

# **Central Zone Abalone** **(*Haliotis laevis* & *H. rubra*)** **Fishery**

Fishery Assessment Report to PIRSA Fisheries

October 2006

Mayfield, S., Carlson, I.J. and R.C. Chick

This fishery assessment report updates the 2005 report for the Central Zone abalone fishery and is part of SARDI Aquatic Sciences ongoing assessment program for the fishery. The aims of the report are to assess the current status of the resource, identify the uncertainty associated with the assessment and to identify future research needs for the fishery.

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## TABLE OF CONTENTS

<b>EXECUTIVE SUMMARY .....</b>	<b>i</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>iii</b>
<b>1. GENERAL INTRODUCTION.....</b>	<b>1</b>
<b>1.1 Overview .....</b>	<b>1</b>
<b>1.2 Description of the fishery .....</b>	<b>2</b>
1.2.1 Commercial fishery .....	2
1.2.2 Recreational fishery.....	7
1.2.3 Illegal fishery .....	7
<b>1.3 Key objectives and strategies of the Management Plan .....</b>	<b>8</b>
<b>1.4 Fisheries biology of abalone.....</b>	<b>8</b>
1.4.1 Biology of greenlip abalone in the Central Zone .....	11
1.4.2 Biology of blacklip abalone in the Central Zone .....	14
<b>1.5 Previous stock assessments .....</b>	<b>15</b>
<b>2. GREENLIP ABALONE.....</b>	<b>17</b>
<b>2.1 Catch.....</b>	<b>17</b>
<b>2.2 Effort.....</b>	<b>18</b>
<b>2.3 Catch-per-unit effort (CPUE).....</b>	<b>22</b>
<b>2.4 Standardised CPUE .....</b>	<b>24</b>
<b>2.5 Length-frequency distribution of the catch .....</b>	<b>26</b>
<b>2.6 Estimates of egg production .....</b>	<b>29</b>
<b>2.7 Fishery-independent abalone surveys.....</b>	<b>29</b>
2.7.1 Changes in abundance of greenlip abalone .....	30
2.7.2 Changes in greenlip abalone population length structure .....	30
<b>3. BLACKLIP ABALONE.....</b>	<b>33</b>
<b>3.1 Catch.....</b>	<b>33</b>
<b>3.2 Catch-per-unit effort (CPUE).....</b>	<b>34</b>
<b>3.3 Standardised CPUE .....</b>	<b>39</b>
<b>3.4 Length-frequency distribution of the catch .....</b>	<b>40</b>
<b>3.5 Estimates of egg production .....</b>	<b>41</b>
<b>3.6 Length-based stock assessment model .....</b>	<b>41</b>
3.6.1 Introduction .....	41
3.6.2 Methods .....	44
3.6.3 Model outputs .....	47
<b>4. PERFORMANCE INDICATORS .....</b>	<b>53</b>
<b>4.1 Greenlip abalone .....</b>	<b>53</b>
<b>4.2 Blacklip abalone .....</b>	<b>54</b>
<b>5. GENERAL DISCUSSION .....</b>	<b>57</b>
<b>5.1 Status of the Central Zone abalone fishery .....</b>	<b>57</b>
5.1.1 Greenlip abalone .....	60
5.1.2 Blacklip abalone.....	62
<b>5.2 Future research needs .....</b>	<b>64</b>
<b>6. REFERENCES.....</b>	<b>66</b>

## EXECUTIVE SUMMARY

1. This fishery assessment report updates the 2005 report and assesses the current status of the abalone resource in the Central Zone (CZ).
2. The fishery is concentrated in four of 12 fishing areas (21, 26, 27 and 29).

### GREENLIP ABALONE

3. Since 2001, an average of >80% of the catch has been harvested from fishing area 21.
4. Catches have declined in six fishing areas since 1990. Current catches from several of these are among the lowest on record.
5. Mean CPUE in the CZ and fishing area 21 have both declined significantly since 2001. Declines over a similar time period were also evident in the standardised CPUE.
6. Mean daily catch in fishing area 21 declined significantly between 2001 and 2005. This included a significant, 18% decrease between 2004 and 2005.
7. Since 2002, the mean length and proportion of the catch >145 mm SL have increased.
8. The abundances of total, legal-sized, sub-legal-sized and mature greenlip abalone observed on fishery-independent surveys have increased significantly since 2001.
9. Eight of the 13 performance indicators (PI) that triggered, did so in a negative direction. Four of the five PI that were positive were based on fishery-independent surveys.

### BLACKLIP ABALONE

10. Since 2001, ~80% of the catch has been harvested from three fishing areas – all on Kangaroo Island. Area 26 contributed >35% of the total catch.
11. CPUE in the CZ and in fishing area 26 in 2005 were at the lowest level since 1999, >8% lower than that in 2004 and ~20% below maximum observed levels. Decreases in CPUE in fishing area 29 were more substantial. Standardised CPUE has declined significantly since 1985.
12. Mean daily catch has declined significantly in fishing area 26 since 2001. It also declined in fishing areas 26, 27, 29 and 30 between 2004 and 2005.
13. The mean length of abalone in the commercial catch declined and the proportion of the catch <145 mm SL increased substantially between 2003 and 2005. Similar patterns were observed in fishing areas 26, 27 and 29.
14. Estimates of retained egg production have been below 50% since 2002.
15. Six of the 10 PI that triggered, did so in a negative direction.

## CONCLUSIONS

16. Unambiguous assessment of the greenlip abalone stocks in fishing area 21 is prevented by the inconsistent inferences from the available data. The most striking contrast is between the recent (five-year) trends in the fishery-dependent and fishery-independent data. Resolving the ambiguity between the inferences from these data is a key issue for future research.
17. Assessment of the greenlip stocks in the remaining fishing areas is impeded by limited data. Nevertheless, the downward trends observed in two areas suggest that these areas may not be able to sustain the higher levels of catch necessary to maintain both the current TACC and 'catch cap' on Tiparra Reef.
18. There is strong evidence that blacklip abalone abundance in the CZ has declined. This conclusion was supported by consistent declines in the mean length and modal length class of the commercial catch, CPUE, mean daily catch, standardised CPUE and estimates of retained egg production.
19. The resource weakened despite the voluntary reductions in catch between 2002 and 2004. It remains unclear as to whether the recent, successive, substantial reductions in the TACC are sufficient to arrest the declines in this stock.

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# **1. GENERAL INTRODUCTION**

## **1.1 Overview**

This fishery assessment report for the Central Zone (CZ) of the South Australian abalone fishery updates the previous fishery assessment report (Mayfield *et al.* 2005a) and is part of SARDI Aquatic Sciences ongoing assessment program for the fishery.

The aims of the report are (1) to assess the current status of the resource; (2) to identify the uncertainty associated with the assessment and; (3) to identify future research needs for the fishery.

The report covers the period 1 January 1968 to 31 December 2005. It is divided into five sections.

The first section is the general introduction that (1) outlines the aims and structure of the report, (2) describes the CZ abalone fishery including the fisheries history, current management arrangements, and the level of recreational and illegal harvest, (3) identifies the biological performance indicators, (4) summarises biological knowledge of South Australian abalone, and (5) provides a synopsis of previous stock assessment reports on the fishery.

Sections two and three provide an assessment of the fishery-dependent and fishery-independent data for greenlip and blacklip abalone, respectively, from 1968 to 2005. Where appropriate, this includes spatial and temporal analyses of catch, effort, raw and standardised catch-per-unit effort (CPUE), length-frequency distribution of the catch and fishery-independent diver surveys. Section three includes preliminary outputs and sensitivity analyses from a length-structured stock assessment model that is being developed to aid assessment of the status of the blacklip abalone stocks in the fishery.

In section four, the performance of the greenlip and blacklip abalone fisheries is assessed against the performance indicators and reference points identified in the management plan (Nobes *et al.* 2004).

Section five is the general discussion. It synthesises the information presented in the previous sections, identifies areas of uncertainty in current knowledge and outlines future research needs for the fishery.

## 1.2 Description of the fishery

### 1.2.1 Commercial fishery

Management arrangements have evolved since the inception of the fishery in 1964. A review of the management history is provided by Shepherd & Rodda (2001). The major management milestones are listed in Table 1.1. Summaries of the fishery can be found in Prince & Shepherd (1992), Zacharin (1997), Keesing & Baker (1998) and Nobes *et al.* (2004).

The fishery expanded rapidly in the late 1960s, exceeding 100 entrants by 1970. Licences were made non-transferable in 1971 to reduce the number of operators in the fishery. By 1976 the number of operators had declined to 30 and an additional five licences were issued. There are currently 35 licence holders in the fishery.

In 1971 the South Australian abalone fishery was divided into three Zones (Western, Central and Southern) to facilitate more effective management (Figure 1.1). The CZ of the South Australian abalone fishery includes all coastal waters of South Australia between Meridians 136°30'E and 139°E (Figure 1.2). The fishing season extends from 1 January to 31 December each year.

Greenlip abalone comprises 77.2% of the total allowable commercial catch (TACC) in the CZ (2005 TACC: 143.1 t whole weight). The remainder, 22.8%, comprises blacklip abalone (2005 TACC: 29.7 t whole weight; Table 1.2). The greenlip abalone TACC was increased by 16.6 t to 159.7 t from 2006. This was contingent on the additional catch being harvested off Cowell (after Dixon *et al.* 2004, Carlson *et al.* 2006). In contrast, the TACC for blacklip abalone was reduced from 29.7 t (2005) to 24.3 t from 2005.

From 1997, the fishery operated under the control of a formal Management Plan (Zacharin 1997; Nobes *et al.* 2004). This Plan ensures that the fishery is managed through a regime of input (*e.g.* limited entry) and output (*e.g.* minimum legal length, quotas) controls. The current management arrangements in the CZ are provided in Table 1.3.

Minimum legal lengths (MLL) of 130 mm shell length (SL) were imposed on both species in 1971. Quotas were imposed on the CZ from 1990.

To monitor catches and facilitate compliance with quota limits, fishers must complete a Catch and Disposal Record (CDR) form immediately upon landing. In addition, a research logbook must also be completed for each fishing day and submitted to SARDI Aquatic Sciences at the

end of each month. Commercial catch and effort data on this fishery have been collected since 1968. The logbook provides information on the date of fishing, the fishing area, the amount of time spent fishing, whether or not an underwater vehicle was used, the diving depth and the total catch landed.

Only two changes have been made to the data collection system over the last 30 years. In 1978, sub zones and fishing blocks were replaced by spatially smaller map numbers (= fishing areas) and map codes (see Figure 1.1). In 2002, the logbook datasheet was revised and additional data fields (*e.g.* GPS position, number of abalone harvested) were inserted. The logbook data supplied by divers and licence holders are used annually by SARDI Aquatic Sciences to provide analyses of catch, effort and catch-per-unit-effort in relevant Fishery Assessment Reports for each Zone (see Mayfield *et al.* 2005a,b,c,d).

**Table 1.1: Management milestones in the CZ of the South Australian abalone fishery.**

Date	Milestone
1964	Fishery started
1971	Licences made non-transferable Fishery divided into three Zones Minimum legal length set at 130 mm for both species
1976	30 Licences remained; 5 additional licences issued
1978	Sub Zones and fishing blocks replaced by map numbers and codes
1980	Licences became transferable
1989	Quota introduced
1993	Abolition of owner-operator regulation
1997	Management Plan implemented
2004	Management Plan reviewed Fishery assessed against the Principles of Ecologically Sustainable Development
2005	Blacklip abalone TACC reduced from 42.3 to 29.7 t (shell weight) Greenlip abalone catch capped at 90 t (shell weight) in fishing area 21
2006	Blacklip abalone TACC reduced from 29.7 to 24.3 t (shell weight) Greenlip abalone TACC increased from 143.1 to 159.7 <sup>#</sup> t (shell weight)

<sup>#</sup> 16.6 t to be harvested from Cowell

Each year, the Abalone Fishery Management Committee (AFMC) recommends a separate TACC for greenlip and blacklip abalone in the CZ to the Minister for Agriculture, Food and Fisheries. This advice is structured by the objectives and strategies of the Abalone Management Plan (see Section 1.3 below) and based on the annual Fishery Assessment Reports submitted to PIRSA by SARDI Aquatic Sciences and additional information

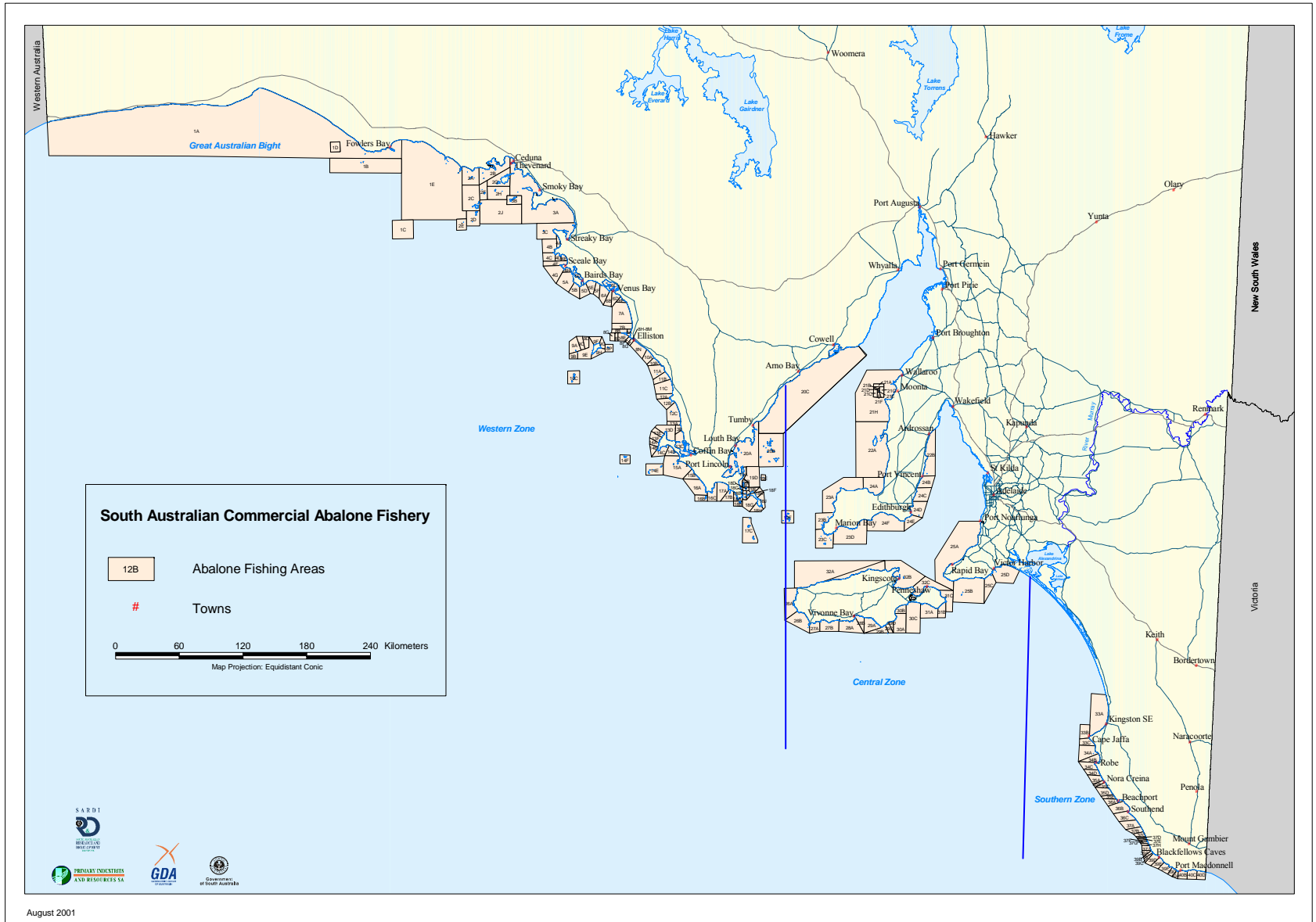
provided to PIRSA and the AFMC. Each licence holder is allocated an annual Individual Transferable Quota (ITQ) that is an equal share of the TACC.

Three substantial changes in the management arrangements for the fishery have been implemented in recent years. Firstly, the blacklip abalone TACC was reduced by about 30% between 2004 and 2005 (from 42.3 to 29.7 t shell weight) and by a further 18% between 2005 and 2006 (from 29.7 to 24.3 t shell weight). Secondly, the catch from fishing area 21 (that incorporates Tiparra Reef) was capped at 90 t (shell weight) from 2005, reflecting a reduction in catch of ~20% from this area. Thirdly, extensive fishery-dependent and fishery-independent surveys in an ‘unfished’ area off Cowell (NW Spencer Gulf; Dixon *et al.* 2004, Carlson *et al.* 2006) led to an increase in the greenlip abalone TACC (16.6 t shell weight), contingent on this catch being obtained from this ‘spatially-managed’ area.

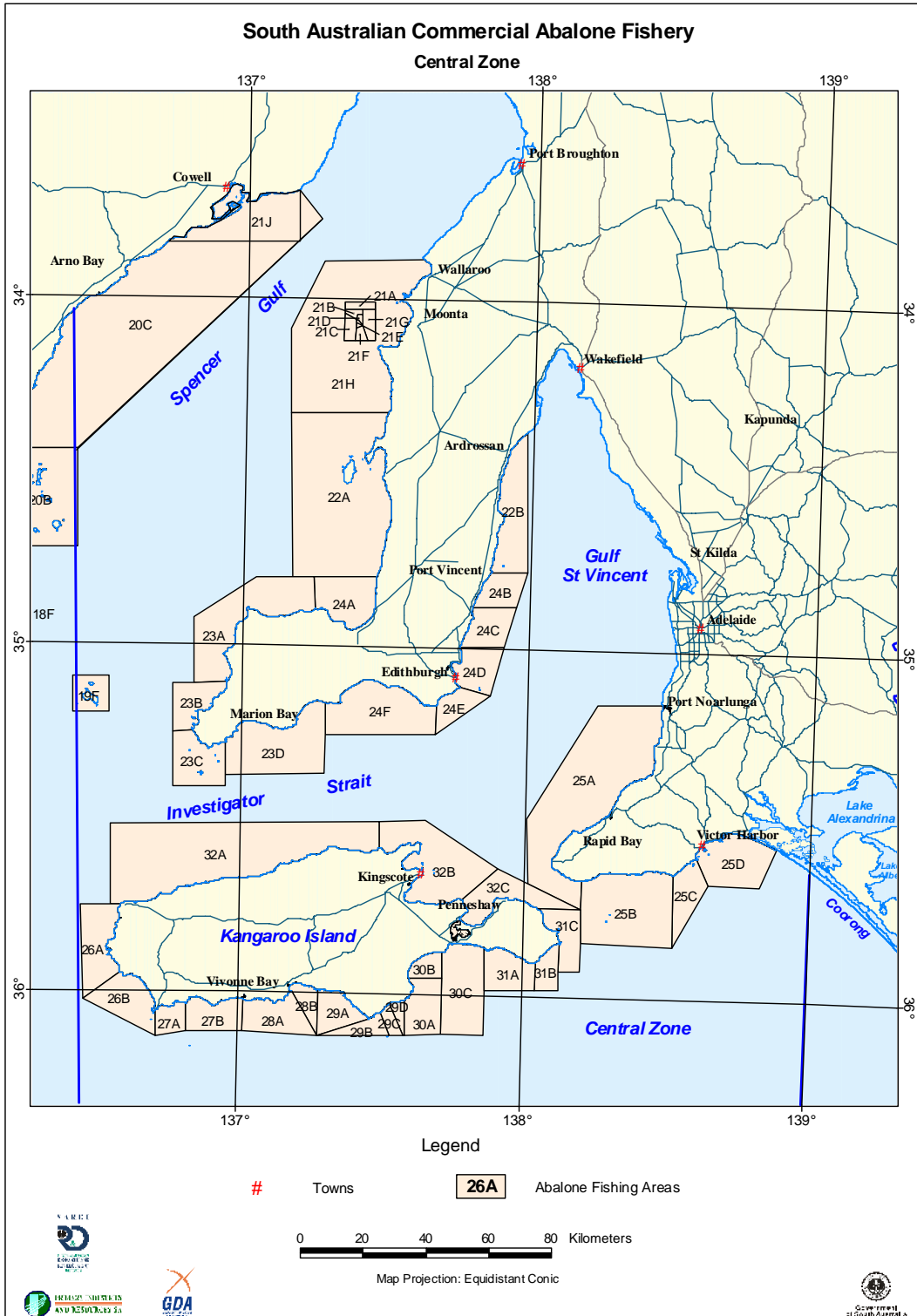
**Table 1.2: Total Allowable Commercial Catches (tonnes, whole weight) for the CZ of the South Australian abalone fishery from 1990 to 2006.**

Fishing season	Greenlip abalone SL > 130 mm	Blacklip abalone SL > 130 mm
1990	142.2	41.1
1991	142.2	41.1
1992	142.2	41.1
1993	142.2	41.1
1994	143.1	42.3
1995	143.1	42.3
1996	143.1	42.3
1997	143.1	42.3
1998	143.1	42.3
1999	143.1	42.3
2000	143.1	42.3
2001	143.1	42.3
2002	143.1	42.3
2003	143.1	42.3
2004	143.1	42.3
2005	143.1	29.7
2006	159.7 <sup>#</sup>	24.3

<sup>#</sup> 16.6 t to be harvested from Cowell



**Figure 1.1: Fishing Zones and fishing areas of the South Australian abalone fishery**



**Figure 1.2: Fishing areas of the CZ of the South Australian abalone fishery.**

**Table 1.3: Summary of the current management arrangements for the CZ commercial abalone fishery.**

Management strategy	CZ
Licence holders	6
Targeted species	Greenlip abalone Blacklip abalone
Minimum legal length	Blacklip 130 mm SL Greenlip 130 mm SL
Quota year	1/1 to 31/12
Quota transferability	Yes
Method of capture	By hand
Bycatch	Nil

### 1.2.2 Recreational fishery

The total recreational abalone harvest in South Australia was estimated at 17 780 abalone for the period May 2000 to April 2001 (Henry & Lyle 2003). As few of these were harvested from the CZ (Jones & Doonan 2005), the recreational catch from this Zone appears small (*c.a.* 1000 abalone; ~ 0.5 t). This represents about 0.3% of the TACC. Future estimation of the total catch of abalone by recreational fishers would be enhanced by regular creel surveys.

### 1.2.3 Illegal fishery

It is difficult to accurately estimate the level of the illegal catch, as many information reports are unsubstantiated. During 2005, PIRSA identified through information and other reports, 40 421 individual abalone may have been taken illegally. In addition to this, information reports also indicated that approx 571 kg (meat weight) of abalone may have been illegally harvested within the CZ. It would be expected that PIRSA would not have been notified of all reports alleging that abalone theft activity had occurred within the CZ during 2005, so the actual extent of illegal take of abalone is likely to have been higher. By attributing an estimate of 113 g to the meat weight of an illegal harvested whole abalone, the estimated total illegal catch of abalone in the CZ equates to ~4.5 t (meat weight). This estimate represents ~8% of the TACC in the CZ.

### **1.3 Key objectives and strategies of the Management Plan**

The management plan for the South Australian abalone fishery (Nobes *et al.* 2004) identifies biological, economic, environmental and social management objectives and strategies. The biological objectives are (1) to control, measure and regulate all catches/extractions from the resource; (2) to maintain sufficient egg and sperm production to provide for adequate levels of recruitment; and (3) to monitor and control disease.

Associated with these biological objectives are five strategies. These are:

1. To collect and collate fishery-dependent information (Strategy 1);
2. To set the TACC using the best available information (Strategy 2);
3. To harvest at an appropriate minimum legal length (Strategy 3);
4. To maintain abalone population densities (Strategy 4); and
5. To identify disease-infected areas (Strategy 5).

Performance indicators are linked with the five strategies, each of which has specific trigger points. The biological performance indicators and trigger points for each of the strategies for the blacklip and greenlip abalone fisheries in the CZ are provided in Tables 1.4 and 1.5. The performance indicators to be addressed in this report are shown in bold. Annual reports on the harvest discard and illegal catch, recreational harvest and the diver's assessment of the status of the stock are provided by PIRSA Fishwatch, PIRSA Fisheries and the Abalone Industry Association of South Australia, respectively.

### **1.4 Fisheries biology of abalone**

Abalone (Family: Haliotidae; Genus: Haliotis) are marine gastropods inhabiting nearshore reefs (Day & Shepherd 1995) from the shallow subtidal zone to depths around 400 m (Geiger 1999). They have a world-wide distribution in tropical and temperate waters with the richest abalone faunas found in Australia, Japan and South Africa (Geiger 1999). Over 50 species of abalone are currently recognised (Geiger 1999).

Large genetic differences exist between the northern and southern temperate species and within the southern temperate species assemblages (Brown 1991). Even on more localised scales, genetic variation can occur (Brown & Murray 1992, Elliott *et al.* 2000, Hancock 2000), suggesting limited dispersal between 'metapopulations' (Fleming 1997).

