 fishing season. Confidence intervals have been estimated using re-sampling to take into account uncertainty in the estimates of biomass, M and F. Note that the estimates of sustainable biomass do not take into account the economics of harvesting abalone of different sizes.

	Estimates derived using survey data only		**Estimates derived using survey data and information on commercial catches**	
	Estimates of biologically sustainable catch	Estimates of biomass of current catch	Estimates of biologically sustainable catch	Estimates of biomass of current catch
	$F_{targe\ t} = 0.6\ F_{limit}$ or $= 0.75\ F_{limit}$	F = 0.34-0.49 $year^{-1}$	$F_{targe\ t} = 0.6$ or $0.75\ F_{limit}$	F = 0.34-0.49 $year^{-1}$
		Flinders Island		
Estimate	130 or 130	174	140 or 160	228
± 95% CIs		89-356		129-431
		Cape Leeuwin		
Estimate	350 or 410	356	440 or 510	495
± 95% CIs		193-792		277-980
		Cosy Corner		
Estimate	30 or 30	74	80 or 90	169
± 95% CIs		31-243		128-330
		Cape Freycinet		
Estimate	50 or 50	101	50 or 50	101
± 95% CIs		30-303		30-303
		Low priority		
Estimate	20 or 20	0	20 or 20	0
± 95% CIs				
		All sanctuaries		
Sum of estimates	**580 or 640**	**705**	**730 or 830**	**993**

Table 3.6 Estimates (kg, bled meat weight), for Brownlip abalone in the proposed sanctuaries, of sustainable catch biomass, as derived from the reference point analyses, and average annual catch, as determined by applying an estimate of F on harvest biomass (estimate of F provided by DoF). Both analyses assume M = 0.25 year-1 and were performed on both the biomass estimates derived from the survey data, and on the biomass estimates adjusted for commercial catches reported from the proposed sanctuaries during the 2006/07 fishing season. Confidence intervals have been estimated using re-sampling to take into account uncertainty in the estimates of biomass, M and F. Note that the estimates of sustainable biomass do not take into account the economics of harvesting abalone of different sizes.

	Estimates derived using survey data only		Estimates derived using survey data and information on commercial catches	
	Estimates of biologically sustainable catch	Estimates of biomass of current catch	Estimates of biologically sustainable catch	Estimates of biomass of current catch
	$F_{targe\ t} = 0.6\ F_{limit}$ or $= 0.75\ F_{limit}$	$F = 0.29\text{-}0.37$ year^{-1}	$F_{targe\ t} = 0.6\ F_{limit}$ or $= 0.75\ F_{limit}$	$F = 0.29\text{-}0.37$ year^{-1}
		Flinders Island		
Estimate	10 or 10	25	10 or 10	30
± 95% CIs		9-134		13-101
		Cape Leeuwin		
Estimate	180 or 180	297	210 or 230	363
± 95% CIs		117-702		188-1,029
		Cosy Corner		
Estimate	10 or 10	25	20 or 20	38
± 95% CIs		11-282		22-318
		Cape Freycinet		
Estimate	40 or 40	70	40 or 40	70
± 95% CIs		28-186		28-186
		Low priority		
Estimate	20 or 20	56	20 or 20	56
± 95% CIs		26-445		26-445
		All sanctuaries		
Estimate	**260 or 260**	**473**	**300**	**557**

4.0 Discussion

The procedures to estimate the levels of catch in the proposed sanctuaries involve many steps and assumptions. The overall approach and important assumptions are discussed before the estimates of catches foregone in the proposed sanctuaries are documented and interpreted in sections 4.3 and 4.4.

4.1 Preliminary sample size analyses

As the preliminary analyses for sample size, based on the existing DoF data for Roei and Greenlip, demonstrated that the RSE for mean density declined substantially as the number of replicate samples increased from 4 to 20, but declined only marginally with further increases in sample size, ~20 replicates is likely to be a sufficient sample size for these two species. In the case of Roei, for which between 20 to 48 replicate quadrats were able to be sampled in each sanctuary zone, the RSE values (as determined using untransformed survey data for mean density of all sizes – data not shown) ranged between 17 and 29. For Greenlip, for which between 16 and 38 replicate transects (pooled data for the two 30 x 1m transects at each site) were recorded for each sanctuary zone, the RSE values ranged between 27 and 41. It is likely that the higher RSE values for Greenlip than Roei are due to greater natural variability in Greenlip densities in the proposed sanctuaries.