**Table 1.4: Biological strategies and associated performance indicators, spatial scale of application and trigger points prescribed for performance assessment of the greenlip abalone fishery in the CZ of the South Australian abalone fishery. The performance indicators to be addressed in this report are shown in bold.**

Strategy	Performance Indicator	Scale of Application	Trigger Point
1	<b>Commercial logbooks</b>	-	<100% received
	<b>Catch and effort database</b>	-	<100% of logbooks received entered into the database
	Stock assessment report	Fishing Zone	Annual report not produced
	Illegal catch	Fishing Zone	Annual report not produced
	Recreational catch	Fishing Zone	Annual report not produced
2	Illegal catch	Fishing Zone	Statistically significant 5-year trend (no. of prosecutions)
	Recreational catch	Fishing Zone	25% increase in catch
	Diver assessment of stock status	Fishing areas contributing >10% of the TACC	Change in stock status
	<b>Commercial catch</b>	Fishing Zone	<90% of TACC harvested
	<b>Commercial effort</b>	Fishing Zone	Statistically significant 5-year trend
	<b>Spatial distribution of catch</b>	Four most important fishing areas (by catch)	Change in order or composition
	<b>Mean daily catch</b>	Fishing areas contributing >10% of the TACC	(1) Statistically significant inter-annual change (2) Statistically significant 5-year trend
	<b>Mean daily effort</b>	Fishing areas contributing >10% of the TACC	
	<b>CPUE</b>	Fishing areas contributing >10% of the TACC	
	<b>Mean length</b>	Fishing areas contributing >10% of the TACC	
<b>Abundance of legal-sized abalone</b>	Tiparra Reef		
<b>Abundance of sub-legal-sized abalone</b>			
3	<b>% Egg production relative to pristine egg production</b>	Tiparra Reef	<50% of the pristine level
4	<b>Abundance of abalone &gt;L<sub>50</sub></b>	Tiparra Reef	(1) Statistically significant inter-annual change (2) Statistically significant 5-year trend
5	Harvest discard	Fishing Zone	-

**Table 1.5: Biological strategies and associated performance indicators, spatial scale of application and trigger points prescribed for performance assessment of the blacklip abalone fishery in the CZ of the South Australian abalone fishery. The performance indicators to be addressed in this report are shown in bold.**

Strategy	Performance Indicator	Scale of Application	Trigger Point
1	<b>Commercial logbooks</b>	-	<100% received
	<b>Catch and effort database</b>	-	<100% of logbooks received entered into the database
	Stock assessment report	Fishing Zone	Annual report not produced
	Illegal catch	Fishing Zone	Annual report not produced
	Recreational catch	Fishing Zone	Annual report not produced
2	Illegal catch	Fishing Zone	Statistically significant 5-year trend (no. of prosecutions)
	Recreational catch	Fishing Zone	25% increase in catch
	Diver assessment of stock status	Fishing areas contributing >10% of the TACC	Change in stock status
	<b>Commercial catch</b>	Fishing Zone	<90% of TACC harvested
	<b>Commercial effort</b>	Fishing Zone	Statistically significant 5-year trend
	<b>Spatial distribution of catch</b>	Four most important fishing areas (by catch)	Change in order or composition
	<b>Mean daily catch</b>	Fishing areas contributing >10% of the TACC	(1) Statistically significant inter-annual change (2) Statistically significant 5-year trend
	<b>Mean daily effort</b>	Fishing areas contributing >10% of the TACC	
	<b>CPUE</b>	Fishing areas contributing >10% of the TACC	
	<b>Mean length</b>	Fishing areas contributing >10% of the TACC	
<b>Abundance of legal-sized abalone</b>	Cape du Couedic, Cape Bouger, Cape Gantheaume		
<b>Abundance of sub-legal-sized abalone</b>			
3	<b>% Egg production relative to pristine egg production</b>	Three most important fishing areas (by catch)	<50% of the pristine level
4	<b>Abundance of abalone &gt;L<sub>50</sub></b>	Cape du Couedic, Cape Bouger, Cape Gantheaume	(1) Statistically significant inter-annual change (2) Statistically significant 5-year trend
5	Harvest discard	Fishing Zone	-

Abalone have separate sexes. Spawning is generally seasonal and synchronised. Fertilisation success is strongly influenced by adult density. Larval duration ranges between 5 and 10 days and is predominantly influenced by water temperature. As the larvae are free swimming, dispersal distances are influenced by local hydrodynamics (Prince *et al.* 1987). Recruitment may vary widely from year to year and the relationship between stock size and subsequent recruitment is uncertain (McShane *et al.* 1988; Prince *et al.* 1988; Shepherd 1990; McShane 1991; McShane & Smith 1991; Shepherd *et al.* 1992).

Growth rates are initially high and length-dependent for the first 5 years (Shepherd 1988). Thereafter, they decline and follow a von Bertalanffy model (Shepherd & Hearn 1983) with year classes becoming indistinguishable by length. Water temperature, water movement and the quantity and species of macroalgae available for consumption are the primary determinants of abalone growth rates (Day & Fleming 1992, Zacharin 1997). Recently settled abalone prefer encrusting coralline algae (Shepherd & Turner 1985, Shepherd & Daume 1996) that provide an important source of food, and protection from predation (Shepherd & Cannon 1988).

As juvenile abalone grow, their diet shifts from crustose coralline algae (individuals 5-10 mm SL) to drift red algae (Shepherd & Cannon 1988). Other abundant algae may be largely avoided, ostensibly due to non-palatability. Small abalone are preyed upon by a range of predators, including fish, crabs, starfish and octopus. Shells are frequently bored by whelks that then feed on the foot muscle. Boring polychaetes also erode the shells and spire (Shepherd 1973).

#### 1.4.1 Biology of greenlip abalone in the Central Zone

Greenlip abalone (*Haliotis laevis*) are contiguous throughout southern Australia, with their distributions ranging from Corner Inlet (Victoria) to Cape Naturaliste (Western Australia). They commonly inhabit reefs at depths between 1 and 30 m. They occur in clusters of local populations, separated from other similar clusters over a range of spatial scales. This pattern of disaggregated spatial distribution is reflected in the population genetics with clusters representing putative 'metapopulations' (Shepherd & Brown 1993; Dr Nick Elliott, CSIRO Hobart, pers. comm.).

The length at sexual maturity of greenlip abalone can vary significantly among areas. Fifty percent of individuals were sexually mature ( $L_{50}$ ) between 75 (Tiparra Reef) and 87 mm SL (West Island; Table 1.6). Greenlip abalone spawned synchronously between October and March at both West Island and Tiparra Reef (Shepherd & Laws 1974, SARDI unpublished).

These data match the pattern of larval settlement onto artificial collectors (Keesing *et al.* 1995, Rodda *et al.* 1997). Sex ratios seldom differ from 1 male: 1 female (SARDI, unpublished data). Relationships between biological components including length, whole weight, meat weight, bled meat weight and fecundity for greenlip abalone from Tiparra Reef, Cowell and West Island are well established (Tables 1.7 & 1.8). Fresh meat weight and bled meat weight represent about 41.5 and 33.5% of whole weight respectively (SARDI, unpublished data).

Rates of growth vary throughout the life history stages of abalone with smaller individuals generally growing faster than larger ones. The rate of growth is, however, dependent on environmental conditions that often vary through time and space. Juvenile *H. laevisgata* grew rapidly and attained a length of 40 mm within one year at West Island (~0.9 mm.week<sup>-1</sup>). However, their growth rates vary temporally; at West Island the mean juvenile growth rate was 0.41 mm.week<sup>-1</sup> five years later (Shepherd 1988). Sub-adult growth rates in the CZ ranged between 20.3 and 20.9 mm.yr<sup>-1</sup> (Table 1.9). Adult greenlip abalone growth is non linear and can be represented by the parameters K and L<sub>∞</sub> from the von Bertalanffy growth equation. K (rate of growth) ranged from 0.16 (Cowell) to 0.48.yr<sup>-1</sup> (West Island) and L<sub>∞</sub> (maximum attainable length) between 130.4 (Cowell) and 137.9 mm (West Island; Table 1.10).

As for growth, rates of natural mortality vary spatially and temporally. Natural mortality rates (M) of greenlip abalone at West Island were 0.26 year<sup>-1</sup>. This was greater than that observed at Tiparra Reef (M = 0.22 year<sup>-1</sup>; Table 1.11). For juvenile *H. laevisgata* at West Island, M was 0.24 month<sup>-1</sup> (0-8 months); individuals between 1 and 4 years of age had a natural mortality rate of 0.23 – 0.4 year<sup>-1</sup> (Shepherd & Baker 1998).

**Table 1.6: Length at 50% maturity (mm, shell length) for greenlip (*H. laevisgata*) abalone in the CZ of the South Australian abalone fishery.**

Site	Length at 50% maturity (mm)	Reference
West Island	87	Shepherd & Laws (1974)
Tiparra Reef	75	Shepherd & Laws (1974)
Tiparra Reef	79	SARDI unpublished data
Tiparra Reef	78	SARDI unpublished data
Tiparra Reef	85	SARDI unpublished data
Cowell	79	SARDI unpublished data
Cowell	85	SARDI unpublished data
Cowell	77	SARDI unpublished data

**Table 1.7: Relationship between shell length (SL, mm) and shell weight (SW, g) for greenlip abalone in the CZ. The equation is of the form  $SW = aSL^b$ .**

Site	a ( $\times 10^{-5}$ )	b	r	n	Reference
Tiparra Reef	10	3.08	0.95	97	SARDI unpublished data
Tiparra Reef	2	3.35	0.99	82	SARDI unpublished data
Tiparra Reef	1.26	3.51	-	-	Shepherd & Baker (1998)
Tiparra Reef	1.00	4.71	0.97	129	SARDI unpublished data
Tiparra Reef	0.10	2.91	0.94	224	SARDI unpublished data
West Island	1.7	3.41	-	-	Shepherd & Baker (1998)
Cowell	2.4	3.37	0.98	105	SARDI unpublished data
Cowell	2.9	3.32	0.97	66	SARDI unpublished data
Cowell	2.16	3.39	0.96	106	SARDI unpublished data

**Table 1.8: Relationship between fecundity (F, millions of eggs) and shell weight (SW, g) for greenlip abalone at Tiparra Reef and West Island in the CZ. The equations are of the form  $F = c + dSW$  and  $F = aSL^b$**

Site	a	b	c	d	Reference
Tiparra Reef	-	-	-1.51	0.02	Shepherd & Baker (1998)
Tiparra Reef	0.0023	4.143	-	-	SARDI unpublished data
West Island	-	-	-0.36	0.015	Shepherd & Baker (1998)

**Table 1.9. Growth rate ( $\text{mm}\cdot\text{yr}^{-1}$ ) of greenlip abalone tagged and recaptured in the CZ of South Australia's abalone fishery.**

Site	Length range	Growth rate $\pm$ SE	Reference
West Island	42-141	20.3 $\pm$ 0.4	Shepherd (1988)
Tiparra Reef	51-129	20.9 $\pm$ 0.7	Shepherd & Triantafillos (1997)
Cowell	99-168	2.65 $\pm$ 0.4	SARDI unpublished data
Cowell	72-144	3.11 $\pm$ 0.8	SARDI unpublished data

**Table 1.10: Growth rate, K ( $\text{yr}^{-1}$ ) and  $L_{\infty}$  (mm SL) for greenlip abalone tagged and recaptured in the CZ of the South Australian abalone fishery. Length ranges are shell length (mm).**

Site	Length range	K ( $\text{yr}^{-1}$ ) $\pm$ SE	$L_{\infty}$ $\pm$ SE	Reference
West Island	42-141	0.479 $\pm$ 0.029	137.9 $\pm$ 1.9	Shepherd & Hearn (1983)
Tiparra Reef	51-129	0.406 $\pm$ 0.047	130.8 $\pm$ 2.5	Shepherd & Hearn (1983)
Cowell	99-168	0.164	130.4	SARDI unpublished data
Cowell	72-144	0.245	147.2	SARDI unpublished data

**Table 1.11: Natural mortality rates ( $M \text{ yr}^{-1}$ ) for adult (emergent) greenlip abalone at two sites in the CZ.**

Site	$M \pm SE$	Reference
West Island	$0.26 \pm 0.06$	Shepherd <i>et al.</i> (1982)
Tiparra Reef	$0.22 \pm 0.10$	Shepherd <i>et al.</i> (1982)

#### 1.4.2 Biology of blacklip abalone in the Central Zone

Blacklip abalone (*Haliotis rubra*) are contiguous throughout southern Australia between Coffs Harbour (New South Wales) and Rottnest Island (Western Australia). They commonly occur in shallow water (0 – 30 m) along rocky coastlines.

Blacklip abalone have a broad-scale population structure (Brown 1991); however, significant genetic differentiation can occur between sites less than 15 km apart (Shepherd & Brown 1993).

The length that 50% of the blacklip abalone population are sexually mature ( $L_{50}$ ) can vary significantly among areas.  $L_{50}$  was reached at 76 and 99 mm SL at West Island and Cape Bedout respectively (Table 1.12). Blacklip abalone spawn during summer and autumn, though spawning is poorly synchronised (Shepherd & Laws 1974). The annual spawning cycle may be driven by seasonal fluctuations in water temperature (Shepherd & Laws 1974).

Rates of growth vary throughout the life history stages of abalone with smaller abalone generally growing faster than larger abalone. The rate of growth is, however, dependent on environmental conditions that often vary through time and space. Emergent blacklip abalone growth is non linear and best represented by the von Bertalanffy growth model. Model parameter  $K$  ranged from 0.32 (Tiparra Reef) to 0.34  $\text{yr}^{-1}$  (West Island) while  $L_{\infty}$  varied between 138.8 (West Island) and 142.6 mm SL (Tiparra Reef; Table 1.13).

As for growth, rates of natural mortality vary spatially and temporally. Natural mortality rates of blacklip abalone were estimated at  $0.36 \text{ year}^{-1}$  at West Island and  $0.21 \text{ year}^{-1}$  at Tiparra Reef (Table 1.14).

**Table 1.12: Length at 50% maturity (mm, shell length) for blacklip (*H. rubra*) abalone in the CZ of the South Australian abalone fishery. The equation is of the form  $f(x) = a/(1+\exp(-(x-L_{50})/b))$ .**

Site	a	b	$L_{50}$	n	Reference
West Island	-	-	76		Shepherd & Laws (1974)
Tiparra Reef	-	-	93		Shepherd & Laws (1974)
Cape Bedout	1.00	5.50	99	352	SARDI unpublished
Cape de Couedic	1.00	6.91	95	1702	SARDI unpublished
Weirs Cove	0.99	5.47	96	646	SARDI unpublished

**Table 1.13:  $K$  ( $\text{yr}^{-1}$ ) and  $L_{\infty}$  (mm SL) for blacklip abalone tagged and recaptured in the CZ of the South Australian abalone fishery. Errors provided are standard errors. Length ranges are shell length (mm).**

Site	Length range	$K$	$L_{\infty}$	Reference
West Island	52-142	$0.34 \pm 0.034$	$138.8 \pm 2.9$	Shepherd & Hearn (1983)
Tiparra Reef	73-140	$0.32 \pm 0.063$	$142.6 \pm 4.3$	Shepherd & Hearn (1983)

**Table 1.14: Natural mortality rates ( $\text{yr}^{-1}$ ) for adult (emergent) blacklip abalone at two sites in the CZ of South Australia's abalone fishery.**

Site	$M$	Reference
West Island	$0.36 \pm 0.28$	Shepherd <i>et al.</i> (1982)
Tiparra Reef	$0.21 \pm 0.10$	Shepherd <i>et al.</i> (1982)

### 1.5 Previous stock assessments

The first assessment of the South Australian abalone resource was published by the South Australian Department of Fisheries in 1984 (Lewis *et al.* 1984). That report documented catch, effort and CPUE data from the start of the fishery to 1983 and concluded that fishing effort required capping at the 1971 level.

In 1996, the abalone research arrangements were reviewed (Andrew 1996). This review highlighted the need for (1) expansion of the fishery-independent surveys to include blacklip abalone in all three Zones of the fishery, (2) evaluation of the impacts of the 'fish-down' areas on blacklip abalone populations in the Southern Zone, (3) comprehensive re-assessment of the distribution of commercial catch and effort, and (4) estimation of both the recreational and illegal catch.

Fishery assessment reports were produced annually between 1998 and 2000 (Rodda *et al.* 1998, Shepherd *et al.* 1999, Rodda *et al.* 2000). The development of a Management Reporting System for the commercial catch and effort data permitted a re-evaluation of the commercial catch and effort information, particularly with respect to the distribution of effort and catch since the start of the fishery (Keesing *et al.* 2003).

The 2001 stock assessment report provided fishery statistics for all three Zones of the fishery (Mayfield *et al.* 2001) and provided the basis for more detailed stock assessments for each Zone during 2002 (Mayfield *et al.* 2002a,b, Mayfield and Ward 2002). The first dedicated CZ report (Mayfield and Ward 2002) synthesised all fisheries data for the CZ from 1968 to 2001. That report was updated in 2003 (Mayfield and Ward 2003) and 2004 (Mayfield *et al.* 2004). Substantial improvements to the previous report included the generation of standardised catch rates, estimation of egg production for each species and implementation of outputs from an age-based integrated stock assessment model to aid assessment of the greenlip abalone stocks in fishing area 21.

The last three reports (Mayfield and Ward 2003; Mayfield *et al.* 2004, 2005a) each identified that the information available for blacklip abalone indicated that those stocks were declining. The most recent report, Mayfield *et al.* (2005a), also highlighted that declines in the abundance of sub-legal-sized abalone, low estimates of retained egg production and high levels of catch from Tiparra Reef were likely to impact the sustainability of future catches at this level from this area.

## **2. GREENLIP ABALONE**

Commercial catch and effort data for this fishery have been collected since 1968. Fishers complete a research logbook for each fishing day and submit those data to SARDI Aquatic Sciences at the end of each month. The logbook data supplied have been used to provide the spatial and temporal analyses of catch, effort and catch-per-unit-effort (CPUE), from 1 January 1968 to 31 December 2005, presented in this section of the report. CPUE was computed using the mean ratio estimator (after Rice 1995). Data on the length-frequency distribution of the commercial catch were obtained from samples provided by commercial fishers. The CPUE was standardised and estimates of egg production, relative to those in an unfished (virgin) population determined, using models developed by SARDI Aquatic Sciences. Estimates of greenlip abalone abundance were obtained from fishery-independent diver surveys.

Fishery statistics in this section are provided at three spatial scales. These are (1) the whole greenlip abalone fishery (*i.e.* all areas of the CZ combined), (2) individual fishing areas, and (3) Tiparra Reef (mapcodes 21A-21G). Data are presented as mean  $\pm$  1 standard error (SE). Catch harvested from Cowell during exploratory fishing in 2004 and 2005 has been excluded unless otherwise stated.

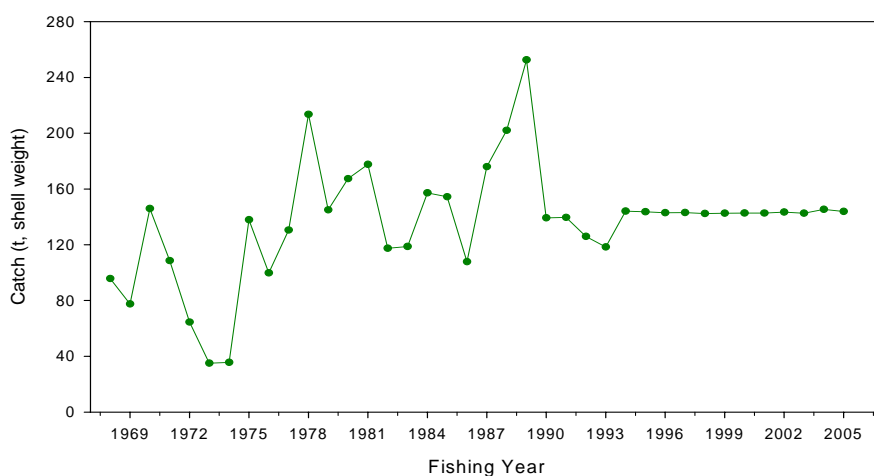
### **2.1 Catch**

Catch of greenlip abalone in the CZ increased significantly from  $<100 \text{ t.yr}^{-1}$  in 1968 and 1969 to a maximum of 252 t in 1989 (Linear Regression (LR):  $r^2 = 0.62$ ,  $df = 20$ ,  $p < 0.001$ ; Figure 2.1). Small catches were obtained in 1973 and 1974 ( $<50 \text{ t.yr}^{-1}$ ), but since 1978 catches have exceeded  $100 \text{ t.yr}^{-1}$ . Since 1990, the catch has been limited by quotas that have generally remained unchanged (Table 1.2; Figure 2.1).

Since 1984, the mean proportion of the greenlip abalone catch that has been harvested from fishing area 21 has increased from  $\sim 48\%$  to  $>80\%$  (Tables 2.1a-c). Over the last five years (2001 – 2005),  $\sim 85\%$  of the greenlip abalone TACC was harvested from fishing areas 21 and 24.

Similar patterns are also apparent when the spatial distribution of the catch is examined at a finer temporal scale. Prior to, or soon after, the implementation of the TACC (1990), the greenlip abalone catch was more evenly distributed among the available fishing areas

(Figure 2.2). Since the early 1980s, >35% of the greenlip abalone catch has been obtained from fishing area 21 (range: 35.7% in 1990 to 95.9% in 2001).



**Figure 2.1: Catch (t, shell weight) of greenlip abalone in the CZ of the South Australian abalone fishery from 1968 to 2005. Includes catch from Cowell.**

Catches have fluctuated inter-annually within the fishing areas of the CZ (Figure 2.3). The catch of greenlip abalone increased in fishing area 21 between 1990 and 2001 (from ~50 to >125 t.yr<sup>-1</sup>), whereafter it has declined. The catch from this area in 2005 was 87.6 t. In contrast, the catch of greenlip abalone declined between 1990 and 2002 in fishing area 22 (from >25 to 0 t.yr<sup>-1</sup>), whereafter it increased to >15 t in 2005. In the remaining fishing areas of the CZ, the catch of greenlip abalone has either declined (fishing areas 24, 29, 30 and 31) or fluctuated among years with no indication of a long-term trend (fishing areas 23, 25, 26, 27, 28 and 32) over the last 15 years. In some fishing areas the declines in catch over the last 15 years have been substantial. For example, catch of greenlip abalone declined from ~30 to ~10 t.yr<sup>-1</sup> in fishing area 24.

## 2.2 Effort

Estimates of total and mean daily effort on greenlip abalone in fishing area 21 and at Tiparra Reef were computed from only those daily records where the blacklip abalone catch was zero because few blacklip abalone are harvested from these areas. This was done to overcome the problem caused by effort not being differentiated among species on each fishing day.

Total fishing effort in fishing area 21 increased from ~400 hr in 1978 to >2 800 hr in 1989 (Figure 2.4). Following the imposition of TACC from 1990, fishing effort declined to <800 hr within one year. Effort increased from 756 hours in 1990 to >1 700 hours in 1994, whereafter it has declined significantly (LR:  $r^2 = 0.65$ ,  $df = 10$ ,  $p < 0.01$ ) to 1 004 hr in 2005. The temporal patterns in total fishing effort at Tiparra Reef closely match those of fishing area 21.