The RSE values for Brownlip, which were sampled at the same sites and times as Greenlip, were often higher than for Greenlip, probably because of the lower abundances and more patchy distribution of Brownlip in the proposed sanctuaries than Greenlip. It should also be noted that the RSE values for all species are lower than those reported when derived using transformed data (as we used for the biomass analyses) than untransformed data.

4.2 Sampling design

4.2.1 Identification of sampling areas through commercial fisher knowledge

Due to the short time line for our study (approximately 9 months to design and undertake the surveys, and to analyse the results), it was not feasible to undertake a rigorous, systematic approach to survey for abalone stocks in each of the proposed sanctuaries of the Capes marine park, as was undertaken by Carlson *et al*. (2006). In our study, we thus identified those locations within the sanctuaries that house abalone in commercial quantities through approaching those fishers with knowledge of those locations. The information provided to us independently by different fishers on the locations of abalone stocks within the proposed sanctuaries was very consistent, which provides us with some confidence that the areas identified in this way contained the most important abalone stocks. We thus consider that our approach of employing fisher knowledge in a study such as ours was very effective.

Although there is a possibility that, in some circumstances, there may be disincentives for certain fishers to provide accurate information on the location of abalone stocks in areas proposed as future sanctuaries, we believe the biomass estimates produced in this study point very strongly to the conclusion that the areas within the proposed sanctuaries identified by commercial fishers were indeed those which contained the most important abalone stocks. In this context, it is relevant that the previous estimates provided by industry of loss of product through implementing the proposed sanctuaries in the Capes region were higher than those derived by DoF based on the commercial log book data.

4.2.2 Prioritisation of sampling areas

As outlined in section 2.1, we have prioritised our sampling in those areas which, on the basis of the consensus of information provided by the commercial fishers, were considered to be currently commercially-fished. All areas identified by the commercial fishers were sampled for Roei, except for 1) two strata at Cape Naturaliste Option 1 and at Cape Leeuwin, which were unable to be sampled due to weather conditions and for which data from the metropolitan region were used as a surrogate (see methods) and 2) Cowaramup Bay, a recreation zone, which thus would not be accessible to commercial fishers operating in the Capes Marine Park. Although the Roei fishers interviewed mostly indicated that this area has been left by the commercial abalone industry to recreational fishers, and that it has not been fished commercially for a number of years, there was a view put forward that at least one commercial fisher still operates in Cowaramup Bay.

The decision to target our sampling for Greenlip and Brownlip largely towards those (high priority) areas identified by fishers through the provision of GPS positions was based on our view that these are the locations that are most likely to be currently fished. As GPS data were not provided for those sanctuaries in the northern part of the Capes region and for which the commercial log book data clearly show that almost no Greenlip and Brownlip have been taken from these areas over the last 10 years, those northern zones were not sampled. We acknowledge that those areas identified only from fishers' sketches (low priority areas) were not sampled intensively and thus the biomass estimates for those areas are far less reliable than those for the high priority areas.

4.2.3 Rationale for sampling methodology for Roei

The method used to sample Roei followed the standard methodology employed by DoF to survey this species, *i.e.* systematic sampling using quadrats placed at equally-spaced intervals along transect lines (*e.g.* Hancock, 2004). We decided to use systematic sampling for Roei, as this method was likely to enable more quadrats to be sampled during the short time available in the project for sampling, *i.e.* less moving between sampling locations, and as DoF staff routinely use this methodology in their Roei stock monitoring programs in the Perth metropolitan region. There is some debate as to whether it is more appropriate to use random sampling (or stratified random sampling) rather than systematic sampling. If neighbouring sampling units are not independent, it is not as statistically appropriate to assess error (Bourdeau, 1954). However, some workers argue for systematic sampling due to its ease of applicability in the field and their belief that such sampling is more likely to include the variations of the population throughout the habitat, and in some cases, this has been demonstrated to be true (see Bourdeau, 1954). A major determinant of the variability in Roei density and size is the offshore habitat gradient (Hancock, 2004). As, in the Capes region, Roei typically occur over a very narrow band along shore (~ 6 m wide), systematic sampling would have helped ensure the habitats were sampled adequately. We acknowledge the potential that our samples were not completely statistically-independent. If this was the case, the estimates of error for the calculated values of biomass will be underestimated. There would also be value in comparing various other statistical approaches for determining abundance or biomass of Roei, *e.g.* kriging.