**Table 2.1a: Average catch of greenlip abalone (t, shell weight), % of total catch and cumulative % for the fishing areas of the CZ for the period 1980 – 1984.**

Fishing area	Catch (t)	%	Cumulative %
21	71.2	48.2	48.2
24	42.2	28.6	76.8
25	7.1	4.8	81.6
29	6.4	4.3	85.9
22	5.4	3.7	89.6
23	3.9	2.7	92.2
30	3.7	2.5	94.8
31	2.8	1.9	96.6
32	1.9	1.3	97.9
27	1.4	0.9	98.9
26	1.2	0.8	99.7
28	0.5	0.3	100

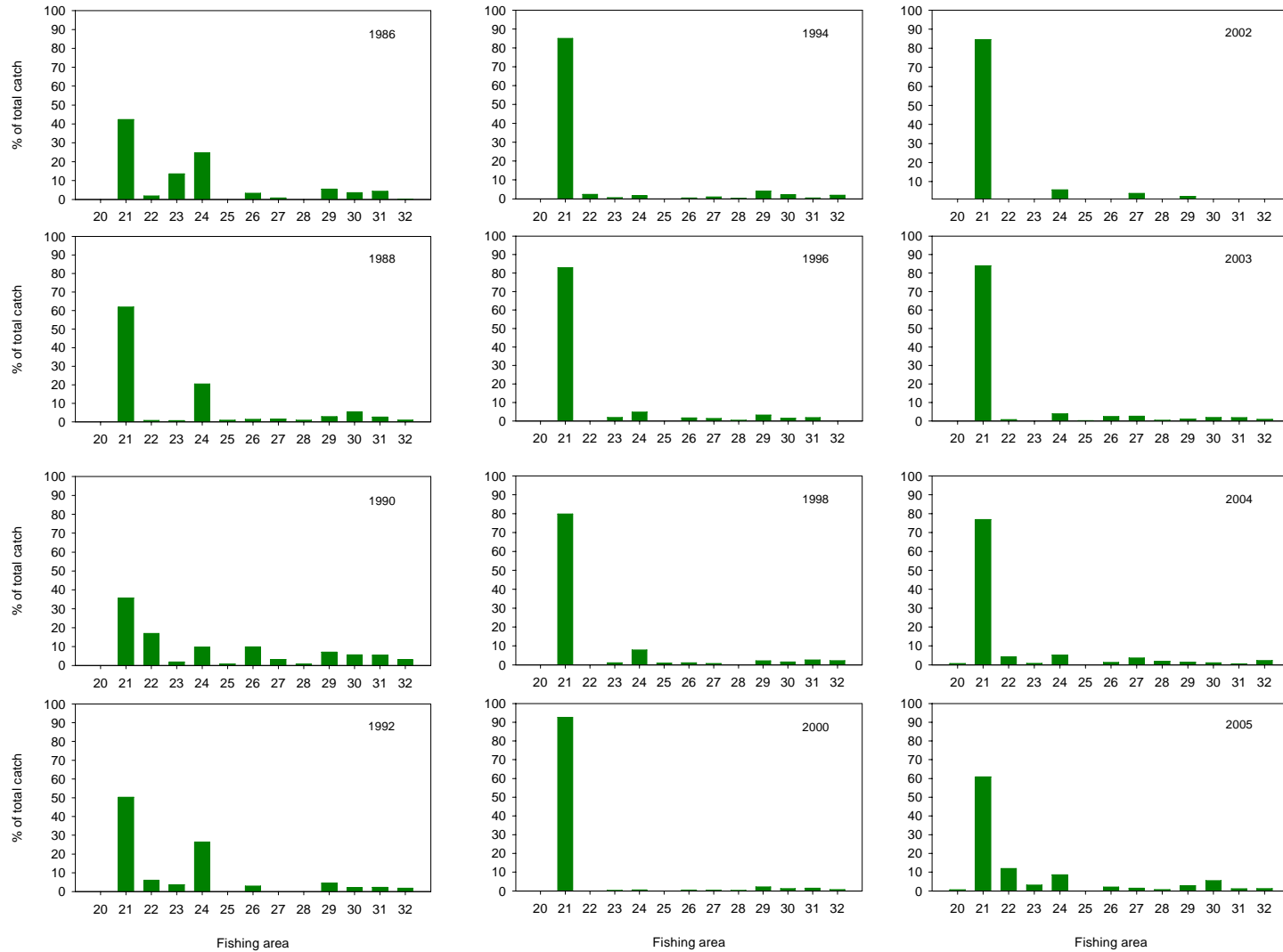
**Table 2.1b: Average catch of greenlip abalone (t, shell weight), % of total catch and cumulative % for the fishing areas of the CZ for the period 1991 – 1995.**

Fishing area	Catch (t)	%	Cumulative %
21	86.7	64.5	64.5
24	21.0	15.6	80.1
22	9.4	7.0	87.1
29	4.2	3.1	90.2
30	3.1	2.3	92.5
23	2.6	1.9	94.4
31	2.2	1.6	96.1
32	2.1	1.5	97.6
26	1.9	1.4	99.0
27	0.9	0.7	99.7
25	0.3	0.2	99.9
28	0.1	0.1	100

**Table 2.1c: Average catch of greenlip abalone (t, shell weight), % of total catch and cumulative % for the fishing areas of the CZ for the period 2001 – 2005.**

Fishing area	Catch (t)	%	Cumulative %
21	115.5 <sup>#</sup>	80.6	80.6
24	6.7	4.7	85.3
22	4.9	3.4	88.7
27	3.6	2.5	91.2
30	2.7	1.9	93.1
29	2.4	1.6	94.7
26	2.3	1.6	96.3
32	1.5	1.0	97.4
31	1.4	0.9	98.3
23	1.2	0.8	99.1
28	1.1	0.8	99.9
25	0.1	0.1	100

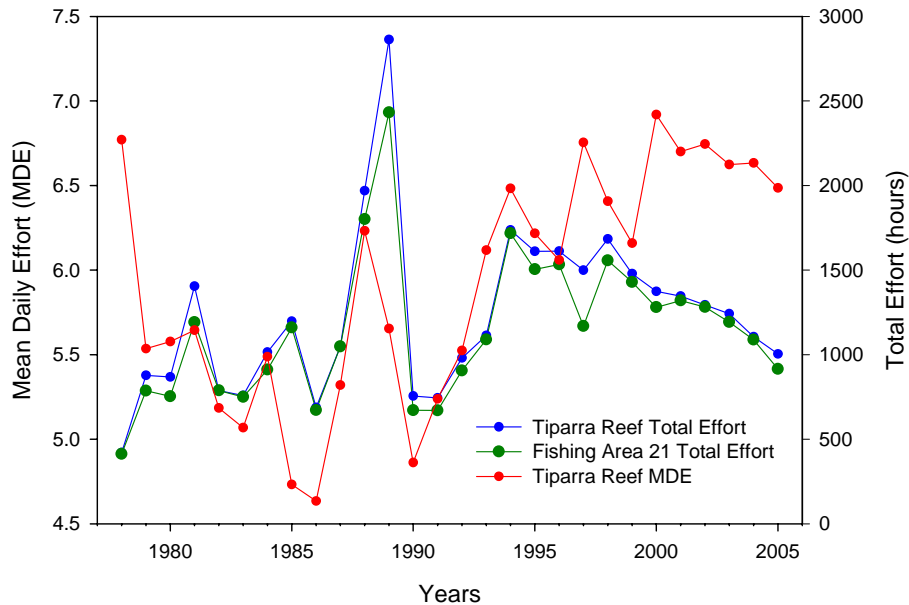
<sup>#</sup>Includes catch from Cowell in 2004 and 2005



**Figure 2.2: Spatial distribution of the greenlip abalone catch (% of total catch) among each of the fishing areas in the CZ in 1984, 1986, 1988, 1990, 1992, 1994, 1996, 1998, 2000, 2002, 2003, 2004 and 2005. Includes catch from Cowell in 2004 and 2005.**



**Figure 2.3: Catch of greenlip abalone (t, shell weight) in each of the fishing areas comprising the CZ from 1978 to 2005.**



**Figure 2.4: Total effort in fishing area 21 and at Tiparra Reef, and mean daily effort at Tiparra Reef from 1978 to 2005.**

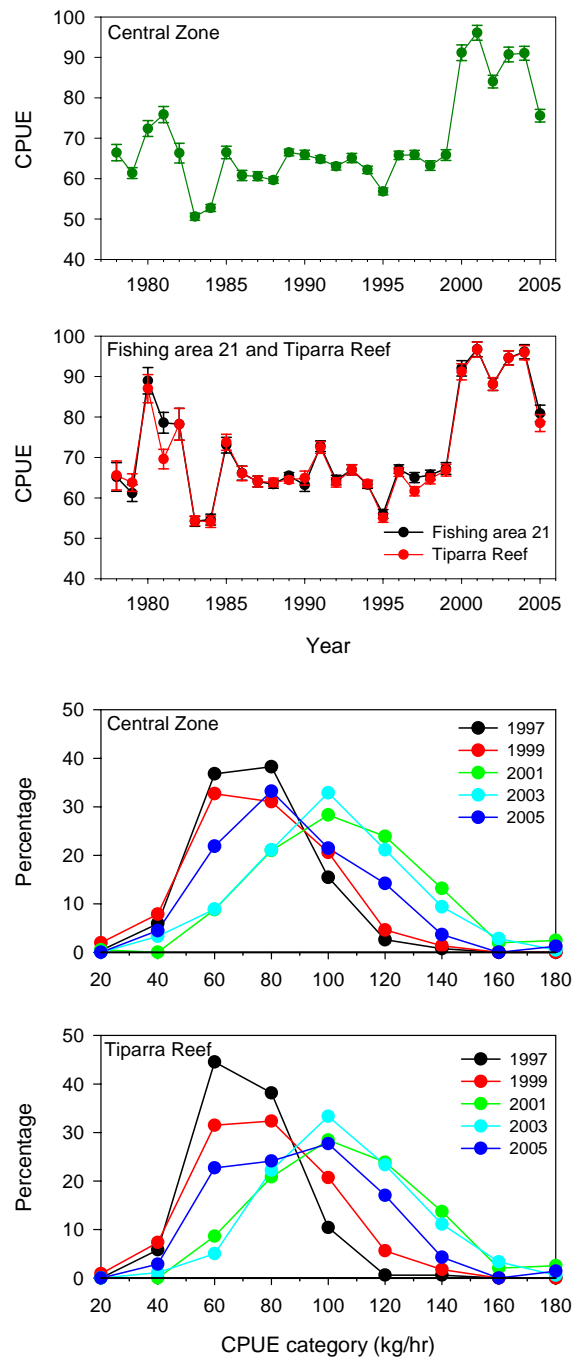
Mean daily effort on Tiparra Reef declined rapidly from 6.8 to 4.6 hr.day<sup>-1</sup> from 1978 to 1986. Between 1987 and 2000, it increased significantly (LR:  $r^2 = 0.58$ ,  $df = 12$ ,  $p < 0.01$ ), reaching 6.9 hr.day<sup>-1</sup> in 2000. Mean daily effort has declined over the last five years. In 2005 it was 6.5 hr.day<sup>-1</sup>, the lowest level since 1999 (6.2 hr.day<sup>-1</sup>).

### 2.3 Catch-per-unit effort (CPUE)

The CPUE on greenlip abalone was defined as greenlip abalone catch (kg) / total daily effort (hours) computed from only those daily records where the blacklip abalone catch was zero. This was justified for three reasons: (1) most (>70%) fishing records between 1978 and 2005 report a blacklip abalone catch of zero; (2) more than 80% of the greenlip abalone catch in this Zone is obtained on fishing days when no blacklip abalone are harvested and; (3) greenlip and blacklip abalone are typically harvested from different fishing areas within the CZ (see Sections 2.1 & 3.1).

The CPUE on greenlip abalone, in all fishing areas of the CZ combined, fluctuated between  $50.5 \pm 0.9$  (1983) and  $75.8 \pm 2.0$  kg.hr<sup>-1</sup> (1981) from 1978 to 1985 (Figure 2.5). Between 1986 and 1999, CPUE was relatively stable, ranging from  $56.8 \pm 0.9$  (1995) to  $66.5 \pm 0.8$  kg.hr<sup>-1</sup> (1989). The CPUE in 2000 ( $91.1 \pm 1.9$  kg.hr<sup>-1</sup>) was substantially greater than the mean CPUE from 1978 to 1998 ( $63.1 \pm 0.3$  kg.hr<sup>-1</sup>) and significantly greater than that in 1999 ( $65.8 \pm 1.3$  kg.hr<sup>-1</sup>; t-test:  $t = 10.82$ ,  $df = 378$ ,  $p < 0.01$ ). Between 2001 and 2004 the mean CPUE remained high, relative to historical values, ranging between  $84.0 \pm 1.6$  kg.hr<sup>-1</sup> (2002) and  $96.1 \pm 1.8$  kg.hr<sup>-1</sup> (2001). However, the mean CPUE declined substantially between 2004 ( $91.0 \pm 1.7$  kg.hr<sup>-1</sup>) and 2005 ( $75.6 \pm 1.6$  kg.hr<sup>-1</sup>). The mean CPUE in 2005 was at the lowest level since 1999 ( $65.8 \pm 1.3$  kg.hr<sup>-1</sup>).

The temporal trends in CPUE observed in fishing area 21 and at Tiparra Reef are similar to those observed for the CZ (Figure 2.5). This arises primarily from the high proportion of the TACC harvested from this area. These trends were also evident in differences in the frequency distribution of catch rates among years, that were right-skewed in 1997, 1999 and 2005, relative to 2001 and 2003 (Figure 2.5). These patterns suggest there may have been (at least temporary) local depletion of the stock in this fishing area.



**Figure 2.5: CPUE (kg.hr<sup>-1</sup>) on greenlip abalone for all fishing areas of the CZ combined in fishing area 21 and at Tiparra Reef from 1978 to 2005 (top) and frequency distribution of catch rates in the CZ and at Tiparra Reef in 1997, 1999, 2001, 2003 and 2005 (bottom).**

## 2.4 Standardised CPUE

To account for the effects of technological advancement, diver behaviour and diver efficiency on effective fishing effort, the historical catch and effort data, for all fishing areas of the CZ combined, and at Tiparra Reef, were standardised in conjunction with information from licence holders on their fishing practices (Mayfield *et al.* 2003) from 1982, using a generalised linear model (GLM). 1982 was selected as the reference year as it was the first year for which substantial information was available from licence holders. The two models used were, respectively:

$$\text{Ln}(\text{catch}_g) = \mu + \beta_0(\text{season}) + \beta_1(\text{map}) + \beta_2(\text{month}) + \beta_3(\text{licence, c-diver}) + \beta_4 \ln(\text{effort}) + \beta_5(\text{licence, UWV}) + \beta_6(\text{licence, GPS}) + \beta_7(\text{licence, ECHO}) + \beta_8(\text{licence, HWS}) + \varepsilon$$

and

$$\text{Ln}(\text{catch}_g) = \mu + \beta_0(\text{season}) + \beta_1(\text{code}) + \beta_2(\text{month}) + \beta_3(\text{licence, c-diver}) + \beta_4 \ln(\text{effort}) + \beta_5(\text{licence, UWV}) + \beta_6(\text{licence, GPS}) + \beta_7(\text{licence, ECHO}) + \beta_8(\text{licence, HWS}) + \varepsilon$$

where

$\mu$  is the global mean of log-transformed catch and is a constant;

$\beta_0(\text{season})$  captures the relative abundance of greenlip abalone in the different fishing seasons;

$\beta_1(\text{map})$  captures the relative differences in abundance of greenlip abalone in the different fishing areas comprising the CZ;

$\beta_1(\text{code})$  captures the relative differences in abundance of greenlip abalone in the different mapcodes comprising the Tiparra Reef;

$\beta_2(\text{month})$  is the relative monthly change in fishing efficiency arising from changes in seasonally varying factors, such as swell and underwater visibility;

$\beta_3(\text{licence, c-diver})$  captures the differing fishing efficiency of individual divers employed by each licence;

$\beta_4 \ln(\text{effort})$  captures the effect of fishing effort in that a 1% change in fishing effort gives approximately a  $\beta_4\%$  change in the greenlip abalone catch;

$\beta_5(\text{licence, UWV})$  captures the effect from the use of an under-water vehicle (cage) for each licence in the fishery;

$\beta_6(\text{licence, GPS})$  captures the effect of use of a GPS for each licence in the fishery;

$\beta_7(\text{licence, ECHO})$  captures the effect of use of an echo sounder for each licence in the fishery;

$\beta_8(\text{licence, HWS})$  captures the effect of use of a hot-water suit for each licence in the fishery; and

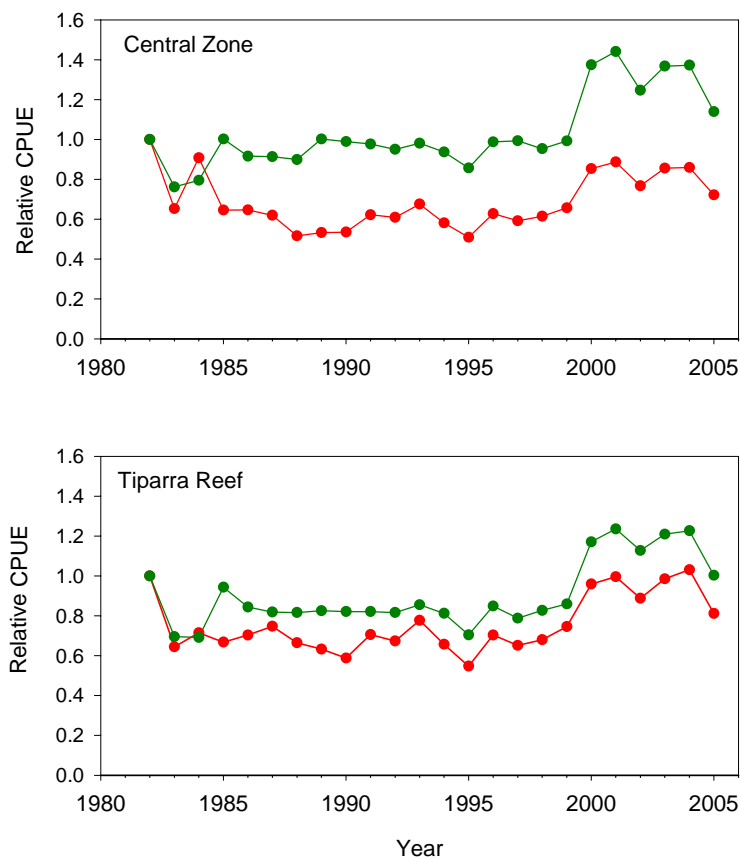
$\varepsilon$  is the error term (assumed to be log-normally distributed with a mean of zero and a constant variance).

The standardised and raw (observed) CPUE show dissimilar temporal patterns in the CZ (Figure 2.6). There was no evidence of a long-term trend in raw CPUE between 1982 and 1999 (LR:  $r^2 = 0.15$ ,  $df = 16$ ,  $p < 0.01$ ). Raw CPUE increased substantially between 1999 and

2000, and exceeded that in 1982 by between 25 and 44% from 2000 to 2004. Raw CPUE declined substantially between 2004 and 2005, but remained 14% greater than that in 1982.

In contrast, the standardised CPUE in the CZ declined significantly between 1982 and 1995 (LR:  $r^2 = 0.42$ ,  $df = 12$ ,  $p < 0.01$ ), increased significantly between 1996 and 2004 (LR:  $r^2 = 0.63$ ,  $df = 7$ ,  $p < 0.01$ ), and declined substantially between 2004 and 2005. Notably, the standardised CPUE in 2005 was 72% of that in 1982.

Temporal patterns in raw and standardised CPUE were more evident at Tiparra Reef (Figure 2.6). Both marginally decreased between 1982 and 1995, both increased significantly from 1996 to 2004 (LR:  $r^2 = 0.77$ ,  $df = 8$ ,  $p < 0.01$  and LR:  $r^2 = 0.71$ ,  $df = 8$ ,  $p < 0.01$ , respectively), and both declined substantially between 2004 and 2005. Nevertheless, the raw and standardised CPUE over the last six years were substantially greater than the long-term mean.



**Figure 2.6: Relative, to that in 1982, raw (observed, green line) and standardised (red line) CPUE on greenlip abalone in all the fishing areas of the CZ combined (top), and at Tiparra Reef separately (bottom).**

## 2.5 Length-frequency distribution of the catch

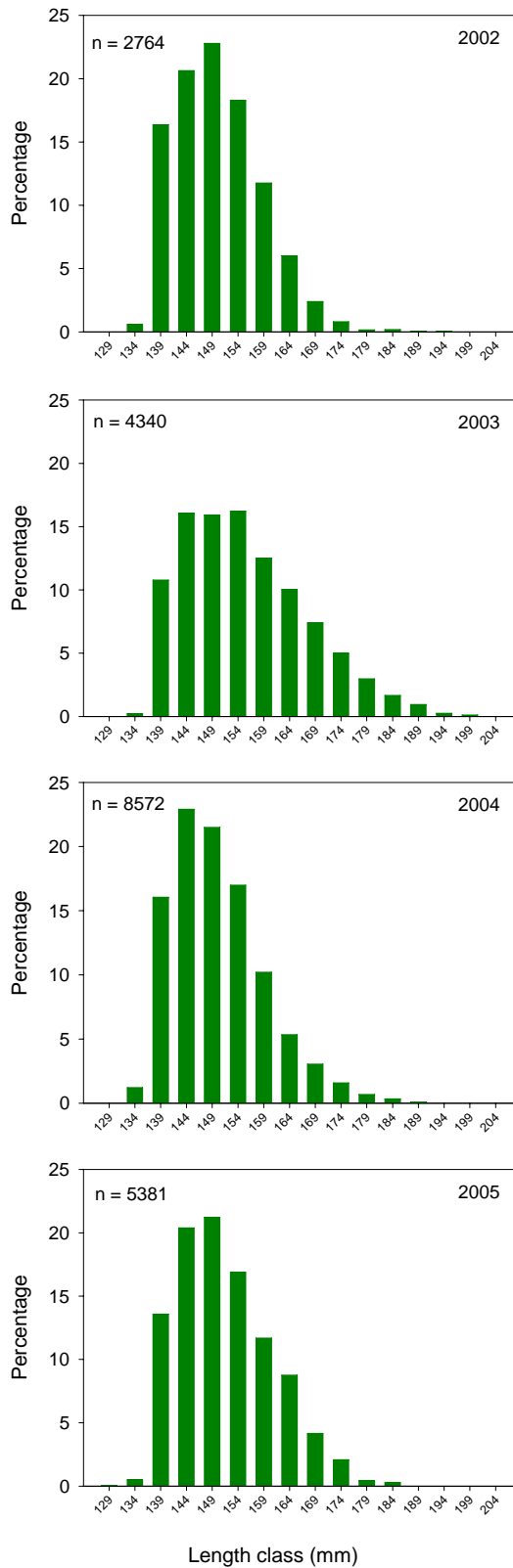
Estimates of the length of individuals in the commercial greenlip abalone catch have been determined from shell samples provided by commercial fishers from 2002 to 2005. Sample sizes range between 2 764 (2002) and 8 572 (2004) shells and represent <2% of the total catch.

About 35% of the greenlip abalone sampled from the CZ during 2002 were smaller than 145 mm SL. The modal length class was 145 – 149 mm SL, and the mean length was  $147.8 \pm 0.2$  mm SL (Figure 2.7). During 2003, the mean length ( $153.2 \pm 0.2$  mm SL) and the modal length class (150 – 154 mm SL) were both larger, and the proportion of the sample smaller than 145 mm SL (26.8%) was lower when compared with those in 2002. However, between 2003 and 2004, the mean length decreased by >5 mm SL (from  $153.2 \pm 0.2$  to  $148.0 \pm 0.1$  mm SL), the modal length class decreased from 150 – 154 to 140 – 144 mm SL and the proportion of the sample smaller than 145 mm SL increased to 39.9%. Differences between 2004 and 2005 were smaller: the mean length increased by 1 mm (to  $149.0 \pm 0.1$  mm SL), the modal length class increased to 145 – 149 mm SL and the proportion of the sample smaller than 145 mm SL decreased to 34.4%.

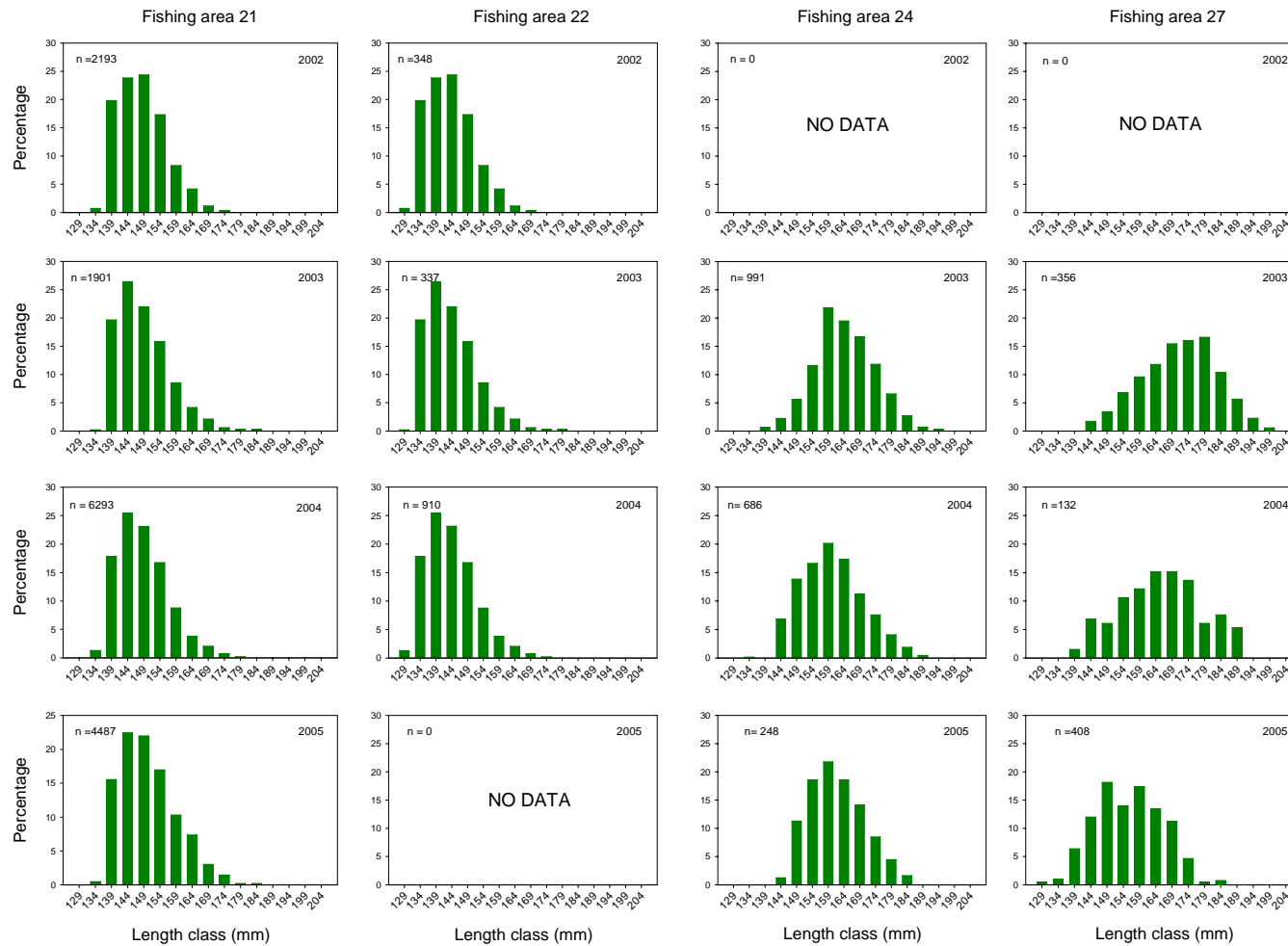
There was substantial spatial variation in the length-frequency distribution of the shells sampled since 2003 (Figure 2.8). During 2003 and 2004, the mean length of greenlip abalone sampled from the commercial catch exceeded 155 mm SL in fishing areas 24 and 27, but was <150 mm SL in fishing areas 21 and 22. Thus, in fishing areas 24 and 27, the mean length exceeded the MLL (130 mm SL) by >25 mm SL. In each of the four years for which data were available, the mean length was smallest in fishing area 21.

There were no obvious changes in the length-frequency distributions of commercial catches in fishing areas 21 (between 2002 and 2005), 22 (between 2002 and 2004) or 24 (between 2003 and 2005; Figure 2.8). However, in fishing area 27, between 2003 and 2005, the mean length decreased by >15 mm SL (from  $168.9 \pm 0.6$  to  $153.6 \pm 0.5$  mm SL), the modal length class declined from 175 – 179 to 145 – 149 mm SL and the percentage of the catch <150 mm SL increased from 5 to 38%. These changes suggest that the exploitation rate in this area has increased substantially since 2003, despite the low, decreasing levels of catch being harvested from fishing area 27.

The only evidence of ‘knife-edge’ fishing (individuals having a high probability of capture as they attain the MLL) on greenlip abalone in the CZ since 2003 was in fishing areas 21 and 22.



**Figure 2.7: Length-frequency distributions obtained from measuring greenlip abalone shells from the commercial fishery in the CZ during 2002, 2003, 2004 and 2005. Length classes are mm SL.**



**Figure 2.8: Length-frequency distributions obtained from measuring greenlip abalone shells from the commercial fishery in fishing areas 21, 22, 24 and 27 of the CZ during 2003, 2004 and 2005. Length classes are mm SL.**

## **2.6 Estimates of egg production**

A simple egg-production model, based on the Beverton & Holt (1957) yield-per-recruit model (after King 1995) that considers the dependence of egg production on growth, age at first capture and fishing mortality (F), was used to estimate the proportion of pristine egg production conserved under the current management arrangements for greenlip abalone in fishing area 21. Full details of the biological data used in the model, and the model assumptions are provided in Appendix 1.

The estimate of the percentage of unfished egg production conserved in fishing area 21 in 2005 was 40.3%. This represented an increase of ~4% over the estimate in 2004 (36.9%). Nevertheless, levels of egg production, relative to that in an ‘unfished’ state, have been below 50% since 2002.

## **2.7 Fishery-independent abalone surveys**

Fishery-independent abalone surveys (FIAS) undertaken by SARDI Aquatic Sciences have been used to monitor changes in greenlip abalone abundance and population structure at Tiparra Reef since 1968. This long-term data set provides information on changes in the relative abundance and length structure of greenlip abalone populations over time.

Up to 22 replicate surveys have been completed each year. In general, each replicate consisted of two divers each doing two 10-minute surveys. During each 10 minute count, all emergent (visible) greenlip abalone observed were measured.

To calculate the relative abalone abundance, two assumptions are made: (1) it takes four seconds to measure each abalone, and (2) 20 metres was covered in 1 minute (Shepherd 1984). The total time taken to measure all the abalone observed in each 10-minute count is subtracted from 10 minutes and the distance swum calculated using assumption 2. This distance is then used in the density estimation. These estimates of ‘abalone density’ are used to assess changes in relative abalone abundance and length-frequency data are used to assess changes in population structure.

SARDI Aquatic Sciences has recently completed a FRDC-funded research project to develop and field-test survey methods for greenlip abalone in South Australia (FRDC 2001/076; McGarvey in press). McGarvey (in press) concluded that divers counting all individuals within 1 m on both sides of leaded-line transects deployed from a vessel at evenly-distributed locations, within a bounded study region provided the most tractable method to estimate the absolute abundance of greenlip abalone. This survey design proved robust in that the

difference in the number of abalone between surveys closely matched the number of abalone removed by commercial fishers undertaking directed 'fish-down' harvesting within pre-defined study regions.

### 2.7.1 Changes in abundance of greenlip abalone

Between 1968 and 1986 greenlip abalone abundance declined significantly (LR:  $r^2 = 0.81$ ,  $df = 10$ ,  $p < 0.01$ ; Figure 2.9). The abundance increased over the next four years to the second-highest recorded value of  $0.76 \pm 0.23$  abalone.m<sup>-2</sup> in 1990. Between 1990 and 1994 the abundance declined by almost 65% to  $0.27 \pm 0.03$  abalone.m<sup>-2</sup>. Since 1998, estimates of abundance have been substantially greater than that observed in 1994. The estimate of abundance in 2005 ( $0.74 \pm 0.08$  abalone.m<sup>-2</sup>) was the third highest value on record.

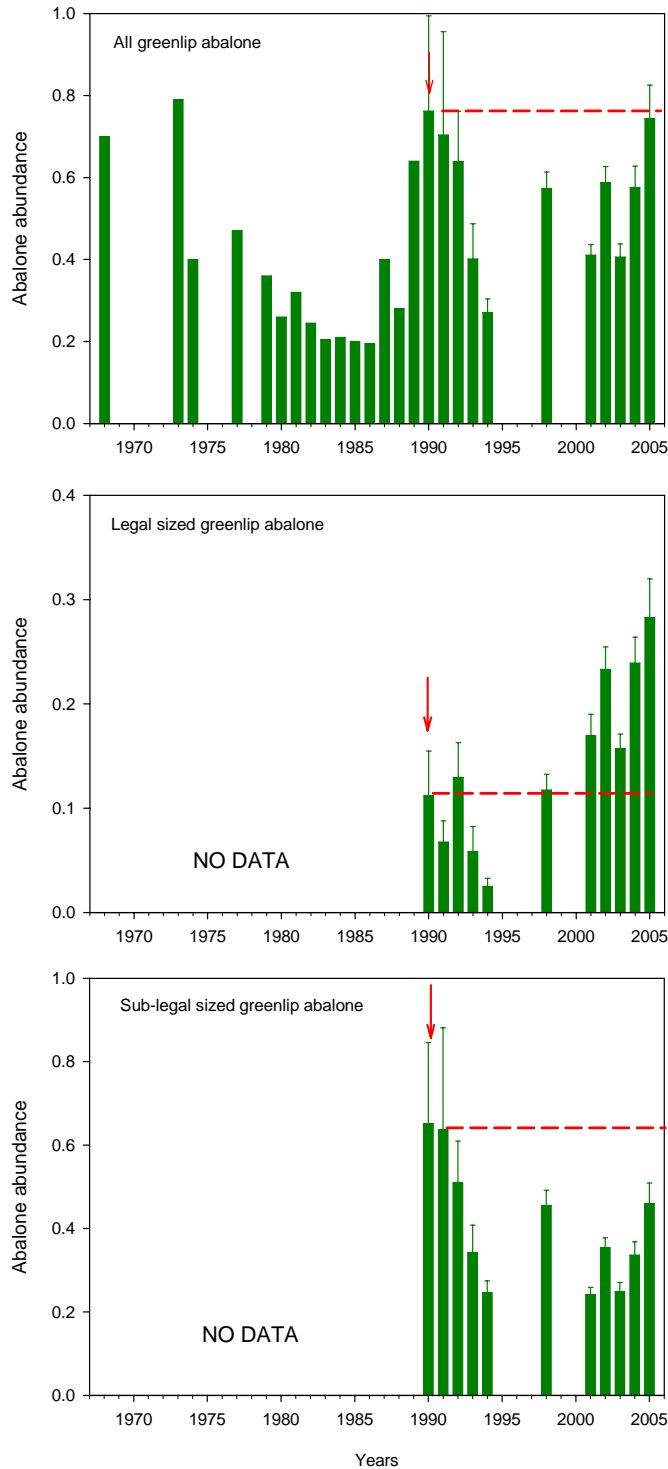
Although the mean abundance of legal-sized greenlip abalone (>130 mm SL) declined substantially between 1990 ( $0.11 \pm 0.04$  abalone.m<sup>-2</sup>) and 1994 ( $0.03 \pm 0.01$  abalone.m<sup>-2</sup>), their abundance increased steadily thereafter (Figure 2.9). Since 1998 (*i.e.* five surveys), the abundance of legal-sized abalone has exceeded that observed in 1990. The estimate of the abundance legal-sized greenlip abalone in 2005 ( $0.28 \pm 0.04$  abalone.m<sup>-2</sup>) was the highest value on record. Importantly, there was a significant correlation between the abundance of legal-sized greenlip abalone and commercial CPUE at Tiparra Reef (LR:  $r^2 = 0.64$ ,  $df = 9$ ,  $p < 0.05$ ).

The mean abundance of sub-legal-sized greenlip abalone (<130 mm SL) declined sharply between 1990 ( $0.65 \pm 0.19$  abalone.m<sup>-2</sup>; Figure 2.9) and 1994 ( $0.25 \pm 0.03$  abalone.m<sup>-2</sup>). The estimate of mean abundance was substantially greater in 1998 ( $0.46 \pm 0.04$  abalone.m<sup>-2</sup>), but again low in 2001 ( $0.24 \pm 0.03$  abalone.m<sup>-2</sup>). Since 2001, estimates of mean abundance have increased substantially. In 2005 the estimate was ( $0.46 \pm 0.05$  abalone.m<sup>-2</sup>), which represented a 37% increase over that observed in 2004.

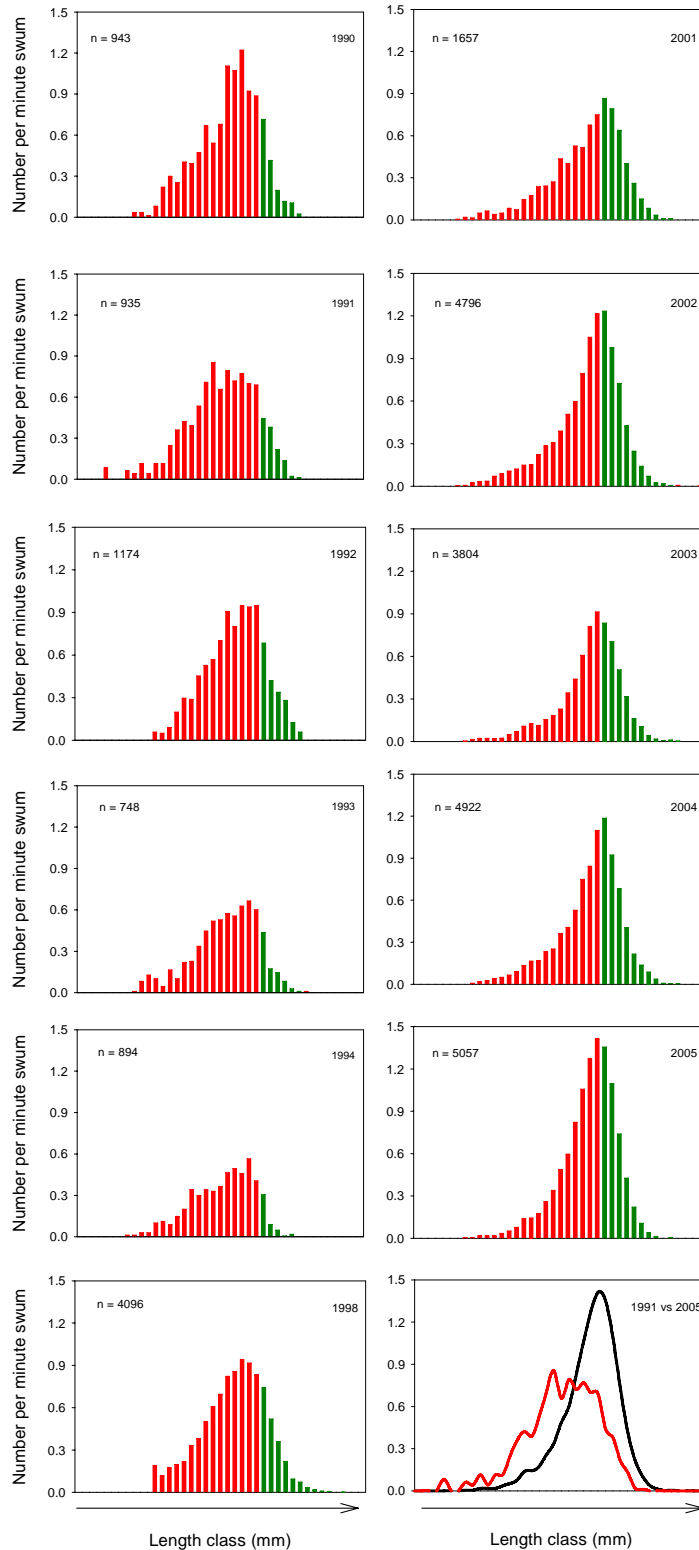
### 2.7.2 Changes in greenlip abalone population length structure

The length-frequency distributions of greenlip abalone at Tiparra Reef show two distinct trends (Figure 2.10). Firstly, the proportion of large greenlip abalone observed has increased over the last decade. This is supported by three lines of evidence: (1) the proportion of legal-sized abalone has increased from <20% (1990 – 1994) to ~40% (2001 – 2005); (2) the modal length class has increased from <125 mm SL (1991–1998) to >125 mm SL (2003 and 2005) and >130 mm SL (2001, 2002 and 2004); and (3) the mean length has increased from between 102 and 112 (1991 – 1998) to >119 mm SL (2001 – 2005). Secondly, the shape of the distribution has changed from bell-shaped (1991, 1992, 1993, 1994 and 1998), to increasingly

left-skewed through the period 2001 – 2005. This is the result of a reduction in the proportion of greenlip abalone in the length range 65–110 mm SL observed on the fishery-independent surveys.



**Figure 2.9: Estimated abundance (abalone.m<sup>-2</sup>) of all (top), legal-sized (middle) and sub-legal-sized (bottom) greenlip abalone at Tiparra Reef from 1968 to 2005. The red horizontal line in each plot indicates the estimated abundance in 1990, the first year in which TACC were implemented (indicated by red arrow).**



**Figure 2.10: Length-frequency distribution of legal-sized (green bars) and sub-legal-sized (red bars) greenlip abalone at Tiparra Reef observed on fishery-independent surveys during 1990, 1991, 1992, 1993, 1994, 1998, 2001, 2002, 2003, 2004 and 2005. The bin size is 5 mm SL. The Y-axis shows numbers.minute swum<sup>-1</sup>.**

### **3. BLACKLIP ABALONE**

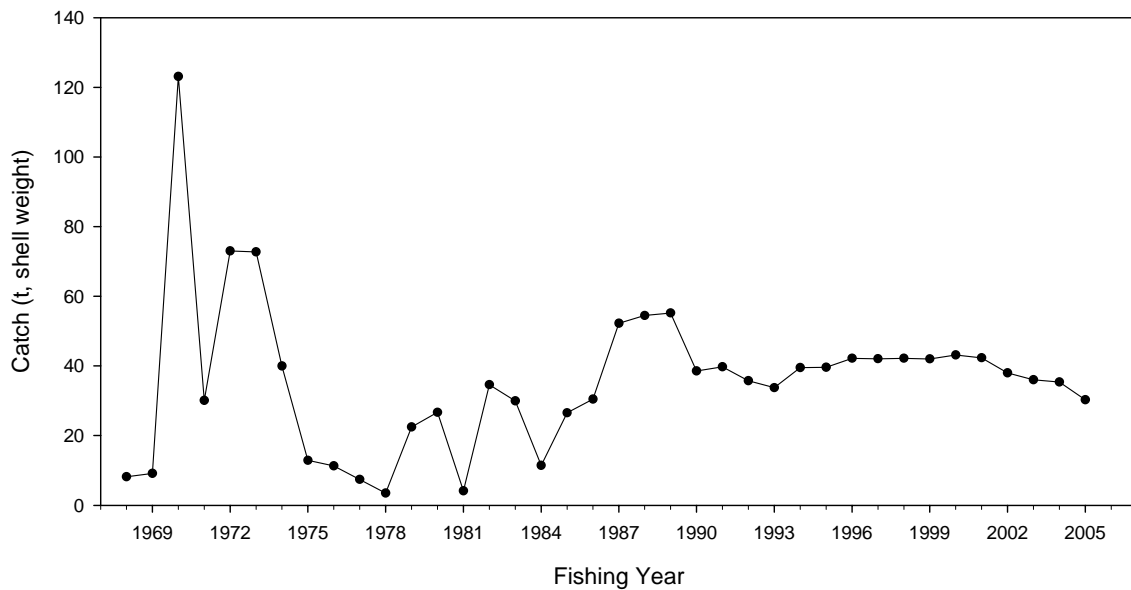
Commercial catch and effort data for this fishery have been collected since 1968. Fishers complete a research logbook for each fishing day and submit those data to SARDI Aquatic Sciences at the end of each month. The logbook data supplied have been used to provide the spatial and temporal analyses of catch, effort and catch-per-unit-effort (CPUE), from 1 January 1968 to 31 December 2005, presented in this section of the report. CPUE was computed using the mean ratio estimator (after Rice 1995). Data on the length-frequency distribution of the commercial catch were obtained from samples provided by commercial fishers. The CPUE was standardised and estimates of egg production, relative to those in an unfished (virgin) population determined, using models developed by SARDI Aquatic Sciences. The integrated length-structured national abalone stock assessment and risk analysis model (FRDC 1999/116; Gorfine *et al.* 2005) was used to aid assessment of the blacklip abalone stocks in the CZ.

Fishery statistics in this section are provided at two spatial scales. These are (1) the whole blacklip abalone fishery (*i.e.* all areas of the CZ combined) and (2) individual fishing areas. Data are presented as mean  $\pm$  1 standard error (SE), unless otherwise stated.

#### **3.1 Catch**

Over the first decade of the fishery (1968 – 1977), the catch of blacklip abalone in the CZ fluctuated between 7 (1977) and 123 t.yr<sup>-1</sup> (1970; Figure 3.1). The lowest reported catch was 3.5 t in 1978. The amount of blacklip abalone harvested increased significantly from ~22 t in 1979 to >55 t in 1989 (LR:  $r^2 = 0.53$ ,  $df = 9$ ,  $p < 0.05$ ). During this period, small catches were obtained during 1981 (4.1 t) and 1984 (11.4 t) while large catches were reported in 1987 (52.3 t) and 1988 (54.5 t). Since 1990, the catch has been limited by quotas that have generally remained unchanged (Table 1.2; Figure 3.1). The TACC was not harvested from 2002 to 2004, with reported catches ranging between 84 and 89% of the TACC. The TACC was reduced from 42.3 t (1994 – 2004) to 29.7 t for 2005. In combination, this has resulted in a substantial decrease (~30%) in the catch of blacklip abalone from this Zone since 2001.

Over the last five years (2001 –2005), an average of ~80% of the blacklip abalone TACC was harvested from fishing areas 26, 27 and 29 (Table 3.1c; Figure 3.2). Since 1980, the number of fishing areas utilised to obtain about 75% of the blacklip abalone catch increased from three (1980 – 1984) to four (1991 – 1995) and then reduced to three again (2001 – 2005; Table 3.1a).



**Figure 3.1: Catch (t, shell weight) of blacklip abalone in the CZ of the South Australian abalone fishery from 1968 to 2005.**

Levels of catch have fluctuated inter-annually within the fishing areas of the CZ (Figure 3.3). For example, blacklip abalone have been harvested from several fishing areas on an intermittent basis. This is particularly noticeable for fishing areas 22, from which blacklip abalone were only harvested during 1985, 1990, 1991 and 1992, and fishing area 25. Other areas from which low or sporadic catches of blacklip abalone have been obtained are 21, 24 and 32. Since TACC were imposed in 1990, the catch of blacklip abalone has increased in fishing areas 27 (from  $\sim 1$  to  $\sim 10$  t.yr<sup>-1</sup>) and 28 (from 0 to  $\sim 3$  t.yr<sup>-1</sup>). In contrast, catches in fishing areas 23 (from 7 to  $< 1$  t.yr<sup>-1</sup>), 29 (from  $> 10$  to  $< 5$  t.yr<sup>-1</sup>), 30 and 31 have declined over the same period. The temporal pattern in fishing area 26 was more complex: catches increased substantially between 1985 and 2000 (from  $\sim 5$  to  $> 20$  t.yr<sup>-1</sup>), whereafter they declined sharply to  $< 6$  t in 2005. This probably reflects the decline in CPUE on blacklip abalone in this fishing area since 2000 (see Section 3.2).

### 3.2 Catch-per-unit effort (CPUE)

The CPUE on blacklip abalone was defined as blacklip abalone catch (kg) / total effort (hours) computed from only those daily records where the blacklip abalone catch was greater than or equal to 50% of the total catch. This was justified for three reasons: (1) few fishing records between 1978 and 2005 report a blacklip abalone catch of zero; (2) only between 10 and 33% of the blacklip abalone catch in this Zone is obtained on fishing days when no greenlip abalone are harvested and; (3) using daily records where the blacklip abalone catch is less than 50% of the total catch is inappropriate as blacklip abalone were probably not being targeted on those days.

**Table 3.1a: Average catch of blacklip abalone (tonnes), % of total catch and cumulative % for the fishing areas of the CZ for the period 1980 – 1984.**

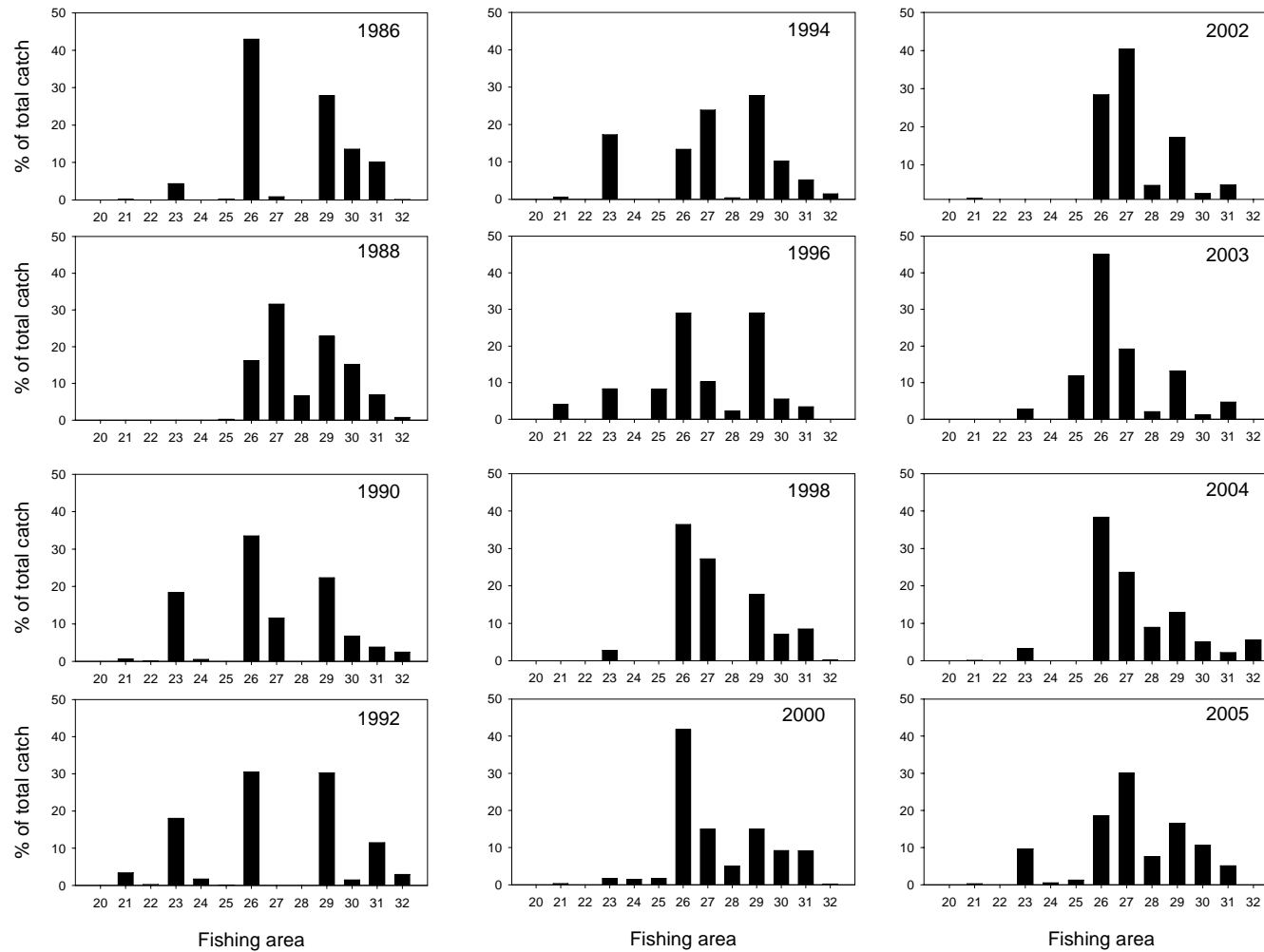
Fishing area	Catch (tonnes)	%	Cumulative %
29	9.3	43.6	43.6
26	4.4	20.7	64.3
31	2.8	13.2	77.4
30	1.8	8.4	85.8
25	1.2	5.6	91.4
27	0.9	4.1	95.5
23	0.6	2.6	98.1
28	0.2	0.7	98.8
21	0.1	0.5	99.4
32	0.1	0.4	100
24	0	0	100
22	0	0	100

**Table 3.1b: Average catch of blacklip abalone (tonnes), % of total catch and cumulative % for the fishing areas of the CZ for the period 1991 – 1995.**

Fishing area	Catch (tonnes)	%	Cumulative %
26	11.5	30.7	30.7
29	10.1	26.9	57.6
23	5.1	13.5	71.1
27	3.2	8.6	79.7
31	2.5	6.7	86.3
30	2.3	6.1	92.4
25	1.6	4.3	96.7
21	0.5	1.2	97.9
32	0.5	1.2	99.2
24	0.2	0.4	99.6
22	0.1	0.3	100
28	0	0	100

**Table 3.1c: Average catch of blacklip abalone (tonnes), % of total catch and cumulative % for the fishing areas of the CZ for the period 2001 – 2005.**

Fishing area	Catch (tonnes)	%	Cumulative %
26	13.5	37.1	37.1
27	9.9	27.1	64.3
29	5.5	15.1	79.3
28	1.8	5.0	84.3
30	1.6	4.3	88.6
31	1.3	3.5	92.2
23	1.1	3.0	95.2
25	1.0	2.7	97.9
32	0.4	1.1	99.0
21	0.3	0.9	99.9
24	0.0	0.1	100
22	0.0	0.0	100