4.2.4 Rationale for sampling methodology for Greenlip and Brownlip

Our sampling approach for Greenlip and Brownlip has been adapted from that of McGarvey *et al.* (in press) (outlined in Carlson *et al.*, 2006) and proved a very time efficient method of sampling these species. In developing the sampling design, an alternate approach was discussed, where patches of abalone were identified, mapped and the biomass of each patch estimated. The latter approach was not considered feasible, primarily due to the short time constraints of the project. However, if future surveys are undertaken, habitat maps and distribution maps for abalone would be valuable.

4.3 Implications of the biomass estimates for the three abalone species

4.3.1 Comparisons between biomass estimates determined with and without commercial catch

As demonstrated by the results of the biomass analyses, all three species occur in commercial quantities in the proposed sanctuaries. Estimates of biomass have been determined using the survey data only and by using both the survey data and reported catches from the proposed sanctuaries. The biomass method from survey data alone assumes that the stock is in equilibrium under the processes of growth, recruitment and fishing mortality, and thus the estimates of biomass derived by this method represent the biomass available at the mid-point of the survey. In contrast, the biomass estimate taking catch into account, assumes that the period from the start of the fishing season to the mid-point of the survey was of such a short duration that growth was negligible (and thus growth had minimal influence on the biomass estimates), the population was closed to recruitment and migration, and that the survey estimate of biomass represents the survival of abalone from both fishing and natural mortality (see appendix 3 for more detail). As the abalone season in the Capes region for the three species concentrated at certain periods of the year, we consider the approach which takes into account commercial catches is the most appropriate method for estimating biomass. The commercial abalone fishers also believe strongly that information on their catches needs to be included in the biomass estimates.

A major difference between the two methods is that the estimate that takes catch into account relies on the accuracy of the reported values of commercial catches taken from the proposed sanctuaries. Although it is not possible to validate completely the reported commercial catch values, they are, as far as can be compared, consistent with the fisher log book data held by DoF. Furthermore, the catch information is entirely consistent with the estimates of biomass derived using the survey data, both overall (1,487 kg whole weight for Roei, and 525.5 and 195 kg bled meat weight, respectively, for Greenlip and Brownlip) and for each proposed sanctuary, *i.e.* estimates were only reported for those sanctuaries that were surveyed (with one exception, a catch of 253 kg of Roei reported from the Injidup sanctuaries, was not included as we have assumed the Injidup sanctuary begins 200 m offshore, as according to the maps of the “Have Your Say” brochure), and the values were almost invariably substantially less than the estimates of harvest biomass calculated using the survey data. Thus, we conclude that the estimates derived by taking catch into account should be used for deriving any estimates of compensation and the results using this estimate are discussed below.

4.3.2 Biomass estimates for Roei

The results from this study highlight that there is substantial harvest biomass of Roei at Wyadup, Cape Naturaliste (at both of the proposed two options) and to a lesser extent, also at Cape Leeuwin. The harvest biomass of Roei (taking catch into account) was greater in the first than second of the proposed options for Cape Naturaliste, *i.e.* 7,186 *vs* 3,558 kg. Furthermore, as the overall area of the strata in which Roei are found at Cape Naturaliste Option 1 (10,420 m^2) is substantially less than at Cape Naturaliste Option 2 (17,900 m^2) (see Table 3), the harvest biomasses per unit area are greater at Cape Naturaliste Option 1 (Figure 5). For the above reasons, Cape Naturaliste Option 1 would be of far more value to commercial Roei fishers than Cape Naturaliste Option 2.

Although the estimate of harvest biomass for Roei was highest at Wyadup (9,881 kg), the overall area in which Roei are found at Wyadup (48,860 m^2) is far larger than, for example, at Cape Naturaliste Option 1. The harvest biomasses per unit area are thus lower for Roei at Wyadup than at Cape Naturaliste Option 1 and the length-frequencies demonstrate that the proportion of Roei above harvest size is far higher at Cape Naturaliste Option 1 (36% harvest size) than at Wyadup (15% harvest size). Thus, the proposed sanctuary at Cape Naturaliste Option 1 may be of greater value to commercial Roei fishers than that at Wyadup.