**Figure 3.2: Spatial distribution of the blacklip abalone catch (% of total catch) among each of the fishing areas in the CZ in 1986, 1988, 1990, 1992, 1994, 1996, 1998, 2000, 2002, 2003, 2004 and 2005.**

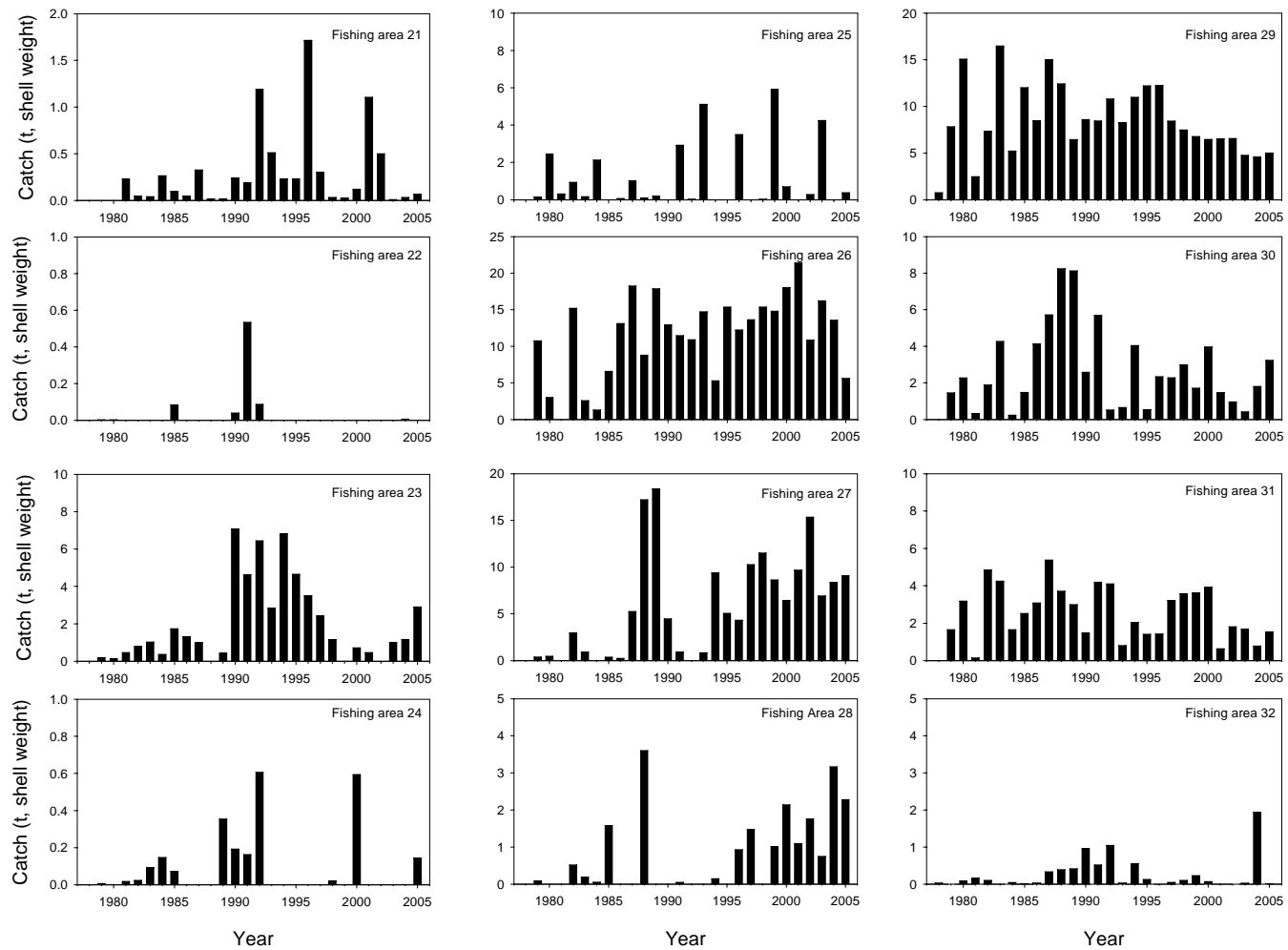
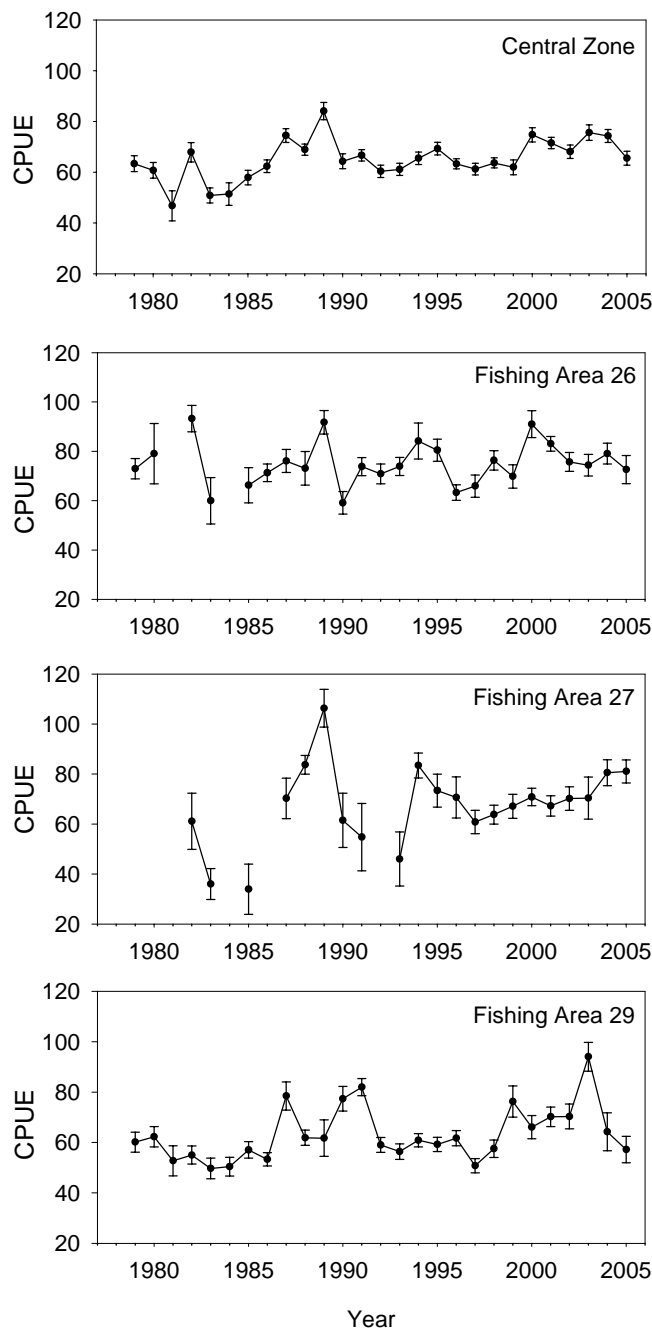


Figure 3.3: Catch of blacklip abalone (tonnes) in each of the fishing areas comprising the CZ from 1978 to 2005.

The mean CPUE, in all fishing areas of the CZ combined, increased from  $63.4 \pm 3.1 \text{ kg.hr}^{-1}$  in 1979 to a maximum of  $84.1 \pm 3.4 \text{ kg.hr}^{-1}$  in 1989 (Figure 3.4). Between 1989 and 1990 the CPUE declined by 23%. From 1990 to 2004 the CPUE fluctuated inter-annually (range  $60.4 \pm 2.4$  in 1992 to  $75.6 \pm 3.1 \text{ kg.hr}^{-1}$  in 2003), but generally increased. During this 14-year period, it remained 10% below maximum observed levels despite exceeding  $74 \text{ kg.hr}^{-1}$  in 2003 and 2004. Notably, the mean CPUE decreased by >11% between 2004 and 2005 ( $65.5 \pm 2.7 \text{ kg.hr}^{-1}$ ), to the lowest level since 1999 (six years).



**Figure 3.4: Catch-per-unit effort (CPUE,  $\text{kg.hr}^{-1}$ ) on blacklip abalone for all fishing areas of the CZ combined, and for fishing areas 26, 27 and 29 separately.**

Temporal trends in CPUE in fishing areas 26, 27 and 29 differed both substantially from that observed for the combined fishing areas (Figure 3.4), and among fishing areas. In fishing areas 26 and 29, mean CPUE generally increased between 1980 and 2000 and between 1980 and 2003, respectively. CPUE has declined substantially (~40%) in fishing area 29 since 2003 ( $94.0 \pm 5.7 \text{ kg.hr}^{-1}$ ); in 2005, the CPUE in fishing area 29 was  $57.2 \pm 5.3 \text{ kg.hr}^{-1}$ , the lowest value since 1998 (8 yr). Recent significant declines in CPUE in fishing area 26 have occurred, with the CPUE decreasing by ~20% from  $91.0 \pm 5.4 \text{ kg.hr}^{-1}$  (2000) to  $72.6 \pm 5.7 \text{ kg.hr}^{-1}$  (2005; LR:  $r^2 = 0.68$ ,  $df = 4$ ,  $p < 0.05$ ). As in fishing area 29, the CPUE on blacklip abalone in fishing area 26 in 2005 was at the lowest level since 1998.

Temporal patterns observed in fishing area 27 are different from those in fishing areas 26 and 29. The CPUE in fishing area 27 has increased significantly (LR:  $r^2 = 0.84$ ,  $df = 7$ ,  $p < 0.01$ ) from  $60.8 \pm 4.7 \text{ kg.hr}^{-1}$  (1997) to  $81.0 \pm 4.6 \text{ kg.hr}^{-1}$  (2005) over the last nine years. Yet, in 2005 it remained ~24% below maximum observed levels ( $106.3 \pm 7.6 \text{ kg.hr}^{-1}$  in 1989).

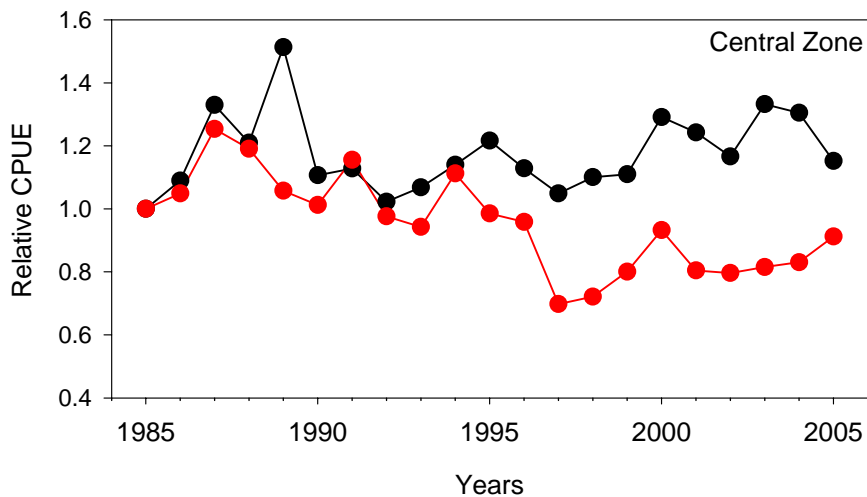
### 3.3 Standardised CPUE

To account for the effects of technological advancement, diver behaviour and diver efficiency on effective fishing effort, the historical catch and effort data (with the main effects of the introduction of quota removed in data pre-processing) were standardised in conjunction with information from licence holders on their fishing practices, using a GLM (Mayfield *et al.* 2003) by year from 1985. 1985 was selected as the reference year as it was the first year for which sufficient catch and effort data were available. The model was of the form:

$$\text{Ln}(\text{catch}_b) = \mu + \beta_0(\text{season}) + \beta_1(\text{map}) + \beta_2(\text{month}) + \beta_3(\text{licence, c-diver}) + \beta_4 \ln(\text{effort}) + \beta_5 \ln(\text{catch}_g) + \beta_6(\text{licence, UWV}) + \beta_7(\text{licence, GPS}) + \beta_8(\text{licence, ECHO}) + \beta_9(\text{licence, HWS}) + \varepsilon$$

The model terms are defined in Section 2.4, with the exception of  $\beta_5 \ln(\text{catch}_g)$ , that models the effect of harvesting greenlip abalone whilst targeting blacklip abalone.

The temporal trends in raw (observed) and standardised CPUE are dissimilar (Figure 3.5). Raw CPUE increased between 1985 and 1989, decreased substantially between 1989 and 1990, increased slowly from 1991 to 2003 and declined thereafter. Notably, in 2005 the raw CPUE was 24% below the maximum observed level (1989). In contrast, the standardised CPUE has declined significantly since 1985 (LR:  $r^2 = 0.54$ ,  $df = 19$ ,  $p < 0.05$ ). In 2005, the standardised CPUE was 23% below the maximum observed level (1987).



**Figure 3.5: Relative, to that in 1985, raw (observed, black line) and standardised (red line) CPUE on blacklip abalone in all fishing areas of the CZ combined.**

### 3.4 Length-frequency distribution of the catch

Estimates of the lengths of individuals in the commercial blacklip abalone catch have been determined from shell samples obtained since 2002. Sample sizes range between 1 185 (2002) and 3 980 (2004) shells and represent <5% of the total catch.

Over 60% of the blacklip abalone sampled from the CZ during 2002 were smaller than 145 mm SL. The modal length class was 140 – 144 mm SL, and the mean length was  $143.4 \pm 0.2$  mm SL (Figure 3.6). During 2003 the mean length ( $147.6 \pm 0.2$  mm SL) was larger, and the proportion of the sample smaller than 145 mm SL (42.4%) was lower when compared with those in 2002. However, between 2003 and 2004, the mean length decreased (from  $147.6 \pm 0.2$  to  $146.8 \pm 0.1$  mm SL) and the proportion of the sample smaller than 145 mm SL increased (from 42.2 to 45.2%). Changes between 2004 and 2005 were substantially greater: the mean length decreased by 1.6 mm SL (from  $146.8 \pm 0.1$  to  $145.2 \pm 0.2$  mm SL) and the proportion of the sample smaller than 145 mm SL increased by ~7% (from 45.2 to 52.2%).

Assessment of temporal changes in the length-frequency distribution of the catch within fishing areas (Figure 3.7) is complicated by the absence of data from fishing area 29 in 2003, and from fishing area 30 in both 2003 and 2005. Nevertheless, several patterns are evident.

Firstly, in fishing area 26, the mean length has declined by >4 mm SL since 2002 (from  $151.3 \pm 0.6$  to  $147.2 \pm 0.3$  mm SL), the modal length class decreased from 145 – 149 mm SL (2002) to 140 – 144 mm SL (2003 – 2005) and the proportion of the sample smaller than 145 mm SL increased substantially from 24% in 2002 to ~40% (2003 – 2005). Secondly, in

fishing area 27, while the mean length and modal length class both increased, and the proportion of the sample smaller than 145 mm SL decreased between 2002 and 2003, these trends were reversed between 2003 and 2005. Notably, over the last three years, the mean length has declined by  $>6$  mm SL (from  $148.8 \pm 0.3$  mm SL in 2003 to  $142.8 \pm 0.3$  mm SL in 2005) and the proportion of the sample smaller than 145 mm SL increased substantially from 36% in 2003 to 64% in 2005. Thirdly, in fishing area 30, the mean length and modal length class declined substantially, and the proportion of the sample  $<145$  mm SL increased substantially (from  $149.0 \pm 0.8$  to  $141.5 \pm 0.6$  mm SL, from 150 – 154 to 135 – 139 mm SL and from 28.7 to 74.3%, respectively) between 2002 and 2004. These data, and the associated patterns, suggest that fishing pressure on blacklip abalone in fishing areas 26, 27 and 30 has increased substantially in more recent years. Contrasting temporal patterns were evident in fishing area 29: the mean length and modal model class both increased, and the proportion of the sample smaller than 145 mm SL decreased between 2002 and 2005.

### **3.5 Estimates of egg production**

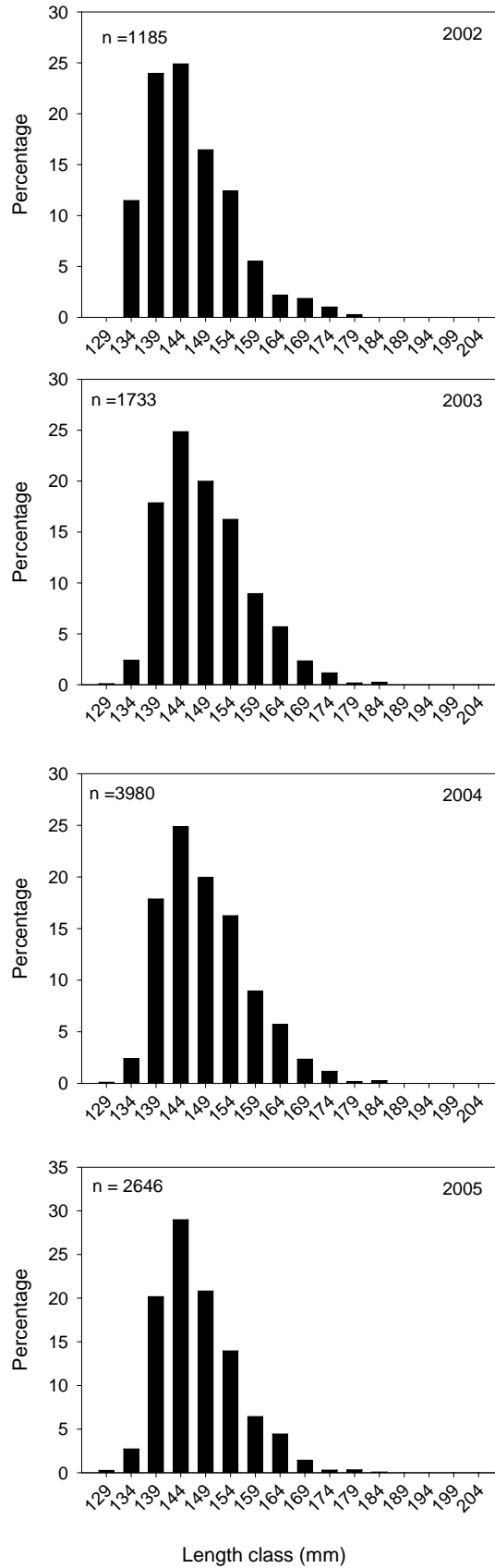
A simple egg-production model, similar to that described in Section 2.6, was used to estimate the proportion of pristine egg production conserved under the current management arrangements for blacklip abalone in fishing areas 26, 27 and 29. Full details of the biological data used in the model, and the model assumptions are provided in Appendix 2.

The estimates of the percentage of unfished egg production conserved in fishing areas 26, 27 and 29 during 2005 were 42.4, 24.2 and 28.0%, respectively. While the estimate of retained egg production increased between 2004 and 2005 in fishing area 29, estimates decreased over the same time period in fishing areas 26 and 27. Notably, estimates of retained egg production have been  $<50\%$  in all fishing areas since they were first determined in 2002.

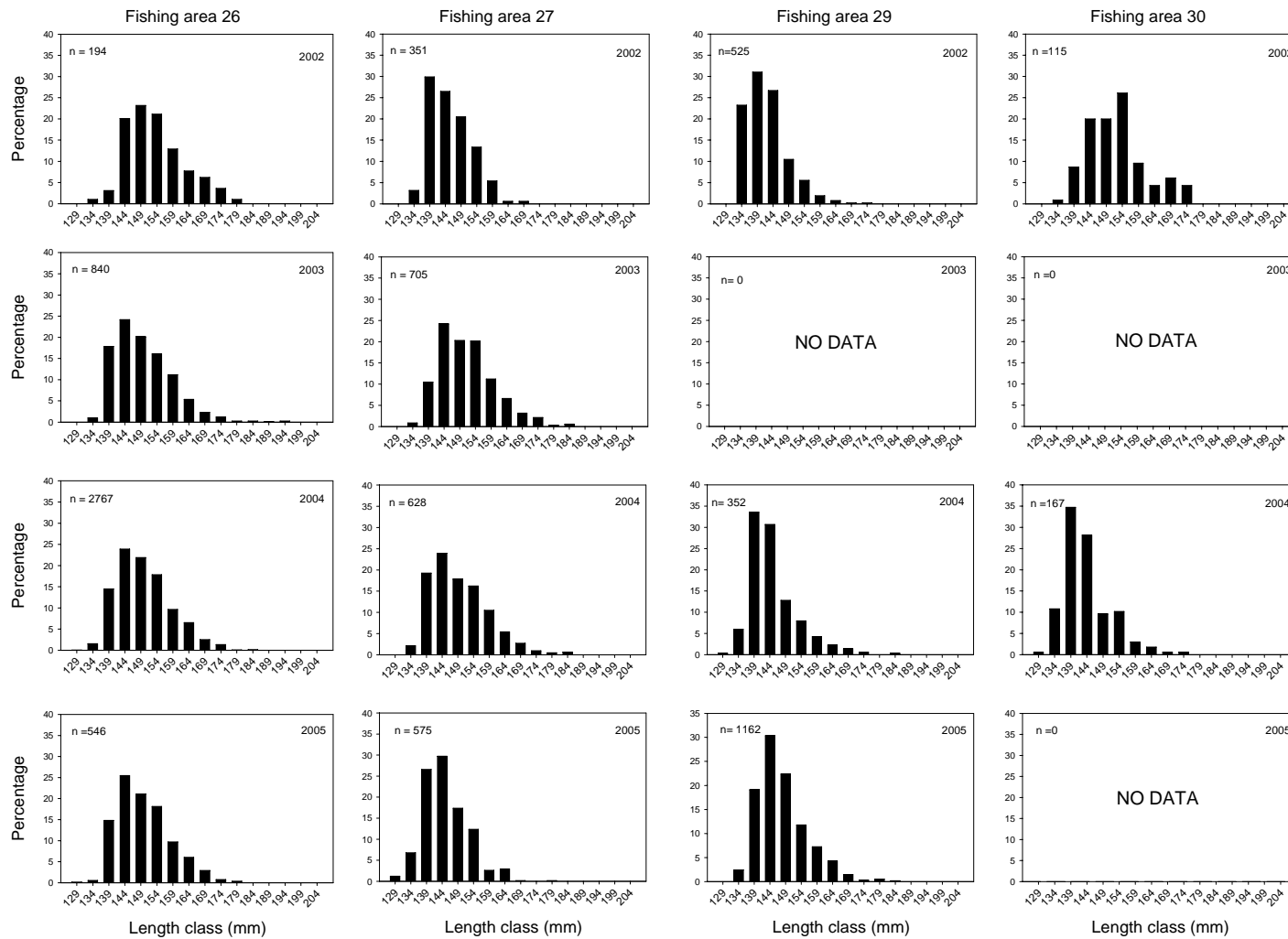
### **3.6 Length-based stock assessment model**

#### **3.6.1 Introduction**

This is the second year in which the integrated, length-structured national abalone stock assessment and risk analysis model (Gorfine *et al.* 2005) was used to assess the status of blacklip abalone stocks in the CZ. The assessment used Bayesian techniques to estimate (1) model parameters; (2) determine the sensitivity of the model outputs to alternative CPUE time series, the magnitude of the observation error on CPUE and the commercial length-frequency data, a possible non-linear relationship between CPUE and biomass, and growth rate; (3) determine current stock status relative to that in 1967 (*i.e.*  $B_0$ ); and (4) determine the uncertainty of those estimates.



**Figure 3.6: Length-frequency distributions obtained from measuring blacklip abalone commercial shell samples from the CZ during 2002, 2003, 2004 and 2005. Length classes are mm SL.**



**Figure 3.7: Length-frequency distributions obtained from measuring blacklip abalone shells from the commercial fishery in fishing areas 26, 27, 29 and 30 of the CZ during 2002, 2003, 2004 and 2005. Length classes are mm SL.**

Three substantial changes were made to improve the application of the model over the previous assessment. Firstly, there was a broader evaluation of the appropriateness of the priors (and their associated distributions) that was extended to the use of both ‘exploratory’ (*i.e.* diffuse) and ‘driving’ (*i.e.* informative) prior distributions. While the exploratory priors can be used to let the model and observations ‘speak for themselves’, model outputs are often associated with high uncertainty. The uncertainty of model outputs can be substantially reduced by using other data (*e.g.* empirical estimates of natural mortality) to estimate informative priors that can substantially reduce the uncertainty of model outputs.

Secondly, we employed a more rigorous suite of diagnostic tools for assessing model performance (*e.g.* temporal patterns in recruitment deviations). Thirdly, the time series of CPUE used to fit the model was extended backwards to 1990 (the first year in which a TACC was implemented). This is consistent with approaches in other States, where the introduction of TACCs have influenced catch rates. Other, more minor changes, including a re-evaluation of the data used within the model were also implemented.

Despite these substantial improvements, it is important to note that the model has only recently been developed, is still being refined and only limited sensitivity testing has been completed. Note, also, that the data (1) defining some model parameters, (2) being used to estimate informative priors and, (3) used to fit the model require ongoing revision to ensure they appropriately represent the blacklip abalone populations in this Zone. Hence, outputs from the model may not be representative of the status of the blacklip abalone stocks in the CZ, and may change substantially as the model, and the data used, are refined in future years.

### 3.6.2 Methods

#### 3.6.2.1 Model description

A detailed description of the model can be found in Gorfine *et al.* (2005). The formulae and parameter priors underpinning the model are provided in Appendix 3. Briefly, the model considers the population divided into small (2 mm) length-classes with the number of abalone in each length-class calculated through time. The numbers of abalone in each length class are calculated by applying growth, fishing mortality, natural mortality and recruitment to each length class each year. Biomass estimates are derived from a length-weight relationship. These calculations provide estimates of model-based catch rates and length-frequency distributions that are compared to the available data (*i.e.* observations). Modelling occurs in two stages: (1) model parameters are estimated using maximum likelihood to provide a good

fit to the observed data and (2) Bayesian posteriors for these parameters are derived using Markov chain-Monte Carlo simulation (*MCMC*).

### 3.6.2.2 Base-case model

A variety of data are required to fit the base-case model to the observed data. This includes the catch and selectivity from each sector of the fishery and a range of biological information.

#### *Commercial, recreational and illegal catches*

Commercial catch data for the period 1968 – 2005 were obtained from research logbooks completed for each fishing day and submitted to SARDI Aquatic Sciences. Recreational and illegal catches were assumed to be zero in all years, as they are likely to have been negligible.

#### *Length-frequency distribution of the commercial catch and fishing selectivity*

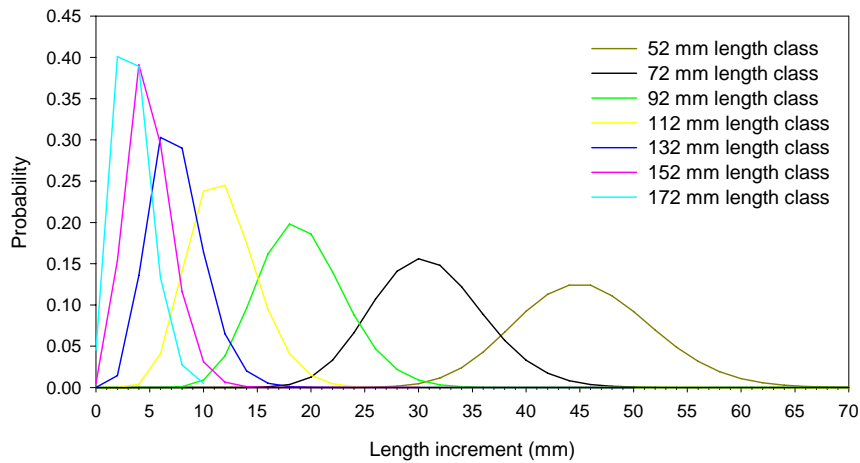
Data on the length-frequency distribution of the commercial catch were available from 2002 to 2005. The relationship between the length-frequency distribution of abalone in the modelled population and these observations is termed the fishing selectivity.

The fishing selectivity relationship from 1971 to 2005 was determined from commercial shell samples obtained from 2002 to 2005 ( $n = 9\ 544$ ). A similar relationship was assumed from 1968 to 1970, with the exception that the MLL was set at 90 mm SL.

#### *Biological data*

Growth was assumed to be constant over time and the same for both sexes. It was incorporated in the model as a transition matrix, where abalone from each 2-mm length class at the start of each season grow into a range of larger (2-mm) length classes during each season (Figure 3.8). The growth transition matrix was determined from tag-recapture data for blacklip abalone at Reef Head, Venus Bay and Sheringa (all Western Zone; after Bardos 2005), because there are no raw tag-recapture data for blacklip abalone in the CZ. Individual abalone with negative growth, were considered to have constituted a measurement error, and were omitted from the data used to calculate the transition matrix.

The proportion of sexually mature individuals within each length class was determined from data obtained from Weirs Cove, Cape Bedout and Cape du Couedic. A logistic curve was fitted to the data (SPSS Inc., Sigma Plot) and used to determine the proportion of sexually mature individuals within each 2-mm length class. The allometric relationship between shell length and whole weight was determined from data obtained at Gerloff's Bay and Douglas Bay (Southern Zone).



**Figure 3.8: Probability of annual length increments for blacklip abalone in the 52, 72, 92, 112, 132, 152 and 172 mm length classes.**

#### *Fitting the observed data*

The base-case model was fitted to two data sets. Model estimates of the biomass of abalone selected by the fishery were fitted to the observed mean CPUE from 1990 to 2005. Model estimates of the proportion of abalone in each length class selected by the fishery were fitted to the commercial length-frequency data from 2002 to 2005.

#### *Markov chain-Monte Carlo simulation (McMC)*

Uncertainty in the mature and exploitable biomass estimates during each year (1968 – 2005) were determined using a *McMC* simulation of 1 200 000 model runs from which the first 200 000 runs were discarded and 5 000 (0.5%) observations systematically sampled thereafter. Estimates of mean mature and exploitable biomass (and associated standard errors) for each year were determined from the 5 000 samples.

#### *Model outputs*

Outputs from the model included (1) fits to each year of commercial-catch-sampling data and observed CPUE; (2) estimates and posterior distributions of the 42 parameters (initial recruitment ( $R_{init}$ ), steepness of the Beverton-Holt stock-recruit relationship ( $h$ ), annual recruitment deviations (the difference between predicted recruitment and model-estimated recruitment for each of the 39 years;  $R_{devs}$ ) and natural mortality ( $M$ )) estimated by the model; and (3) mean values of mature and exploitable biomass for each year, relative to  $B_0$ , with standard errors.

#### 3.6.2.3 Sensitivity analyses

The sensitivity of the base-case model outputs to an alternative CPUE time series, the magnitude of the CPUE and commercial length-frequency observation error, a possible non-linear relationship between CPUE and biomass and growth rate were examined. This was

achieved by (1) fitting the model to raw CPUE from 2002 to 2005 as in previous years (rather than 1990 to 2005); (2) setting the observation error on CPUE at zero as in previous years (rather than at 0.05); (3) setting the CPUE power function at 0.1 (rather than at 1); (4) increasing the growth rate by 30%; and (5) setting the effective sample size for commercial length-frequency data to 25 (rather than to 50). In each case, variability in the mature and exploitable biomass estimates during each year (1968 – 2005) were determined using a *McMC* simulation of 1 200 000 model runs from which the first 200 000 runs were discarded and 5 000 (0.5%) observations systematically sampled thereafter. Estimates of mean mature and exploitable biomass (and associated standard errors) for each year were determined from the 5 000 samples, and compared to those estimates obtained from the base-case model.

### 3.6.3 Model outputs

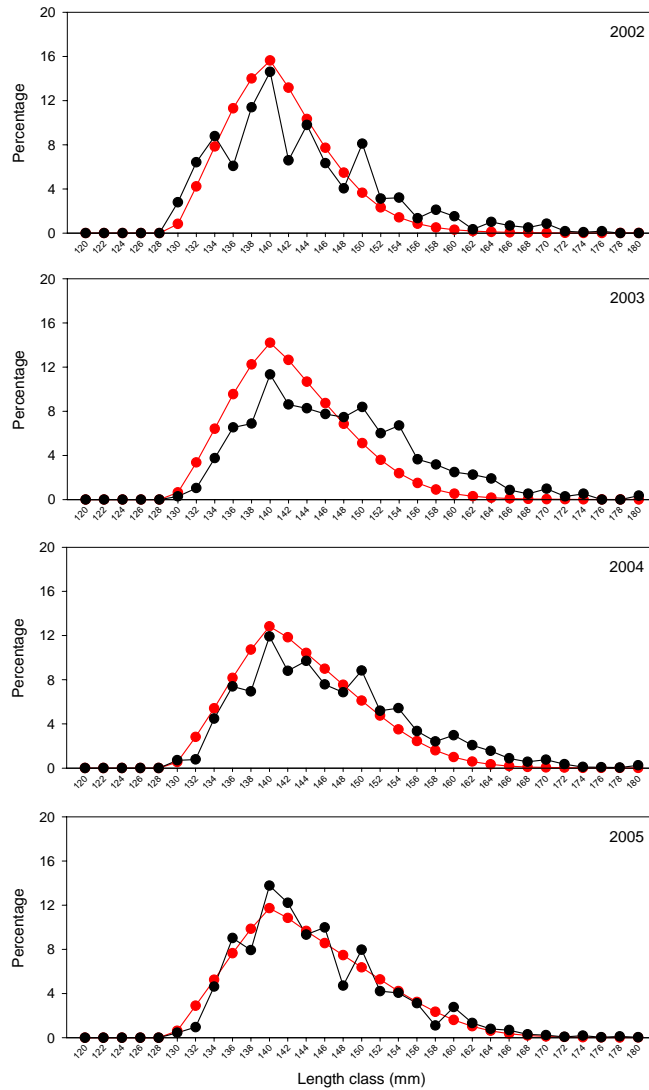
#### 3.6.3.1 Base-case model fits to observed data

The model outputs closely fitted the proportions-at-length from the commercial catch samples (Figure 3.9) and the observed CPUE (Figure 3.10). These fits are of similar quality to those in other abalone models (*e.g.* Worthington *et al.* 2001; Breen *et al.* 2003; Mayfield *et al.* 2005b,c; Chick *et al.* 2006). Perhaps the most significant lack of fit related to the inability of the model to fit apparent annual changes in the proportions at length (*e.g.* 2002 and 2003). While this is also a common feature of other abalone fishery models, it is less clear how such annual changes are caused (*e.g.* changes in sampling and/or selectivity). The base-case model also provided a relatively poor fit to CPUE data from 2001 to 2003, where the decline in observed CPUE was not well fitted by the model.

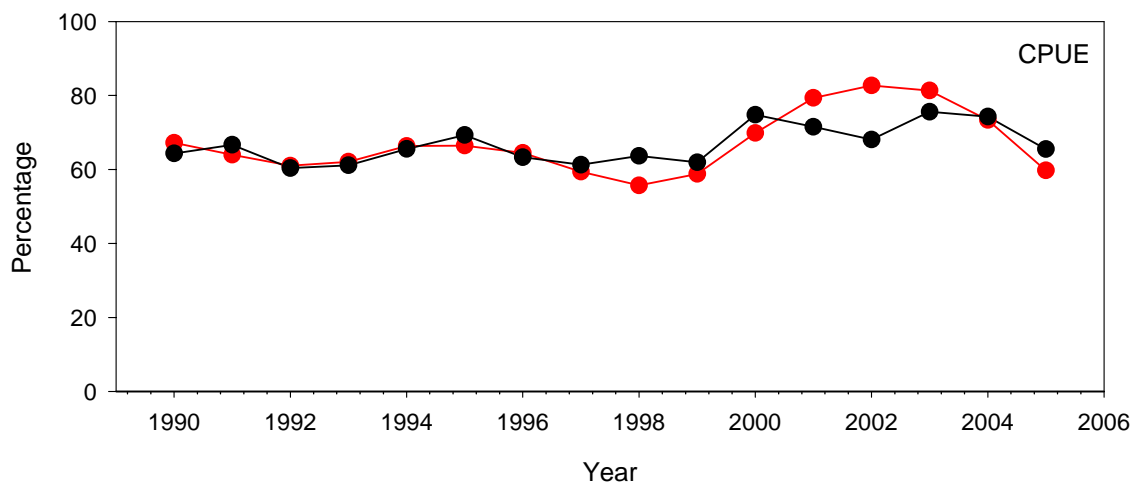
#### 3.6.3.2 Parameter estimates and posterior distributions

Median estimates of  $R_{\text{init}}$ ,  $h$  and  $M$  were 551 241, 0.60 and 0.20, respectively. The base-case model provided information useful to estimation of  $R_{\text{init}}$ , but was less informative for estimating either  $h$  or  $M$  (Figure 3.11), for which the estimated median of the posterior was very similar to that of the prior. Despite the general similarity of the medians among prior and posterior, the base-case model did provide information that suggested the reduced probability of high and low values for both  $h$  and  $M$ .

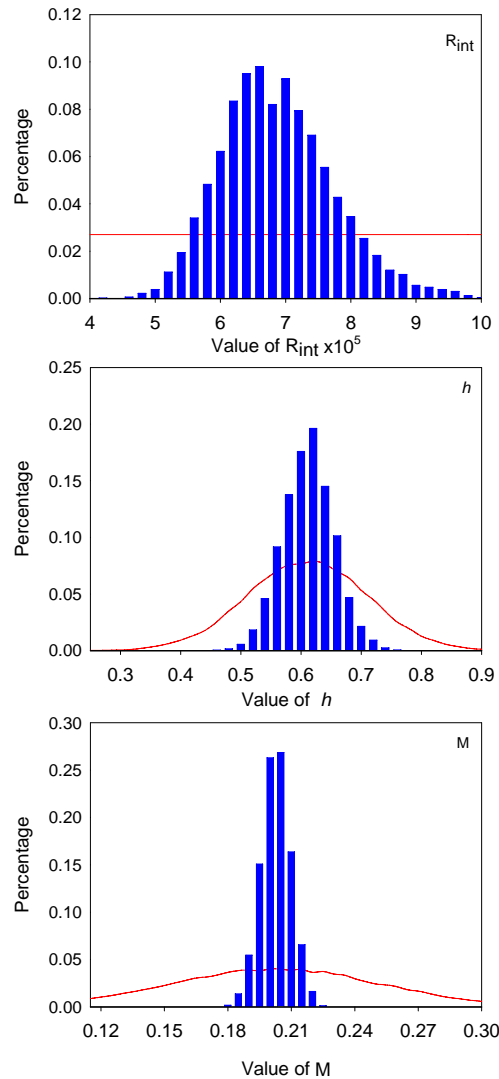
The base-case model was also informative in determining the  $R_{\text{devs}}$ . This was evident both in the temporal patterns in recruitment and in the posterior distributions (relative to the prior) of  $R_{\text{dev}}$  within years (Figure 3.12). These outputs suggest that recruitment was above average between 1986 and 1996, but that recruitment was low from 1997 to 2001.



**Figure 3.9: Model fit (red lines) to the proportion-at-length observed (black lines) in the commercial catch from 2002 to 2005.**



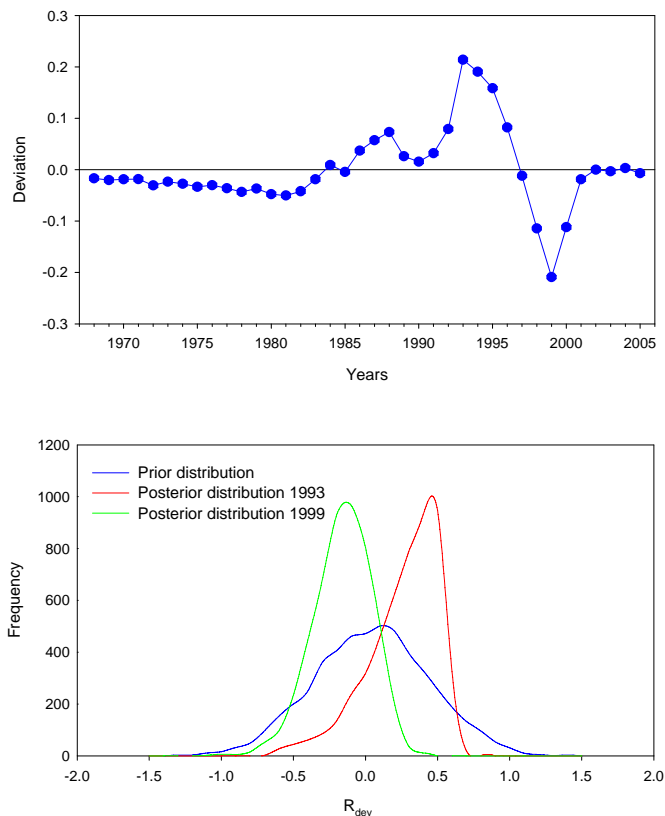
**Figure 3.10: Model fit (red line) to raw (observed) CPUE from 1990 to 2005.**



**Figure 3.11: Posterior distributions (blue bars) of  $R_{init}$ ,  $h$  and  $M$ , relative to the prior distribution (red lines) obtained from the base-case model.**

### 3.6.3.3 Temporal patterns in mature and exploitable biomass

Base-case model outputs suggest that mature and exploitable biomass declined rapidly during the first six years of the fishery (1968 – 1974; Figure 3.13). Both increased between 1974 and 1978, whereafter estimates of mature and exploitable biomass declined gradually, reaching 42% and 12%, relative to  $B_0$ , during 1992 and 1997, respectively. The most substantial decline in exploitable biomass occurred between 1970 and 1971 and primarily reflected implementation of the MLL (130 mm SL). Estimates of mature biomass increased slightly between 1992 and 1997, whereafter they declined rapidly. The estimate of mature biomass in 2005, relative to  $B_0$ , was 36.1% – the fourth lowest value since 1968 (Figure 3.13; Table 3.2). Model estimates of exploitable biomass increased minimally from 1997 to 2001. More rapid declines in the estimates of exploitable biomass since 2002 culminated in the estimate of exploitable biomass in 2005, relative to  $B_0$ , of 11.4% – the lowest value since 1968 (Table 3.2).



**Figure 3.12: Estimated recruitment deviation ( $R_{devs}$ ) between 1967 and 2005 (top) and posterior distributions (bottom) of  $R_{devs}$  in 1993 (blue line) and 1999 (green line), relative to the prior distribution (red line), obtained from the base-case model.**

Contemporary reductions in mature and exploitable biomass are considerably smaller (Table 3.2). For example, estimates of mature and exploitable biomass in 2005, relative to  $B_{1990}$ , were 84% and 81%, respectively. This illustrates that biomass decreases since the introduction of a TACC (1990) have been relative smaller than those prior to quota introduction, and highlights the need to select an appropriate reference year(s) as a ‘benchmark’ for assessment of this fishery.

These high depletion levels, that are suggestive of the need for biomass rebuilding, need to be considered in the light of (1) the preliminary nature of this assessment, (2) the substantial uncertainties that remain, and (3) the need for ongoing model development.

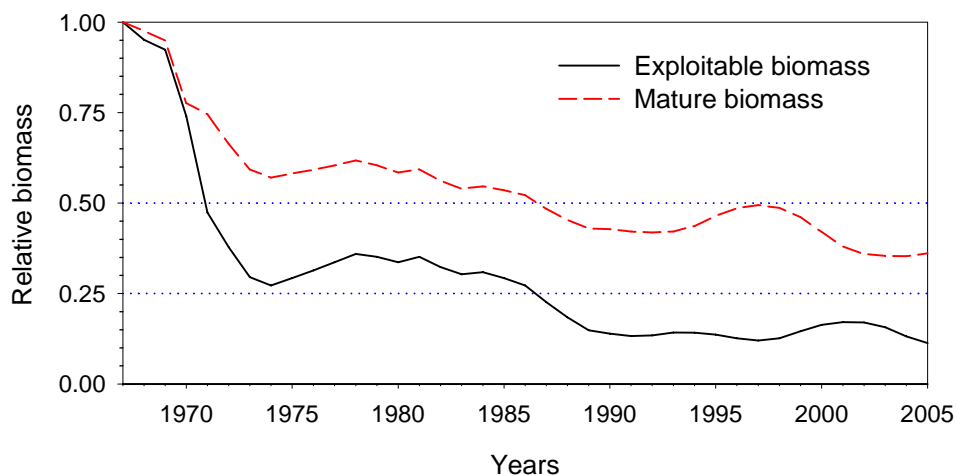
#### 3.6.3.4 Sensitivity analyses

Deviations from the base-case model were relatively small for each of the five sensitivity analyses considered (Figure 3.14), although the different CPUE series did have a more substantial effect on estimates of exploitable biomass. Estimates of mature and exploitable biomass in 2005 ( $B_{2005}/B_0$ ) were elevated, relative to the base-case model, when the model was fitted to the shorter CPUE time series, the observation error on CPUE was reduced and

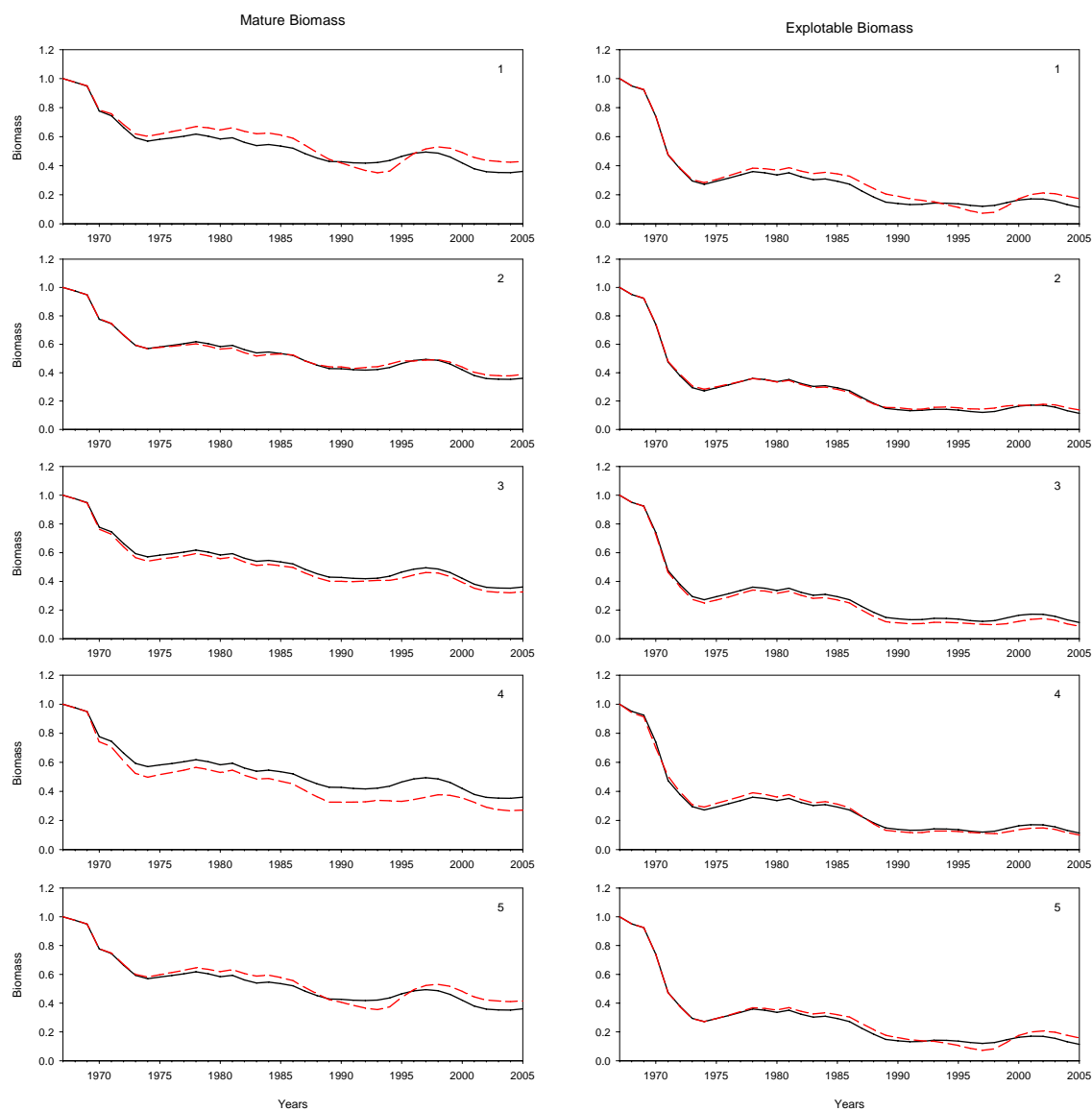
the hyperstability of the relationship between CPUE and biomass was increased. Conversely, increasing the growth rate by 30% and reducing the effective sample size (*i.e.* weighting, observation error) on the commercial length-frequency data resulted in depressed estimates of mature and exploitable biomass in 2005, relative to the base-case model. The variability of the responses of the base-case model to the sensitivity analyses, in that some sensitivity tests provided more optimistic (*i.e.* less depleted) and others more pessimistic (*i.e.* more depleted) scenarios highlights the need for ongoing model development.

**Table 3.2: Mean estimates of mature and exploitable biomass, relative to  $B_0$  and  $B_{1990}$  obtained from the base-case model from 2000 to 2005.**

Fishing season	Mature biomass		Exploitable biomass	
	Mean $B_t/B_0$	Mean $B_t/B_{1990}$	Mean $B_t/B_0$	Mean $B_t/B_{1990}$
2000	0.420	0.982	0.164	1.173
2001	0.380	0.887	0.171	1.226
2002	0.360	0.840	0.170	1.220
2003	0.354	0.827	0.157	1.122
2004	0.352	0.824	0.132	0.944
2005	0.361	0.844	0.114	0.814



**Figure 3.13: Trajectories of mature (dashed red line) and exploitable (continuous black line) biomass, relative to  $B_0$ , obtained from the base-case model from 1967 to 2005. Horizontal blue lines are for reference only and indicate 50% and 25% of  $B_0$ .**



**Figure 3.14: Sensitivity (black lines) of the mature and exploitable biomass outputs from the base-case model (red lines) to (1) fitting the model to raw CPUE from 2002 to 2005 (rather than 1990 to 2005); (2) setting the observation error on CPUE at zero (rather than at 0.05); (3) setting the effective sample size for commercial length-frequency data to 25 (rather than to 50); (4) increasing the growth rate by 30%; and (5) setting the CPUE power function at 0.1 (rather than at 1).**

## **4. PERFORMANCE INDICATORS**

This section provides a report on the performance of the fishery against the reference points for the CZ as defined in the Management Plan (Nobes *et al.* 2004) and documented in Tables 1.4 and 1.5 (Section 1.3).

### **4.1 Greenlip abalone**

There are 31 biological PI specified for greenlip abalone in the CZ in 2005. Of these, 26 are addressed in this report. The remaining five PI (diver assessment of stock status (in fishing areas 21 and 22); harvest discard; illegal catch; and recreational catch) are addressed in other reports submitted to PIRSA Fisheries.

Data are available to assess the performance of the greenlip abalone fishery against 20 of the 26 (77%) PI to be addressed in this report. Thirteen of these 20 PI (65%) have triggered (Table 4.1; Appendix 4). Of these, five (38%) may be considered positive for the fishery.