4.3.3 Biomass estimates for Greenlip and Brownlip

In terms of harvest biomass (taking catch into account), Cape Leeuwin was by far the most important of the proposed sanctuaries for both Greenlip and Brownlip, although the densities of harvest size animals were slightly higher in the areas sampled for Greenlip at Flinders Island than at Cape Leeuwin. Substantial biomass > 200 kg (bled meat weight) of Greenlip was also found in the proposed sanctuaries at Flinders Island, Cosy Corner and Cape Freycinet, and for Brownlip at Flinders Island and Cosy Corner.

4.4 Interpretation of the results of the catch estimates based on harvest fishing mortality and reference point analyses

Two methods have been employed that may potentially provide estimates of the average current annual catch of each abalone species from the proposed sanctuaries. The first employs estimates of fishing mortality for harvest size animals (provided by DoF) and the second employs a reference point analysis. The validity of using the former method depends on the accuracy of the available estimates of fishing mortality, natural mortality, and of harvest biomass. In comparison, the validity of using the reference point method for estimating current annual catch depends on the accuracy of the estimates for natural mortality and mature biomass, on the appropriate choice of reference points (*i.e.* values of F corresponding to the limit and target catch), and on the assumption that the stock is fully-exploited (biologically).

The fact that the catch values produced using the two different methods were similar, in the case of Roei and Greenlip indicate that these two species in the proposed sanctuaries are currently harvested close to, or at full biological exploitation. In the case of Brownlip, the estimates of catch produced by the reference point analyses were higher than those derived by applying the DoF estimates of fishing mortality for harvest size animals (which would indicate over-harvesting), but the data for Brownlip were far less than for the other two species and insufficient to draw a reliable conclusion as to its current level of biological exploitation.

Although both the method of applying *F* on harvest biomass and the reference point based analysis could potentially be used to provide estimates of catch foregone, we consider the estimates of catch forgone derived from the former method are most appropriate. This conclusion is based on our view that use of the reference point analysis for estimating catch forgone should require 1) a sound knowledge of the current levels of biological exploitation of each of the three abalone species in the proposed sanctuaries (which we do not have), and 2) determination, through consultation with all stakeholders, of the most appropriate choice of reference point, as the objectives associated with the choice of reference point are likely to differ between stakeholders.

4.5 Considerations for further research

1. The time line for the current project was very short (*i.e.* ~9 months to design the sampling regime, undertake the analyses and interpret the results). As growth of abalone can be highly variable between locations, it would have been ideal to derive the estimates of mortality used for the subsequent analyses more directly by using age composition data for abalone in the areas in question, or at least, from using growth data derived for abalone from the proposed sanctuaries (see also discussion in appendix 4).
2. The results of many of the analyses in this report are dependant on estimates of natural mortality and fishing mortality that were taken from the literature or from data in other areas. If the proposed sanctuaries are implemented, these would provide an ideal opportunity for further work on to estimate natural mortality for each of the three species in the region, which would be valuable for a variety of purposes.

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6.0 Appendices

Appendix 1. Preliminary analyses for determining required number of samples

A1.1 Data of other abalone stocks employed for the analysis

The available data for Roei were collected by DoF in 2006 from the inner and mid-platform habitats of the Perth metropolitan area. These habitats are most similar to those where Roei are found in the Capes region. The Greenlip data were a subset of the data that had been collected by DoF from Hopetoun in 2003. The decision to use data from Hopetoun, rather than from the Capes region, was based on the fact that the type of sampling used to produce the data subset from Hopetoun was most similar to that employed in this study. In the absence of data from the Capes region, we assumed that the sampling intensity required to achieve a specified relative precision in the estimates of mean abundance for each species would be the same in the Capes Region as in the regions from which the data were drawn. No data were available for Brownlip stocks. It should be noted that, while the analysis guides the design of the sampling protocol, the actual precision of the estimates of abundance would be determined by the distribution of abalone, in combination with the sampling protocol and would be calculated when the resultant data were analysed.

A1.2 Analysis

Using the above data sets, a parametric approach (see Hilborn and Walters, 1992) was used to determine, for both Roei and Greenlip, the relationship between level of uncertainty in estimates of mean density of a species (expressed as relative standard error (RSE), *i.e.* standard error divided by the mean x 100) and sample size. The corresponding density data for Roei and Greenlip were $\log_e(X+1)$ transformed (so that the transformed data were now approximately normally distributed), and the mean and standard deviation then calculated. The “RAND” and “NORMSINV” functions in Microsoft Excel™ were used to draw random $\log_e$-transformed values for samples of abalone density from a normal distribution, as defined by the values calculated for the mean and standard deviation for each species. The randomly drawn values were then back-transformed, and the mean and RSE values calculated for each species with different numbers of samples. The procedure was repeated 500 times by re-sampling from the normal distribution for each species and the median values for the resultant 500 mean and RSE estimates calculated and plotted. The optimal number of samples for a species was selected to be the number of samples where the RSE had declined to a value of 0.2-0.3, *i.e.* 20-30% of the mean.

Appendix 2. Determination of available abalone biomass within commercially-fished areas of the proposed sanctuaries

A2.1 Biomass available to fishers

We have assessed the total biomass available to fishers, $B_{\text{Available}}$, using the survey data only, and using the survey data after adjusting for catches taken from the proposed sanctuaries during the 2006/07 fishing season. It would be appropriate to determine $B_{\text{Available}}$ from the survey data only if the stock was in equilibrium under the processes of growth, recruitment and fishing mortality. As the survey was carried out over a period of time, the biomass estimates produced from the survey results represent estimates of the average total biomass during the survey period. Thus, the biomass values determined from the above analysis provide an estimate of the biomass of abalone in the commercially-fished areas of the proposed sanctuaries at the midpoint of the survey. Therefore, if the assumption that the stock is in equilibrium under fishing is true, $B_{\text{Available}}$ may calculated as: $B_{\text{Available}} = B$, where B is survey biomass estimate (= biomass at the midpoint of the survey).

A2.2 Estimates of abalone biomass from scientific surveys led by DoF

For each category of each of the three abalone species, *i.e.* abalone that were visible (non-cryptic), above mature, legal and minimum harvest size, the mass of each individual abalone whose length was measured during the study was determined using the appropriate length-weight relationship for that species. The biomasses were then summed for all individuals within the category, in each 0.5 m^2 quadrat, in the case of Roei, and for the two pooled 30 x 1 m^2 transects at each site (*i.e.* equivalent of one 60 m transect at each site), in the case of Greenlip and Brownlip. (It should be noted that we have based our calculations for estimating biomass of Roei on data for individual quadrats. This assumes that quadrats along a transect line are independent, and if this is not true, the confidence intervals for the values of biomass have been underestimated).

For each category of each species of abalone, the biomass within each of the areas of the reserves identified as containing significant stocks of abalone (B_i, *i.e.* the biomass of the i^{th} stratum) was determined as $B_i = (1 - p_i)\bar{x}_i \left(A_i / a\right)$, where p_i is the probability that a quadrat (or pooled 60 m transect for Greenlip and Brownlip) within this stratum contains zero biomass, $\bar{x}_i$ is the average biomass in each quadrat of the i^{th} stratum that contains non-zero biomass, A_i is the area of the *i*th stratum (estimated using computer GIS software) and a is the area of each quadrat sampled within the stratum. The values of biomass recorded for the quadrats within the stratum are assumed to have a delta log-normal distribution. Thus the mean value of biomass in each quadrat of the i^{th} stratum for those quadrats with non-zero biomass $\bar{x}_i$ is estimated by back-transforming the mean of the logarithmically-transformed values of the non-zero biomasses $\bar{y}_i$ and correcting for the bias resulting from the transformation, *i.e.* $\bar{x}_i = \exp\left(\bar{y}_i + 0.5 s_{y_i}^2\right)$, where s_{y_i} is the standard deviation of the log-transformed values of the non-zero biomasses within the quadrats for that stratum. The overall biomass of each category of each species in the reserves of the Capes Marine Park was determined as the sum of the biomasses calculated for all strata, *i.e.* $\sum_{i=1}^{N} B_i$ and N is the number of strata.

For greenlip and brownlip, the “high priority” strata in each proposed sanctuary and “low priority” strata across all proposed sanctuaries sampled were pooled for the biomass calculations. We pooled the similar strata for the biomass calculations to increase the precision of the biomass estimates, a strategy which follows that suggested by Pennington (1996) in cases when the lognormal model is used and sample sizes are low. We did not consider it appropriate to combine the strata for the biomass calculations for Roei as differences in the habitats of the strata, *i.e.* level of exposure, are known to be an important factor affecting the localised abundance/biomass of this species.