The proportion of the TACC harvested from fishing areas 22, 24 and 30 increased between 2004 and 2005 (from 4.3% to 12.0%, from 5.2% to 8.6% and from 1.1% to 5.5%, respectively). In contrast, the proportion of the TACC harvested from fishing area 27 decreased over the same period (from 3.7% to 1.5%). These changes resulted in change to the composition, and sequence, of the four most important fishing areas, by catch, between 2004 and 2005.

Mean daily catch decreased significantly in fishing areas 21 and 22 between 2004 and 2005, and in fishing area 21 from 2001 to 2005. Similarly, CPUE decreased significantly in fishing areas 21 and 22 between 2004 and 2005, and in fishing area 21 from 2001 to 2005.

Estimates of egg production in fishing area 21 were 40.3% of 'unfished' levels.

The mean length of greenlip abalone in the commercial catch increased significantly in fishing area 21 between 2004 and 2005.

The abundance of legal-sized (>130 mm SL) and sub-legal-sized (<130 mm SL) greenlip abalone, and the abundance of greenlip abalone larger than  $L_{50}$  (the length at which 50% of individuals were sexually mature; 85 mm SL) all increased significantly between 2001 and 2005 at Tiparra Reef. The abundance of sub-legal-sized greenlip abalone at Tiparra Reef also increased significantly between 2004 and 2005.

**Table 4.1: Assessment of the performance of the greenlip abalone fishery in the CZ (CZ) and in fishing areas 21 and 22 against the Performance Indicators prescribed in the Management Plan.**

Performance indicator	Temporal scale	CZ	Area 21	Area 22
Commercial catch	Annual			
Commercial effort	5-year trend			
Spatial distribution of catch	Inter-annual			
Mean daily catch	Inter-annual			
	5-year trend			
Mean daily effort	Inter-annual			
	5-year trend			
CPUE	Inter-annual			
	5-year trend			
Mean length	Inter-annual			
	5-year trend			
Abundance of legal-sized abalone	Inter-annual			
	5-year trend			
Abundance of sub-legal-sized abalone	Inter-annual			
	5-year trend			
Egg production/pristine	Annual			
Abundance of abalone larger than L <sub>50</sub>	Inter-annual			
	5-year trend			



#### 4.2 Blacklip abalone

There are 63 biological PI specified for blacklip abalone in the CZ in 2005. Of these, 56 are addressed in this report. The remaining seven PI (diver assessment of stock status (in fishing areas 26, 27, 29 and 30); harvest discard; illegal catch; and recreational catch) are addressed in other reports submitted to PIRSA Fisheries.

Data are available to assess the performance of the blacklip abalone fishery against 30 of the 56 (54%) PI to be addressed in this report. Ten of these 30 PI (33%) have triggered (Table 4.2; Appendix 5). Six (60%) of these would be considered negative for the fishery.

**Table 4.2: Assessment of the performance of the blacklip abalone fishery in the CZ and fishing areas 25, 26, 27 and 29 against the Performance Indicators prescribed in the Management Plan.**

Performance indicator	Temporal scale	CZ	Area 26	Area 27	Area 29	Area 30
Commercial catch	Annual					
Commercial effort	5-year trend					
Spatial distribution of catch	Inter-annual					
Mean daily catch	Inter-annual					
	5-year trend					
Mean daily effort	Inter-annual					
	5-year trend					
CPUE	Inter-annual					
	5-year trend					
Mean length	Inter-annual					
	5-year trend					
Egg production/pristine	Annual					

Performance indicator	Temporal scale	Cape du Couedic	Cape Bouger	Cape Gantheaume
Legal-sized abalone abundance	Inter-annual			
	5-year trend			
Sub-legal-sized abalone abundance	Inter-annual			
	5-year trend			
Abundance of abalone larger than L <sub>50</sub>	Inter-annual			
	5-year trend			



Fishing effort on blacklip abalone has decreased significantly from 589 hr (2001) to 389 hr (2005) over the last five years.

The proportion of the TACC harvested from fishing areas 26 and 28 declined between 2004 and 2005 (from 8.9% to 7.5% and from 38.3% to 18.6%, respectively). In contrast, the proportion of the TACC harvested from fishing areas 27 and 29 increased over the same period (from 23.6% to 30.0% and from 12.9% to 16.6%, respectively). These changes resulted in change to the composition, and sequence, of the four most important fishing areas, by catch, between 2004 and 2005.

Mean daily catch decreased significantly in fishing area 26 between 2001 and 2005.

Mean daily effort decreased significantly in fishing area 26 between 2004 and 2005. CPUE increased significantly between 2001 and 2005 in fishing area 27.

The mean length of blacklip abalone in the commercial catch decreased significantly in fishing area 27 between 2004 and 2005, but increased significantly in fishing area 29 during the same time period.

Estimates of egg production in fishing areas 26, 27 and 29 ranged between 42.4 and 24.4% of 'unfished' levels.

## **5. GENERAL DISCUSSION**

### **5.1 Status of the Central Zone abalone fishery**

Substantial information and data are available to aid the assessment of abalone stocks in the CZ. These include: (1) a well documented history and management of the commercial fishery; (2) a broad suite of performance indicators; (3) fine-scale catch and effort data from 1968 to 2006; (4) data from commercial-catch sampling; (5) long-term fishery-independent surveys at Tiparra Reef (greenlip abalone only); (6) substantial biological data; and (7) outputs from three models: a GLM to standardise CPUE; a simple egg-production model; and a length-based (blacklip abalone only) Bayesian stock assessment model. There are few data on the magnitude of the illegal and recreational catches, which prevents reliable estimation of the total catch and, hence, impedes assessment of the fishery.

Data and information with which to assess the status of greenlip abalone in this Zone are balanced among those provided by commercial fishers (*e.g.* catch, effort and catch-sampling data), that collected by SARDI Aquatic Sciences (*i.e.* biological and fishery-independent survey data) and outputs from two models. In contrast, assessment of the blacklip abalone stocks is heavily weighted by the commercial catch and effort data, supplemented by outputs from three models. Data from planned fishery-independent surveys and more robust outputs from the range of developing numerical models will substantially improve future assessments for this species. As in all fishery assessment reports, the data and information are used within the limitations governed by their level of uncertainty.

In this assessment, we have used CPUE to assess stock status, based on the assumption that change in CPUE reflects a change in the size of the fishable stock (Tarbath *et al.* 2005). CPUE can be strongly influenced by numerous factors, and is often viewed as a biased index of change in abalone abundance (Harrison 1983; Breen 1992; Prince & Shepherd 1992; Gorfine *et al.* 2002). For example, catch rates may remain high as a result of re-aggregation of abalone (hyperstability), masking fluctuations in population size arising from local depletion (Officer *et al.* 2001a,b). In contrast, declines in catch rates are strongly considered to reflect decreases in the fishable stock.

The difficulties in interpreting the effort and CPUE data are further complicated by the necessity to apply different decision rules when calculating the level of ‘directed effort’ and CPUE on each species. While this approach has been used in both Regions of the Western Zone for several years (Mayfield *et al.* 2005c; Mayfield *et al.* 2005d) and in this Zone since 2003, the appropriateness of this decision rule requires scrutiny. For example, this approach

fails to consider the effect of harvesting greenlip abalone on the blacklip abalone CPUE. As such, re-evaluating this approach is critical, particularly because temporal patterns in CPUE are the primary driver of the integrated, length-based model.

Less than 2% of the commercial catch has been measured since 2002. These data may not be representative of either the catch from the major fishing areas or the abalone populations in this Zone. This lack of robust commercial length-frequency data to reliably detect and quantify significant temporal changes in the mean, mode and shape of the length structure of commercially fished abalone, substantially increases the uncertainty and limits the assessment of stock status. This is because changes to the length structure of the commercial catch are frequently strongly indicative of the pressures exerted on those stocks. This deficiency is particularly notable for blacklip abalone, for which no data are available from fishing area 30 in 2003 and 2005 or from fishing area 29 in 2003. It is also important to note that there were no data available for greenlip abalone from fishing area 22 in 2005, despite this area contributing >10% of the TACC.

Three models were used to aid assessment of the stocks. These were: (1) a generalised linear model (GLM; Mayfield *et al.* 2003) that standardised the CPUE data for each species; (2) a simple egg-production model that estimated egg production for each year; and (3) an integrated, length-based, stock assessment model for blacklip abalone. Each model combines multiple data sets from a variety of sources. Their outputs are limited by the spatial extent and quality of input data and have considerable levels of associated uncertainty. Uncertainty around the outputs from the GLM and the egg-production models are well documented (Mayfield *et al.* 2005a). This arises, primarily, from the absence of historical information on changes in technology or diver behaviour, and from the wide range of required biological data, model assumptions (particularly constant recruitment) and the need to estimate fishing mortality (F) from shell samples (Parrack and Cummins 2003).

This is the second year in which an integrated, length-based stock assessment model has been used to aid assessment of the blacklip abalone stocks in this Zone. This model is still being refined and only limited sensitivity testing has been completed. Nevertheless, the model has been used in the assessments of the blacklip abalone stocks in both the Southern (Mayfield *et al.* 2005b) and Western (Mayfield *et al.* 2005c; Chick *et al.* 2006) Zones of the South Australian abalone fishery, and in the Victorian fishery (Dr Harry Gorfine, PIRVic, personal communication). Improvements to the model developed during assessments of those stocks have been incorporated into the version used in this report. Additionally, other substantial improvements were made to the application of the model over the previous assessment.

Despite these changes, the level of precision in the outputs is limited by the short time series of the data being fitted, and the absence of data from fishery-independent surveys. Reliability of the outputs is also strongly influenced by: (1) growth rate, especially the degree to which the growth parameters reflect the magnitude and variability of growth in the Zone; (2) the model's reliance on CPUE; (3) the degree to which the biological data reflect blacklip abalone populations in the Zone; and (4) the spatial scale at which the model was applied. Notably, estimates of growth rates developed for the growth matrix by 'Estimatrix' that were based on a probabilistic Gompertz model (Bardos 2005) appear overly optimistic. Thus, current model outputs are likely to overestimate the productivity of the stock while underestimating the level of depletion. Alternative (length-transition) models for fitting the growth data, such as the inverse logistic (A/Professor Malcolm Haddon, Tasmanian Aquaculture and Fisheries Institute, personal communication) and polynomial (McGarvey and Feenstra 2001) functions, are available and need to be evaluated. Refinement of the model, and the data used in future years possibly change the model outputs considerably. Consequently, current outputs from the model may not be representative of the status of the stock.

For convenience, we have generally reported estimates of current mature and legal biomass (termed  $B_{2005}$  or  $B_{\text{current}}$ ) relative to that in 1967 (termed  $B_0$ ). While there is uncertainty in determining the current biomass levels, the value of  $B_0$  is typically even more poorly estimated by fisheries models, because 'initial biomass' generally occurred well before the commencement of any sampling. There is strong evidence for this – simulations by Punt (2003) have shown that despite having a model that is a correct representation of the population with standard inputs (*e.g.*  $M$ ) known without error, estimates of  $B_0$  are heavily biased and uncertain. Consequently, consideration needs to be given to (1) the manner in which current biomass levels, relative to historical levels, are reported, and (2) development of model-based performance indicators for the fishery.

In NSW, model outputs are presented as  $B_{\text{current}}/B_{1994}$  because, as a consequence of the annual fishery-independent surveys undertaken since 1994,  $B_{\text{current}}/B_{1994}$  is considered better defined than  $B_{\text{current}}/B_0$  (Worthington *et al.* 2001). Similarly, for the Victorian blacklip abalone fishery, current biomass is presented relative to that in 2000 ( $B_{\text{current}}/B_{2000}$ ) because, in the absence of information on the minimum level of egg production required to ensure a sustainable fishery, it was considered undesirable for the mature biomass to decline to less than  $B_{2000}$  (Anon 2002). If these approaches were followed for blacklip abalone in the CZ, appropriate historical reference points could include  $B_{1990}$  (the year in which the TACC was implemented) or  $B_{2002}$  (the first year for which data on the length-frequency distribution of the commercial catch are available).

### 5.1.1 Greenlip abalone

As in 2005, assessment of the greenlip abalone stocks in the CZ is complicated because the inferences of stock status derived from the different data sets are inconsistent and data outside of fishing area 21 are limited. In fishing area 21, that includes Tiparra Reef, the most striking contrast is between the recent (five-year) trends in the fishery-dependent and fishery-independent data.

The fishery-independent data provide strong evidence that the abundance of total, legal-sized, mature ( $>L_{50}$ ) and sub-legal-sized greenlip abalone have increased substantially in recent years. Their increases observed on surveys since 2001 are significant. Moreover, in 2005, the abundance of legal-sized greenlip abalone was at the highest observed level, and more than double that observed in 1990. Inferences drawn from these patterns were supported by the small increase in mean length and proportion of the commercial catch larger than 145 mm SL from Tiparra Reef over the last four years. These changes in the length-frequency structure of the catch were reflected in increasing estimates of retained egg production, relative to ‘virgin’ levels, between 2002 and 2005.

In contrast, inferences drawn from most of the fishery-dependent data over a similar time period support the alternative conclusion that the abundance of legal-sized abalone has recently declined. For example, raw and standardised CPUE and mean daily catches have decreased substantially since 2000. Notably, the CPUE on greenlip abalone in fishing area 21 and at Tiparra Reef during 2005 were at their lowest levels since 1999, and ~18% below that observed in 2004. Similar reductions were evident in mean daily catch. The declines in CPUE and mean daily catch in fishing area 21 from 2001 to 2005 and between 2004 and 2005 were significant. The reductions in these fishery-dependent, stock-performance measures are consistent with the conclusions of the 2005 assessment report (Mayfield *et al.* 2005a), and are of concern given reductions in catch from Tiparra Reef since 2001. Resolving the dichotomy between the conflicting inferences regarding the status of the greenlip abalone stocks in fishing area 21 is central to ensuring future sustainability of this important stock.

Prior to the introduction of a TACC (1990) catches were relatively evenly distributed throughout the CZ. Between 1990 and 2004, the spatial distribution of the catch changed substantially, to the extent that, from 2000 to 2004, >85% of the TACC was harvested from one fishing area (21). The catch from Tiparra Reef was limited to 90 t (shell weight) from 2005. This represented a substantial reduction (>20%) in catch from this area between 2004 and 2005. As the TACC remained at 143.1 t (shell weight), the ‘catch cap’ on Tiparra Reef resulted in several changes in the spatial distribution of the catch in 2005.

Among the most evident changes was a large increase in the catch harvested from fishing area 22, from <1 t in 2003 to >17 t in 2005. This was the largest catch from this area since 1991, and the fifth highest since 1978. While information on the abalone stock in this area is limited, there is evidence to suggest that the magnitude of the catch in 2005 is not sustainable. Firstly, the CPUE in fishing area 22 declined by >25% between 2004 and 2005. Secondly, mean daily catch decreased by ~27% over the same time period. Substantial increases in catch between 2004 and 2005 were also observed in fishing area 30. While data from this area are even more limited, sharp declines in CPUE (>35%) between 2003 and 2005 again suggest that the magnitude of the catch in 2005 is not sustainable. Further, despite decreasing catches in fishing area 27, the mean length and modal length class of the commercial catch have declined substantially since 2003. The changes in these fishery-dependent patterns also suggest that, outside of fishing area 21, large populations of greenlip abalone that can sustain relatively large catches (~10 t.yr<sup>-1</sup>) are rare. There are neither fishery-dependent, length-frequency data nor fishery-independent surveys from fishing areas 22 or 30 to confirm this assessment.

There are other trends that warrant consideration. For example, since 1990, catches have declined in seven fishing areas. Reductions in catch from three of these exceed 50% and current catches from many areas are among the lowest on record. The mass mortality of greenlip abalone in fishing area 24 during the mid 1980s (Goggin & Lester 1995) may explain the reduction in catch from this area. The reasons for the declines in catch from the other fishing areas are less clear, and should be investigated and documented. Long-term temporal changes in the level of catch from individual fishing areas may be explained by at least two possible hypotheses. Changing patterns may reflect altered fisher behaviour unrelated to abalone abundance. For example, technological changes in the fishing fleet, such as the trend to larger boats and trailers could restrict the number of access points along the coast, that would be reflected as increased and decreased levels of catch in 'more accessible' and 'less accessible' fishing areas, respectively. An alternative hypothesis is that the uneven distribution of catch among the 12 fishing areas comprising this Zone, and substantial declines in catches in several previously productive areas reflect a depleted stock. Fishery-independent data to consider these hypotheses are urgently required because the status of greenlip abalone stocks in the 'lightly-fished' areas in the CZ is poorly understood.

In summary, unambiguous assessment of the greenlip abalone stocks in 2005 in fishing area 21 (*i.e.* the principal fishing area) is not possible due to the inconsistent inferences from the available data. While the CPUE and mean daily catch have declined over recent years suggesting a decline in greenlip abalone abundance, evidence from fishery-independent

surveys shows that the abundance of sub-legal-sized, legal-sized and mature greenlip abalone have increased over recent years. Assessment of the stocks in the remaining fishing areas is impeded by limited data. Nevertheless, the downward trends observed in fishing areas 22 and 30 suggest that these areas may not be able to sustain the higher levels of catch necessary to maintain both the current TACC and ‘catch cap’ on Tiparra Reef.

#### 5.1.2 Blacklip abalone

The last three fishery assessment reports (Mayfield & Ward 2003, Mayfield *et al.* 2004, 2005a) provided successive, well-supported evidence that the resource on which the CZ blacklip abalone fishery was based was declining. In particular, the 2005 report (Mayfield *et al.* 2005a) concluded that there was evidence that the resource on which the fishery is based was in its weakest position for several years. This evidence included: (1) the TACC not being harvested from 2002 to 2004; (2) about 80% of the catch being obtained from three fishing areas, all off Kangaroo Island; (3) declining mean daily catches, CPUE, mean length, modal length class and proportion of the catch >145 mm SL in several of the key fishing areas; (6) long-term declines in standardised CPUE; (7) low estimates of retained egg production; and (8) the triggering of nine PI in a direction that would be considered negative for the fishery. This conclusion, in association with the ongoing level of concern over the status of these stocks, prompted a preliminary assessment of the performance of this fishery in 2005 (Mayfield *et al.* 2005e). That assessment, to 30 September 2005, suggested that the downward trends had continued. These patterns were confirmed by the more thorough analyses of the 2005 data presented in this report.

A TACC of 41.1 t was introduced in 1990. It was increased to 42.3 t from 1994, and remained at this level until 2004. The TACC over this 11-year period was 25% greater than the mean catch from 1968 to 1989, and 30% greater than the mean catch from 1980 to 1989 (32.5 t). The TACC was reduced by ~30% between 2004 and 2005 (29.7 t), and represented the largest TACC reduction for blacklip abalone in the history of the South Australian abalone fishery. It was subsequently reduced by a further 18% between 2005 and 2006 to 24.3 t. This resulted in the TACC for 2006 being ~43% lower than that in 2004 and 25% below the mean catch for the 10-year period (1980 – 1989) immediately preceding quota implementation.

The data presented in this report provide an additional year’s information on the status of the stock. Much of this information re-affirms and substantiates the more recent previous assessments of the fishery. This is particularly concerning given the successive reductions in catch of blacklip abalone over the last five years – firstly as an initiative by the CZ abalone fishery licence holders to reduce their catches (2002 – 2004), following divers expressing

concerns at the poor health and status of the stocks in this Zone (Tokley 2004), and secondly through the reduction in the TACC from 2005. The evidence that the status of the blacklip abalone stock declined sharply between 2004 and 2005 is compelling.

Firstly, for the CZ and fishing area 26, the CPUE in 2005 was at the lowest level since 1999, >8% lower than that in 2004 and ~20% below maximum observed levels for each of these areas. Decreases in CPUE in fishing area 29 were more substantial. The CPUE in fishing area 29 declined by ~40% between 2003 and 2005, to the lowest level since 1993. Notably, the standardised CPUE has declined significantly since 1985, and, although it increased between 2004 and 2005, it remained ~27% below the maximum observed value (1987). These patterns in CPUE support the conclusions that the blacklip abalone stocks have recently declined.

Secondly, mean daily catch has declined significantly in fishing area 26 over the last five years. In 2005, it was at the lowest level since 1993. Furthermore, mean daily catch declined in fishing areas 26, 27, 29 and 30 between 2004 and 2005. The decreases in fishing areas 26 and 30 were substantial, and were 19 and 52%, respectively.

Thirdly, the mean length of blacklip abalone sampled from the commercial catch declined by 2.4 mm SL between 2003 and 2005. Concurrent with this decrease in mean length was a 10% increase in the proportion of the catch <145 mm SL – from 42.4% in 2003 to 52.2% in 2005. Similar patterns were observed in fishing areas 26, 27 and 30. The mean length of blacklip abalone sampled from the catch in fishing areas 26, 27 and 30 have decreased by 4.1 (2002 – 2005), 6.1 (2003 – 2005) and 8.3 mm SL (2002 – 2004), respectively. These data suggest that fishing pressure on this species has increased substantially in recent years.

Finally, estimates of retained egg production in fishing areas 26 and 27 during 2005 were lower than estimated in 2004. Further, all estimates for each fishing area have been below 50% since 2002. These levels of egg production could be considered insufficient to sustain long-term exploitation at current catch levels (Shepherd & Baker 1998).

The recent, consistent declines in the mean length and modal length class of the commercial catch, CPUE, mean daily catch, standardised CPUE and estimates of retained egg production are consistent with declining stock abundance. However, the extent of decline in the fishable biomass is not well understood.

Nevertheless, the continuation of the downward trends in recent years is of further concern because spatial and temporal patterns in catch suggest that blacklip abalone have a limited and

'patchy' distribution in this Zone. For example, since 1980, the catch has been harvested from few fishing areas. Over the last five years (2001 – 2005), ~80% of the blacklip abalone TACC was harvested from three fishing areas (26, 27 and 29) – all off Kangaroo Island. Catches from most other areas have been sporadic, suggesting that substantial blacklip abalone populations in areas other than off the south-western corner of Kangaroo Island are rare. There are also strong temporal patterns within fishing areas, the strongest of which are evident in fishing areas 26, 27 and 29. In two of the historically most productive fishing areas, 26 and 29, catches have halved between 2001 and 2005 and between 1995 and 2005, respectively. Comparable increases in catch are evident in fishing areas 27 and 28. These, relatively short-term changes in catch for these four fishing areas triggered the PI related to the spatial distribution of the catch, and are suggestive of a spatial shift in fishing activity (to fishing areas 27 and 28) brought about by reduced abundances of blacklip abalone in other areas (*e.g.* fishing areas 26 and 29), indicated by recent reductions in CPUE.

Despite the strong and generally consistent evidence that the blacklip stocks in this Zone are declining, there are some data that do not necessarily support this conclusion. Firstly, in contrast to fishing areas 26 and 29, the CPUE on blacklip abalone in fishing area 27 has been increasing slowly since 1997, and significantly since 2001. Secondly, in fishing area 29, the mean length and modal length class of blacklip abalone sampled from the commercial catch increased between 2002 and 2005. This may also reflect low recruitment to the fishery. Thirdly, estimates of retained egg production in fishing area 29 increased between 2004 and 2005.

In summary, there is considerable evidence that the resource on which the CZ blacklip abalone fishery is based remains in its weakest position for several years. This conclusion is consistent with previous assessment reports. There is also evidence that the resource has weakened despite the voluntary reductions in catch between 2002 and 2004. Responses of the blacklip abalone populations in the CZ to the recent, successive, substantial reductions in the TACC are not yet evident. Consequently, it remains unclear as to whether these reductions are sufficient to arrest the declines in this stock.

## **5.2 Future research needs**

For the greenlip abalone stocks, there is a clear need to resolve the ambiguity between the conflicting inferences, drawn from the fishery-dependent and survey data. This is central to ensuring future sustainability of the important stock in fishing area 21 and could begin to be addressed through investigation into the standardisation of diver surveys and examining the fishery-dependent data at a finer spatial scale. In addition, there is also a need to obtain

fishery-independent measures of stock status in ‘lightly-fished’ areas. For blacklip abalone, it is important to develop, test, implement and regularly undertake fishery-independent surveys – particularly in fishing areas 26 (Cape du Couedic), 27 (Cape Bouger) and 29 (Cape Gantheaume). These data are essential for (1) validating assessments, and (2) determining changes in the abundance and population structure of blacklip abalone.

Future assessment of this fishery will also be enhanced by obtaining commercial shell samples representative of the scale of the fishery. The length-frequency distribution of the commercial catch varies among areas, divers and days. Thus, sampling at spatial and temporal scales representative of the fishery is required to reliably detect and quantify changes. Determining the appropriate sampling level requires a robust cost-benefit analysis. Andrew and Chen (1997) described the use of Monte Carlo simulations to (1) investigate the influence of numerous sources of variation on the estimates of mean length and length structure in the commercial blacklip abalone catch in NSW and, (2) suggest a representative commercial catch-sampling approach. The relevance of this approach to developing a more robust commercial-catch sampling program should be evaluated.

There is also a need to (1) review the performance indicators for the fishery; (2) refine the biological data and model parameters, and thus the estimates of egg production, and mature and legal biomass from the egg production and integrated stock assessment models, respectively; (3) review the decision rules used in determining the CPUE on each species; and (4) obtain data that are representative of the growth rates (and their associated variability) of blacklip abalone in this zone.

It would also be useful to (1) improve estimates of the recreational and illegal catch; and (2) assess the direct and indirect effects on the ecosystem arising from the harvest of abalone in this Zone. Resolving this latter issue is central to the development of environmental and ecological performance indicators for this fishery.

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## Appendix 1: Greenlip abalone egg-production model

### 1.1 Assumptions and model structure

1. The stock structure is in a steady state and recruitment is constant. Therefore, the total yield (or egg production) in any one year from all age classes is the same as that from a single cohort over its whole lifespan.
2. The model follows a single cohort through its life. Initial recruitment was arbitrarily selected at 100 individuals. The model was run on a monthly basis up to 240 months.
3. Length-at-age was predicted using the von Bertalanffy equation based on parameters estimated for each area. The model is sensitive to changes in either  $K$  or  $L_{\infty}$ .
4. The proportion of mature individuals ( $f(x) = a/(1+\exp(-((x-L_{50})/b)))$ ) and number of eggs in each size class (fecundity =  $aSL^b$ ) were determined from parameters estimated at each site.
5. Egg quality, size and fertilisation rate were considered constant across all sizes of abalone.
6. Selectivity increased linearly from zero at the MLL (130 mm SL) to 1 for abalone larger than the lower limit of the modal size class from the commercial catch ( $L_{msc}$ ). Thus, all abalone larger than  $L_{msc}$  observed by a diver have an equal probability ( $P$ ) of capture.
7. The estimate of  $F_{2005}$  in all areas was determined from commercial shell samples obtained during 2005 after King (1995). There is considerable uncertainty in estimating  $F$ . Estimates of retained egg production are highly sensitive to  $F$ .
8. Growth data are representative of fished areas.

### 1.2 Biological data

Model inputs	Parameter	Size / age	Fishing area 21
Growth rate <sup>1</sup>	$L_{\infty}$	-	179
	$K$	-	0.215
Size at maturity <sup>2</sup>	$a$	-	1.0029
	$b$	-	5.2136
	$L_{50}$	-	80.3
Fecundity <sup>3</sup>	$a$	-	0.0023
	$b$	-	4.143
Natural Mortality <sup>4</sup>	$M$	0 – 6 months	4
		7 – 36 months	0.64
		37 – 48 months	0.5
		49 – 60 months	0.3
		>60 months	0.15
Length fully selected	$L_{msc}$	-	144
Fishing mortality	$F_{2005}$	-	0.377

1. Mean value obtained from individuals tagged and recaptured at Tiparra Reef (Dixon & Day 2004).
2. Parameter estimates for the logistic function describing the relationship between shell length and proportion mature for greenlip abalone at Tiparra Reef in 2003 and 2004.
3. Data from Tiparra Reef (SARDI unpublished data).
4. Data from Shepherd and Breen (1992) and Shepherd and Baker (1998).

## Appendix 2: Blacklip abalone egg-production model

### 2.1 Assumptions and model structure

1. The stock structure is in a steady state and recruitment is constant. Therefore, the total yield (or egg production) in any one year from all age classes is the same as that from a single cohort over its whole lifespan.
2. The model follows a single cohort through its life. Initial recruitment was arbitrarily selected at 100 individuals. The model was run on a monthly basis up to 240 months.
3. Length-at-age was predicted using the von Bertalanffy equation based on parameters estimated for each area. The model is sensitive to changes in either K or  $L_{\infty}$ .
4. The proportion of mature individuals ( $f(x) = a/(1+\exp(-((x-L_{50})/b)))$ ) and number of eggs in each size class (fecundity =  $a SL^b$ ) were determined from parameters estimated at each site.
5. Egg quality, size and fertilisation rate were considered constant across all sizes of abalone.
6. Selectivity increased linearly from zero at the MLL (130 mm SL) to 1 for abalone larger than the lower limit of the modal size class from the commercial catch ( $L_{msc}$ ). Thus, all abalone larger than  $L_{msc}$  observed by a diver have an equal probability (P) of capture.
7. The estimate of  $F_{2005}$  in all areas was determined from commercial shell samples obtained during 2005 after King (1995). There is considerable uncertainty in estimating F. Estimates of retained egg production are highly sensitive to F.
8. Growth data are representative of fished areas.

### 2.2 Biological data

Model inputs	Parameter	Size / age	Fishing area		
			26	27	29
Growth rate <sup>1</sup>	$L_{\infty}$	-	170	170	170
	K	-	0.34	0.34	0.34
Size at maturity <sup>2</sup>	a	-	1.0017	0.9894	1.0005
	b	-	6.9110	5.4712	6.5574
	$L_{50}$	-	95.1783	96.2188	96.0040
Fecundity <sup>3</sup>	a	-	$1 \times 10^{-6}$	$1 \times 10^{-6}$	$1 \times 10^{-6}$
	b	-	5.7143	5.7143	5.7143
Natural Mortality <sup>4</sup>	M	0 – 12 months	3	3	3
		13 – 24 months	0.9	0.9	0.9
		25 – 36 months	0.45	0.45	0.45
		>36 months	0.2	0.2	0.2
Length fully selected	$L_{msc}$	-	142	140	136
Fishing mortality	$F_{2005}$	-	0.269	0.673	0.604

1. Data from Shepherd & Hearn 1983 (K) and estimated from commercial catch samples ( $L_{\infty}$ ).
2. Parameter estimates for the logistic function describing the relationship between shell length and proportion mature for blacklip abalone off SW Kangaroo Island in 2004 (SARDI unpublished data).
3. Data from Cape Bedout & Cape du Couedic (SARDI unpublished data).
4. Data from Shepherd and Breen (1992) and Shepherd and Baker (1998).

## Appendix 3: Length-based stock assessment model (after Gorfine *et al.* 2005)

### 3.1 Model description

The model was developed in AD Model Builder (Otter Research Ltd). It is length based. The lower size limit is 52 mm SL. There are 66, 2 mm SL length classes. Sexes are not distinguished. The model runs on an annual time step. Catches from commercial fishers were used in the model, through a fishing selectivity function.

The model operates by estimating the numbers of abalone in each length class at the start of each season by applying growth, natural mortality, fishing mortality and recruitment to each length class each year. This process is numerically represented by:

$$N_{t,l,m}^c = \alpha_{t,l,m-1} \left( \sum_{l' \leq l} N_{t,l',m-1}^c e^{-M_l^c} [1 - \sum_i F_{t,m-1}^i S_{t,l',m-1}^i] X_{l,l',m-1}^c + \sum_{l' \leq l} N_{t,l',m-1}^{\tilde{c}} e^{-M_l^{\tilde{c}}} X_{l,l',m-1}^{\tilde{c}} \right)$$

$$N_{t,l,m}^{\tilde{c}} = (1 - \alpha_{t,l,m-1}) \left( \sum_{l' \leq l} N_{t,l',m-1}^c e^{-M_l^c} [1 - \sum_i F_{t,m-1}^i S_{t,l',m-1}^i] X_{l,l',m-1}^c + \sum_{l' \leq l} N_{t,l',m-1}^{\tilde{c}} e^{-M_l^{\tilde{c}}} X_{l,l',m-1}^{\tilde{c}} + R_{t,l,m-1} \right)$$

where  $N_{t,l,m}^c$  is the number of abalone in size-class  $l$  in non-cryptic habitat at the start of season  $m$  of year  $t$

$N_{t,l,m}^{\tilde{c}}$  is the number of abalone in size-class  $l$  in cryptic habitat at the start of season  $m$  of year  $t$

$\alpha_{t,l,m-1}$  is the probability that an animal in size-class  $l$  is in the non-cryptic habitat at the end of season  $m-1$  of year  $t$

$M_l^{c/\tilde{c}}$  is the instantaneous rate of natural mortality on animals in size-class  $l$  in the non-cryptic / cryptic habitat

$X_{l,l',m-1}^{c/\tilde{c}}$  is the probability that an animal in the non-cryptic / cryptic habitat and size-class  $l'$  grows into size-class  $l$  at the end of season  $m-1$  (the size-transition matrix)

$F_{t,m-1}^i$  is the fully-selected exploitation rate by sector  $i$  (commercial, recreational, and illegal) during season  $m-1$  of year  $t$

$S_{t,l,m-1}^i$  is the selectivity of sector  $i$  on animals in size-class  $l$  during season  $m-1$  of year  $t$

$R_{t,l,m-1}$  is the recruitment to size-class  $l$  at the end of season  $m'$  of year  $t$

#### 3.1.1 Exploitation rate

The fully-selected exploitation rate for each sector,  $F_{t,m}^i$ , is defined as the ratio of the catch to the exploitable biomass:

$$F_{t,m}^i = \frac{C_{t,m}^i}{B_{t,m}^{e,i}} = \frac{C_{t,m}^i}{\sum_l w_l S_{t,l,m}^i N_{t,l,m}^c e^{-M_l^i \Delta t}}$$

where  $C_{t,m}^i$  is the catch by sector  $i$  at the end of season  $m$  of year  $t$   
 $B_{t,m}^{e,i}$  is the exploitable biomass corresponding to sector  $i$  during season  $m$  of year  $t$ ,  
 $w_l$  is the mean weight of an animal in length-class  $l$   
 $\Delta t$  is one year

### 3.1.2 Growth

Growth parameters are specified by a growth matrix derived from tag-recapture data from Reef Head, Venus Bay and Sheringa generated using Estimatrix (after Bardos 2005).

### 3.1.3 Length-weight relationship

Weight, as a function of size, is given by:

$$w_l = a \bar{l}^b$$

where  $a$ ,  $b$  and  $\bar{l}$  (maximum SL) are the parameters of the weight-size relationship.

### 3.1.4 Fishing selectivity

Fishing selectivity, as a function of length-class is given by the proportion selected:

$$S_{t,l,m}^i = \begin{cases} 0, l < l_{\min,i} \\ p_{t,m}^i + (1 - p_{t,m}^i)(l - l_{\min,i}) / (l_{\max,i} - l_{\min,i}), l_{\min,i} > l > l_{\max,i} \\ 1, l \geq l_{\max,i} \end{cases}$$

where  $l_{50,t}^i$  is the length of 50% selectivity for sector  $i$  during season  $m$  and year  $t$   
 $l_{\min,i}$  is the minimum length fished for sector  $i$  during season  $m$  and year  $t$   
 $l_{\max,i}$  is the first length fully fished for sector  $i$  during season  $m$  and year  $t$   
 $p_{t,m}^i$  is the proportion of animals selected for sector  $i$  at  $l_{\min,t}$  during season  $m$  and year  $t$

### 3.1.5 Transition from cryptic to non-cryptic habitat

Emergence, as a function of length-class, is given by:

$$\alpha_{t,l,m} = (1 + \exp(-\ln 19(\bar{l} - l_{50,t,m}) / \phi_{t,m}))^{-1}$$

where  $\alpha_{t,l,m}$  is the probability of an animal in size-class  $l$  being in non-cryptic habitat at the end of season  $m$  of year  $t$   
 $\phi_{t,m}$  is the width of the emergence ogive during season  $m$  of year  $t$   
 $l_{50,t,m}$  is the size-at-50%- emergence during season  $m$  of year  $t$

### 3.1.6 Maturity

Maturity was specified as a proportion of mature individuals within each length class.

### 3.1.7 Recruitment

The recruitment by size-class, year and season is given by:

$$R_{t,l,m} = \omega_{l,m} \sum_{t' \leq t} \theta_{(t-t')} \frac{(B_{t'}^S / B_{-\infty}^S) e^{\varepsilon_{t'}}}{\tilde{\alpha} + \tilde{\beta} (B_{t'}^S / B_{-\infty}^S)}$$

where  $\omega_{l,m}$  is the fraction of the recruitment that occurs to size-class  $l$  during season  $m$

$\theta_{(t-t')}$  is the weighting from spawning in year  $t'$  to recruitment in year  $t$  (user specified);  $\sum_{t' \leq t} \theta_{(t-t')} = 1$

$\tilde{\alpha}$ ,  $\tilde{\beta}$  are the parameters of the stock-recruitment relationship (defined in terms of the ‘‘steepness’’ of the relationship,  $h$ , and the virgin recruitment,  $R_{-\infty}$ )

$$\tilde{\alpha} = \frac{(1-h)}{4hR_{-\infty}} \quad \text{and} \quad \tilde{\beta} = \frac{(5h-1)}{4hR_{-\infty}}$$

$h$  is the steepness of the stock-recruitment relation so that

$$hR = \frac{0.2}{\alpha + 0.2\beta} \quad \text{and} \quad R = \frac{1}{\alpha + \beta}$$

$B_t^S$  is the mature biomass corresponding to the recruitment during year  $t$ :

$$B_t^S = \sum_l w_l f_l (N_{t',l,m(S)}^c + N_{t',l,m(S)}^{\tilde{c}})$$

$f_l$  is the fraction of animals in size-class  $l$  that are mature

$w_l$  is the weight at length  $l$

$m(S)$  denotes the season of spawning

$\varepsilon_t$  is the ‘recruitment residual’ for year  $t$

## 3.2 Likelihood (estimation) functions

### 3.2.1 Catch-per-unit-effort (CPUE)

$$-\ln L = \sum_t \left[ \ln \sigma_i + \frac{1}{2\sigma_i^2} (\ln A_t - \ln(\hat{q} \sum_l (S_l^i N_{l,t})))^2 \right]$$

where  $N_{l,t}$  is the estimated number

$A_t$  is the observed CPUE

$S_l^i$  is the selectivity of the fishing on animals in the commercial sector I

$\sigma_i$  is the either a given standard deviation or the standard error from the data

$$\hat{q} = \exp\left[\frac{1}{n} \sum_y (\ln A_t - \ln(\sum_l (S_t^r N_{l,t}))^y)\right].$$

### 3.2.2 Commercial and fishery-independent proportion-at-length

The robust likelihood function of Fournier *et al.* (1998) is used:

$$-\log L = -0.5 \sum_t \sum_l \log[2\pi(\xi_{l,t} + 0.1/I)] - \sum_t I \log(\tau_t) + \sum_t \sum_l \log\left[\exp\left\{-\frac{(\rho_{l,t}^{obs} - \rho_{l,t}^{pred})^2}{2(\xi_{l,t} + 0.1/I)\tau_t^2}\right\} + 0.01\right]$$

where  $\rho_{l,t}^{obs}$  is the observed proportion of animals in length class  $l$  and year  $t$

$\rho_{l,t}^{pred}$  is the predicted proportion of animals in length class  $l$  and year  $t$

$$\xi_{l,t} = (1 - \rho_{l,t}^{obs}) \rho_{l,t}^{obs}$$

$$\tau_t^2 = 1 / \min(S_t, N_{eff})$$

$S_t$  is the sample size for the length frequency data for year  $t$

$N_{eff}$  is the effective sample size

$I$  is the number of length classes in the sample

### 3.2.3 Recruitment

Recruitment has a log-normal prior and  $\sigma_{Rec}$  is specified in:

$$-\ln L = -\sum_t (\sigma_t^r)^2 / \sigma_{Rec}^2.$$

## 3.3 Priors, parameter values and parameter posterior distributions

Parameter	Description	(Prior) / Fixed value	Parameter bounds	Estimate Median, 90%CI
$R_{init}$	Initial Recruitment (millions)	<b>U(0.1, 80)</b>	-	0.670, 0.549-0.830
$h$	Steepness of the Beverton Holt recruitment relationship	<b>N(0.6, 0.1)</b>	0.1 – 0.9	0.602, 0.533-0.670
$M$	Natural mortality	<b>N(0.2, 0.05)</b>	0.1 – 0.3	0.200, 0.189-0.211
$R_{dev}$	Recruitment deviations	<b>N(0, 0.4)</b>	-2.3 – 2.3	-
$q$	Power of the relationship between CPUE and biomass	1.0	-	-
$a$	Coefficient of the relationship between weight and length	0.0001	-	-
$b$	Power of the relationship between weight and length	3.09	-	-
$l_{min}$	Minimum size harvested (commercial)	130	-	-
$p$	% of minimum size retained (commercial)	5%	-	-
$l_{max}$	Size at which 100% are retained (commercial)	140	-	-
$N_{eff_{comm}}$	Effective sample size of the commercial length frequency	50	-	-
$N_{eff_{cpue}}$	Observation error on CPUE	0.15	-	-
$N_{eff_{ind}}$	Effective sample size of the independent length frequency	NA	-	-

**Appendix 4: Assessment of the greenlip abalone fishery in the CZ of the South Australian abalone fishery against the biological performance indicators prescribed in the management plan. Values are mean  $\pm$  SE. Red indicates statistical significance.**

Performance Indicator	Units	Spatial Scale	2001	2002	2003	2004	2005	Inter-annual change	5-year trend
Commercial effort	hr	Zone	1367	1475	1387	1355	1532	-	$r^2 = 0.19$ , $df = 3$ $p > 0.05$
Mean daily catch	kg.day <sup>-1</sup>	Area 21 <sup>1,2</sup>	648.4 $\pm$ 17.0	594.1 $\pm$ 15.9	624.8 $\pm$ 16.5	636.1 $\pm$ 17.0	523.0 $\pm$ 15.6	$t = 4.89$ , $df = 320$ $p < 0.05$	$F_{1,901} = 14.0$ $p < 0.05$
		Area 22 <sup>2</sup>	NO DATA	NO DATA	NO DATA	513.8 $\pm$ 32.9	373.8 $\pm$ 14.8	$t = 4.18$ , $df = 56$ $p < 0.05$	-
Mean daily effort	hr.day <sup>-1</sup>	Area 21 <sup>1,2</sup>	6.7 $\pm$ 0.1	6.7 $\pm$ 0.1	6.6 $\pm$ 0.1	6.6 $\pm$ 0.1	6.5 $\pm$ 0.1	$t = 0.71$ , $df = 320$ $p > 0.05$	$F_{1,901} = 1.80$ $p > 0.05$
		Area 22 <sup>2</sup>	NO DATA	NO DATA	NO DATA	5.4 $\pm$ 0.2	5.2 $\pm$ 0.2	$t = 0.36$ , $df = 56$ $p > 0.05$	-
CPUE	kg.hr <sup>-1</sup>	Area 21 <sup>1,2</sup>	96.7 $\pm$ 1.8	88.1 $\pm$ 1.6	94.6 $\pm$ 1.7	96.1 $\pm$ 1.7	80.9 $\pm$ 2.1	$t^3 = 5.67$ , $df = 307.4$ $p < 0.05$	$F^4_{1,901} = 7.98$ $p < 0.05$
		Area 22 <sup>2</sup>	NO DATA	NO DATA	NO DATA	95.8 $\pm$ 8.2	71.5 $\pm$ 2.5	$t^3 = 2.85$ , $df = 13.1$ $p < 0.05$	-
Mean size	mm, SL	Area 21 <sup>1</sup>	NO DATA	146.2 $\pm$ 0.2	146.5 $\pm$ 0.2	146.6 $\pm$ 0.1	147.9 $\pm$ 0.1	$t = 8.10$ , $df = 10778$ $p < 0.01$	-
		Area 22	NO DATA	152.1 $\pm$ 0.4	148.8 $\pm$ 0.5	148.3 $\pm$ 0.3	NO DATA	-	-
Legal-sized abalone abundance	no.m <sup>-2</sup>	Tiparra Reef	0.17 $\pm$ 0.02	0.23 $\pm$ 0.02	0.16 $\pm$ 0.01	0.24 $\pm$ 0.02	0.28 $\pm$ 0.04	$t = 0.99$ , $df = 166$ $p > 0.05$	$F_{1,358} = 6.11$ $p < 0.05$
Sub-legal-sized abalone abundance	no.m <sup>-2</sup>	Tiparra Reef	0.24 $\pm$ 0.02	0.35 $\pm$ 0.02	0.25 $\pm$ 0.02	0.34 $\pm$ 0.03	0.46 $\pm$ 0.05	$t = 2.17$ , $df = 166$ $p < 0.05$	$F_{1,358} = 11.5$ $p < 0.05$
Abundance of abalone >L <sub>50</sub>	no.m <sup>-2</sup>	Tiparra Reef	0.38 $\pm$ 0.03	0.54 $\pm$ 0.04	0.38 $\pm$ 0.03	0.54 $\pm$ 0.05	0.71 $\pm$ 0.08	$t = 1.87$ , $df = 166$ $p > 0.05$	$F_{1,358} = 12.2$ $p < 0.05$
Egg production retained	%	Tiparra Reef	NO DATA	34.2	37.9	36.9	40.3	N/A	N/A

1. Excludes data from Cowell (mapcode 21J) and unknown mapcodes (*i.e.* 21U) in all years.
2. Daily records where catch of blacklip abalone exceeds 0 kg are excluded.
3. Based on the ratio estimator (after Rice 1995).
4. Based on daily CPUE.

**Appendix 5: Assessment of the blacklip abalone fishery in the CZ of the South Australian abalone fishery against the biological performance indicators prescribed in the management plan. Values are mean  $\pm$  SE. Red indicates statistical significance.**

Performance Indicator	Units	Spatial Scale	2001	2002	2003	2004	2005	Inter-annual change	5-year trend
Commercial effort	hr	Zone	589	504	439	426	389	-	$r^2 = 0.92$ , $df = 3$ $p < 0.05$
Mean daily catch <sup>1</sup>	kg.day <sup>-1</sup>	Area 26	521.6 $\pm$ 21.6	475.1 $\pm$ 33.4	459.8 $\pm$ 26.1	496.6 $\pm$ 30.5	402.8 $\pm$ 30.4	$t = 1.87$ , $df = 37$ $p > 0.05$	$F_{1,134} = 3.95$ $p < 0.05$
		Area 27	371.6 $\pm$ 29.2	452.7 $\pm$ 30.9	364.4 $\pm$ 48.4	486.6 $\pm$ 39.2	451.8 $\pm$ 32.7	$t = 0.68$ , $df = 31$ $p > 0.05$	$F_{1,104} = 2.47$ $p > 0.05$
		Area 29	465.2 $\pm$ 34.9	449.8 $\pm$ 43.0	569.6 $\pm$ 34.2	361.7 $\pm$ 56.1	344.2 $\pm$ 45.4	$t = 0.24$ , $df = 20$ $p > 0.05$	$F_{1,55} = 4.98$ $p > 0.05$
		Area 30	209.4 $\pm$ 46.0	NO DATA	NO DATA	589.3 $\pm$ 70.32	278.3 $\pm$ 26.3	$t = 4.14$ , $df = 1$ $p > 0.05$	-
Mean daily effort <sup>1</sup>	hr.day <sup>-1</sup>	Area 26	6.3 $\pm$ 0.2	6.3 $\pm$ 0.4	6.2 $\pm$ 0.2	6.3 $\pm$ 0.1	5.6 $\pm$ 0.3	$t = 2.50$ , $df = 37$ $p < 0.05$	$F_{1,134} = 1.98$ $p > 0.05$
		Area 27	5.5 $\pm$ 0.3	6.5 $\pm$ 0.1	5.2 $\pm$ 0.3	6.0 $\pm$ 0.4	5.6 $\pm$ 0.3	$t = 1.00$ , $df = 31$ $p > 0.05$	$F_{1,104} = 0.33$ $p > 0.05$
		Area 29	6.6 $\pm$ 0.3	6.4 $\pm$ 0.2	6.1 $\pm$ 0.2	5.6 $\pm$ 0.6	6.0 $\pm$ 0.6	$t = 0.46$ , $df = 20$ $p > 0.05$	$F_{1,55} = 2.52$ $p > 0.05$
		Area 30	5.4 $\pm$ 0.8	NO DATA	NO DATA	6.8 $\pm$ 0.3	6.7 $\pm$ 0.5	$t = 0.16$ , $df = 7$ $p > 0.05$	-
CPUE <sup>1</sup>	kg.hr <sup>-1</sup>	Area 26	83.1 $\pm$ 3.0	75.7 $\pm$ 3.8	74.4 $\pm$ 4.4	79.1 $\pm$ 4.2	72.6 $\pm$ 5.7	$t^2 = 0.91$ , $df = 23.3$ $p > 0.05$	$F^3_{1,134} = 1.88$ $p > 0.05$
		Area 27	67.2 $\pm$ 4.1	70.2 $\pm$ 4.7	70.4 $\pm$ 8.4	80.5 $\pm$ 5.2	81.0 $\pm$ 4.6	$t^2 = 0.07$ , $df = 28.6$ $p > 0.05$	$F^3_{1,104} = 5.65$ $p < 0.05$
		Area 29	70.2 $\pm$ 3.9	70.3 $\pm$ 4.9	94.0 $\pm$ 5.7	64.2 $\pm$ 7.5	57.2 $\pm$ 5.3	$t^2 = 0.77$ , $df = 17.9$ $p > 0.05$	$F^3_{1,55} = 1.82$ $p > 0.05$
		Area 30	39.0 $\pm$ 5.79	NO DATA	NO DATA	87.3 $\pm$ 9.24	41.8 $\pm$ 4.1	$t^2 = 4.49$ , $df = 1.43$ $p > 0.05$	-

1. Daily records where catch of greenlip abalone exceeds 50% of the total catch are excluded.
2. Based on the ratio estimator (after Rice 1995).
3. Based on daily CPUE.

**Appendix 5 (continued):**

Performance Indicator	Units	Spatial Scale	2001	2002	2003	2004	2005	Inter-annual change	5-year trend
Mean size	mm, SL	Area 26	NO DATA	151.3±0.6	147.5±0.3	147.6±0.2	147.2±0.3	$t = 1.11, df = 3321$ $p > 0.01$	-
		Area 27	NO DATA	143.2±0.3	148.9±0.3	147.0±0.4	142.8±0.3	$t = 8.84, df = 1201$ $p < 0.01$	-
		Area 29	NO DATA	139.5±0.3	NO DATA	142.5±0.4	145.3±0.0.2	$t = 5.81, df = 1512$ $p < 0.01$	-
		Area 30	NO DATA	149.8±0.8	NO DATA	141.5±0.6	NO DATA	-	-
Egg production retained	%	Area 26	NO DATA	48.7	45.4	46.5	42.4	N/A	N/A
		Area 27	NO DATA	48.3	39.9	43.0	24.2	N/A	N/A
		Area 29	NO DATA	43.5	21.8	24.4	28.0	N/A	N/A