Estimates of the confidence limits for the estimate of total biomass for each category of abalone of each species were calculated by drawing random estimates of the biomass within each stratum from the associated delta log-normal distributions and summing these to produce 1000 estimates of total biomass. For the *i*th stratum, randomly-selected values of p_i and $\bar{y}_i$ were drawn from the distributions of the estimated values of these parameters and combined, as described above, to derive each random estimate of the biomass within each stratum. For this calculation, it was assumed that the observed number of quadrats with zero biomass in the sampled number of quadrats for each stratum represents a sample from a binomial distribution. Values of $\bar{y}_i$ were drawn from the normal distribution for the mean of the log-transformed biomass in quadrats with non-zero biomass, where the standard error of this mean was calculated by dividing s_{y_i} by the square root of the number of such quadrats. The point estimate and 95% confidence intervals were taken as the median and 2.5 and 97.5 percentiles, respectively, of the 1,000 estimates of biomass of abalone.

A2.3 Rationale for assuming a delta-log distribution for producing biomass estimates from the survey data

A preliminary inspection of the biomasses recorded for each species in the survey samples demonstrated that, as is often the case for marine survey data (Pennington, 1996), these data were highly skewed to the right. A common problem in the interpretation and analyses for such skewed data is that the mean is extremely sensitive to extreme large values. However, these large values reflect the spatial distribution of the species and are thus not outliers that can be discarded (*e.g.* McConnaugher and Conquest, 1992, Pennington, 1996). For marine data, the distribution of the non-zero values is often well approximated by a lognormal distribution (Pennington, 1996), and this model has been used for a range of marine abundance data (*e.g.* Ortiz *et al.*, 2000; Folmer and Pennington, 2000; Lo *et al.*, 1992; Madrid-Vera *et al.*, 2007). Preliminary plots constructed of the transformed non zero values demonstrated that they conformed, at least approximately, to a lognormal distribution, *i.e.* the distributions were far more symmetrical.

It should be pointed out that some authors have argued against the use of the lognormal model. Smith (1990) argued that the lognormal model may be incorrect or not robust for small populations, but Pennington (1996) has pointed out that the sort of bias that Smith (1990) was considering is not a concern for marine surveys, where the population size (*i.e.* potential number of samples that may be taken) is very large. Pennington (1991) showed that the argument of Myers and Pepin (1990) that lognormal estimators are not robust as they are sensitive to undetectable deviations from lognormality, was based on simulations in which lognormal distributions were simply contaminated with small values. These small values result in large negative values on the log scale, which cause extreme instability of the lognormal estimators. As pointed out by Pennington (1996), an examination of the raw data shows whether there are values very close to zero and thus whether the data are appropriate for using a lognormal distribution. Our inspection of the raw biomass data indicated that the estimates of harvest biomass (from which catch forgone was determined) would not have been biased by any values of biomass close to zero.

A2.4 Biomass estimates from survey data and commercial catch information

Our method described below for determining $B_{\text{Available}}$ by adjusting the survey biomass estimates for commercial catches taken during the 2006/07 fishing season from the proposed sanctuaries assumes that growth was negligible during the period from the start of the fishing season to the midpoint of the survey, that the population was closed to recruitment and migration, and that the survey estimate of biomass represents the survival of abalone from both fishing and natural mortality. According to this method, $B_{\text{Available}}$ represents an estimate of the abalone biomass within the sanctuaries at the beginning of the 2007 fishing season, *i.e.* B_{2007}. Thus, $B_{\text{Available}} = B_{2007}$.

B_{2007} was calculated from the average survey biomass for that sanctuary and species at the midpoint of the survey, *B*. B_{2007} was determined as: $B_{2007} = B\exp(Z_{2007}T)$, where *B* is the estimate of the average survey biomass at the midpoint of the survey, *T* is the period (years) from the start of the 2007 fishing season to the midpoint of the survey period, and Z_{2007} is the instantaneous rate of total mortality during 2007, where $Z_{2007} = M + F_{2007}$ and F_{2007} is the instantaneous rate of fishing mortality during the 2007 fishing season. From the Baranov equation, assuming growth is negligible, we can express the catch of each abalone species from the beginning of the year, C_{2007}, as

$$C_{2007} = \frac{F_{2007}}{Z_{2007}}\left[1 - \exp\left(-Z_{2007}T\right)\right]B_{2007},$$

Substituting for B_{2007} and Z_{2007}, this may be re-written as

$$C_{2007} = \frac{F_{2007}}{M + F_{2007}}\left\{1 - \exp\left[-\left(M + F_{2007}\right)T\right]\right\}B\exp\left[\left(M + F_{2007}\right)T\right],$$

which, given values of C_{2007}, *B* and *M*, may be solved numerically to determine an estimate of F_{2007}. This estimate may then be used with the values of *B* and *M* to estimate B_{2007} using the earlier equation, $B_{2007} = B\exp(Z_{2007}T)$.

In short, we first estimate F_{2007} from the values of C_{2007}, *B* and *M*, and then determine B_{2007} from the values of F_{2007}, *B* and *M*.

Appendix 3. Estimation of biologically sustainable catch biomass from the proposed sanctuaries

In estimating the biologically sustainable catch biomass for the three species (which, if the fishery was fully biologically exploited, would provide an estimate of current annual catch taken from the proposed sanctuaries), we have assumed that, had the sanctuaries not been introduced, the Department of Fisheries would have imposed appropriate controls on the level of exploitation. This would have ensured that fishing mortality would have been set at an appropriate target level, which would have been less than the limit reference point for fishing mortality, where the latter reference point is determined by the biological characteristics of the stock. Moreover, consistent with accepted standards of fisheries practice in well-managed fisheries elsewhere in the world, uncertainty in parameter estimates would have been taken into account by requiring that the probability of the fishing mortality exceeding the limit reference point is less than a specified value, *e.g.* limit reference point is exceeded less that 20% of the time.

The limit reference point for fishing mortality is typically set at F_{MSY}, the fishing mortality associated with Maximum Sustainable Yield. For fisheries where this value can not be assessed, a proxy calculated from the instantaneous rate of natural mortality is typically used. We have selected to use the limit reference point of $F=M$ in the abalone assessment (*e.g.* Thompson, 1993). We have arbitrarily selected 20% as an appropriately low probability, and have thus undertaken our assessment on the basis that, given the uncertainty of our estimate of the survey biomass and of the instantaneous rate of natural mortality, the allowable catch should be such that the probability of F exceeding the limit reference point should be less than 20%.

The fishing mortality that would be appropriate as the target mortality has been set at $0.75F_{\mathrm{limit}}$ (Restrepo *et al*., 1998) and for an additional and more conservative estimate, $0.6F_{\mathrm{limit}}$ (Perry, 1999).

For a given level of available biomass of abalone, the theoretical catches that would be produced by the target and limit fishing mortalities may be calculated using the Baranov catch equation, *i.e.*

$$C = \frac{F}{M+F}\{1-\exp[-(M+F)]\}B_{\mathrm{Available}}$$

The algorithm that we use to determine the appropriate level of annual catch then uses the following steps. For each of a number of values of catch over the range of possible catches:

1. Draw a random value of survey biomass from the distribution of estimates of this value
2. Calculate the available biomass for the species
3. Draw a random value of the instantaneous rate of natural mortality from a distribution of values of M.
4. Use the value of M to estimate the limit and target fishing mortalities
5. Calculate the theoretical limit and target catches associated with the available biomass, the estimate of M and the respective fishing mortality
6. Compare the selected value of catch with the limit catch and score 1 if the selected catch exceeds the theoretical limit catch, otherwise score zero, accumulating the resulting scores for the limit reference point

7. Compare the selected value of catch with the theoretical target catch and score 1 if the selected catch lies within 10% of the target catch, otherwise zero, and accumulate the resulting scores for the target reference point
8. Repeat 1000 times, then calculate and record the percentages of occasions on which the selected value of catch exceeded that associated with the limit reference point, and on which the selected catch was within 10% of the target catch.

Repeat for each of the range of selected values, then plot the curves. The resultant value of catch derived from this analysis as the appropriate level of annual sustainable catch should be that which maximises the probability of falling within 10% of the target catch, yet for which the probability of exceeding the catch associated with the limit reference point is less than 20%. The estimates produced using this method are based on our estimates of mature biomass.

Appendix 4. Estimates of the current annual biomass of catches taken from the sanctuaries

Estimates of biomass of the current annual commercial catch, *C*, taken from the proposed sanctuaries of the Capes region were determined from the Baranov catch equation, *i.e.*

$C = \frac{F}{Z}\left[1 - \exp(-Z)\right]B_{Harv}$ (Ricker, 1975), where B_{Harv} is the estimate of harvest biomass (as determined from the biomass analyses, for either Assumption A or B), *F* is the fishing mortality (year^{-1}) and *Z* is total mortality (year^{-1}). The estimates of *F* (year^{-1}) provided by DoF (A. Hart, unpublished data) were 0.34-0.54 for Roei, 0.34-0.49 for Greenlip and 0.29-0.37 for Brownlip. To enable incorporation of uncertainty in the estimates of catch, the estimates of *F* for each species were represented by normal distributions, where the 95% confidence intervals for these normal distributions approximated the upper and lower bounds of the estimates provided by DoF. Specifically, the distributions for *F* are described by a mean and standard deviation, respectively, of 0.44 and 0.05 for Roei, 0.42 and 0.04 for Greenlip and 0.33 and 0.03 for Brownlip.

The *F* estimates produced by DoF had been determined using length-converted catch curve analysis (Pauly, 1984, pp. 60-61) using data for the three species from the Capes region, *i.e.* the survey length-composition data for Roei (the only existing commercial length data for Roei in the region) and commercial catch size composition data for Greenlip and Brownlip. The DoF analyses for determining *F* are based on growth information for the three species, as described by Gompertz growth curves: Roei, L_{∞} = 83 mm, *k* (or *g*) = 0.45 year^{-1}, Greenlip L_{∞} = 185 mm, *k* (or *g*) = 0.30 year^{-1}, Brownlip L_{∞} = 200 mm, *k* (or *g*) = 0.30 year^{-1}. As is consistent with other analyses in this study, the DoF estimates of *F* are calculated assuming *M* = 0.25 year^{-1}. The analyses for estimating current catch and the DoF analyses for estimating *F* both assumed *M* = 0.25 year^{-1}. Confidence intervals for current catch estimates were produced by resampling from distributions produced in this study for the estimates of biomass in the proposed sanctuaries, and from those for *F* and *M* (mean and standard deviation for distribution for *M* = 0.25 and 0.05, respectively).

We acknowledge that it would have been preferable to base the catch curve analyses for estimating mortality on direct age estimates, if such data were available. For future related studies, if direct age estimates were not available, alternative length-based approaches which might provide more robust estimates of mortality than that outlined by Pauly (1984) should be investigated.

Appendix 5. Roles of people involved in the project

Murdoch University (Alex Hesp, Neil Loneragan, Norm Hall, Halina Kobryn and Peter Coulson) provided overall co-ordination for the project, including liaising with industry, developing the sampling design, assisting with field sampling, analysing the data and producing the final report. The sampling design was developed with advice from Anthony Hart and Frank Fabris of the Department of Fisheries WA Research Division (DoF), and Jeremy Prince of Biospherics. Feedback on a draft of the materials and methods of the report was provided by Ian Taylor (WA commercial abalone industry). Because of their experience in sampling abalone, knowledge of the Capes area and staff with the appropriate diving qualifications, the Department of Fisheries (Frank Fabris, Jamin Brown, Anthony Hart, Lachlan Strain, David Murphy, Fiona Parker and Mark Davidson) completed the field sampling. Spatial analysis using GIS software was undertaken by Frank Fabris of DoF (for Roei) and Halina Kobryn of Murdoch University (for Greenlip and Brownlip abalone). Useful comments and discussion were provided by Peter Dans, Chris Simpson, John Lloyd, Judy Davidson and Fran Stanley of the Department of Environment and Conservation (DEC), Nick Caputi and Andrew Hill (DoF), and Jessica Meeuwig (University of WA), who has worked with the WA abalone industry and was involved with the planning process for the Capes Marine Park, kindly offered advice on sampling design.

Jeremy Prince is an internationally-recognised expert in abalone biology and fisheries resource assessment. His role in the study was to provide advice on all aspects of the project. Jeremy has previously fished commercially for abalone in New Zealand and currently works on an FRDC project with the abalone industry of Victoria. He has worked with the WA abalone industry in the past.

Rick McGarvey (SARDI) provided an external review of this report.

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