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Biology, history, and assessment of Western Australian abalone fisheries

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Contents

Executive Summary **1**

Current Fishery **3**

1.1 Commercial Fishery 3

1.2 Recreational Fishery 5

1.3 Illegal Fishery 7

2.0 Historical development of the fishery **8**

2.1 Catch History 8

2.2 Management History 10

3.0 Abalone biology and life history parameters **15**

3.1 Greenlip abalone *(Haliotis laevigata)* *15*

3.1.1 Growth 15

3.1.2 Natural mortality 16

3.1.3 Length-weight relationships 17

3.1.4 Size-at-maturity and length-fecundity 19

3.2 Roe's abalone *(Haliotis roei)* *19*

3.2.1 Growth and natural mortality 19

3.2.2 Length-weight relationships 19

3.2.3 Size-at-maturity and length-fecundity relationships 19

3.3 Brownlip abalone *(Haliotis conicopora)* *22*

3.3.1 Growth and natural mortality 22

3.3.2 Length-weight relationships 22

3.3.3 Size-at-maturity and length-fecundity relationships 23

4.0 Research and assessment methodology **24**

4.1 Commercial fisheries data collection 24

4.1.1 Monthly catch and effort logbooks (1975+) 24

4.1.2 Daily catch and effort logbooks 24

4.2 Recreational fisheries data collection 24

4.2.1 Field surveys – Perth metropolitan roe's abalone fishery 24

4.2.2 Weather conditions, license numbers and recreational abalone catch 24

4.2.3 Phone diary surveys – entire state 25

4.3 Fishery independent stock surveys 25

4.3.1 Research diver transect surveys 25

4.3.1.1 Greenlip and Brownlip abalone 25

4.3.1.2 Roe's abalone 27

4.3.2 Digital video surveys 27

4.4 Data analysis and stock assessment 28

4.4.1 Standardised catch per unit effort 28

4.4.2 Fishing mortality 30

4.4.2.1 Data 30

4.4.2.2 Estimation methodology ... 30
4.4.3 Yield-per-recruit and egg-per-recruit analyses ... 31
4.4.3.1 Sensitivity analysis ... 32
4.5 Other Research Projects ... 32
4.5.1 Stock enhancement research *(Haliotis laevigata)* ... *32*
4.5.2 Recovering a collapsed abalone stock through translocation ... 32
4.5.3 Brownlip abalone: Exploration of wild and cultured harvest potential ... 33
4.5.4 Marine Park Abalone surveys: Cape Leeuwin – Cape Naturaliste ... 33
5.0 Greenlip and Brownlip Abalone ... 34
5.1 Commercial fisheries ... 34
5.1.1 Total Catch, effort and CPUE ... 34
5.1.2 Catch, CPUE and meat weights by subregion ... 36
5.1.2.1 Area 2 fishery ... 36
5.1.2.2 Area 3 fishery ... 36
5.1.3 Standardised CPUE ... 38
5.1.4 Average meat weight and length-frequency of catch ... 39
5.1.5 Fishing mortality ... 42
5.2 Stunted stocks ... 43
5.2.1 Stunted individuals ... 43
5.2.2 Stunted populations ... 43
5.2.3 Stunted stock surveys ... 45
5.2.4 Managing harvest from stunted stocks ... 46
5.3 Recreational fisheries ... 47
5.3.1 Catch, effort and CPUE ... 47
5.4 Fishery-independent stock surveys ... 48
5.4.1 Research Diver Transect Surveys ... 48
5.4.1.1 Area 2 ... 48
5.4.1.2 Area 3 ... 51
5.4.2 Digital video surveys ... 54
5.4.3 Discussion: FIS trends and limitations ... 56
5.5 Yield-per-recruit and egg-per-recruit analyses ... 57
5.5.1 Modelling under assumed growth parameters ... 57
5.5.2 Sensitivity analysis: varying growth parameters ... 58
6.0 Roe's Abalone ... 61
6.1 Commercial fisheries ... 61
6.1.1 Catch, effort and CPUE ... 61
6.1.2 Standardised CPUE ... 61
6.2 Recreational fisheries ... 64
6.2.1 Catch, effort and CPUE ... 64
6.2.2 Weather conditions and recreational catch ... 64
6.3 Fishery-independent stock surveys ... 66
6.3.1 Research Diver Surveys ... 66

6.3.2 Predicting future Haliotis roei stock densities ... 70

7.0 Performance Indicators and TACC Assessment ... 71

7.1 Methodology ... 71

7.2 2012/13 TACC Assessments ... 72

7.2.1 Fishery closures ... 73

7.3 Future developments ... 73

7.3.1 Egg Production and Fishing Mortality performance measures ... 73

7.3.2 Harvest Control Rule ... 75

8.0 General Discussion ... 77

9.0 Recommendations for future research ... 78

10.0 References ... 79

11.0 Appendices ... 81

11.1 Performance indicators and biological reference points for each management area and species ... 81

11.1.1 Area 1 Greenlip and Roe's abalone fishery ... 81

11.1.2 Area 2 Roe's abalone fishery ... 81

11.1.3 Area 2 Greenlip abalone fishery ... 82

11.1.4 Area 3 Greenlip abalone fishery ... 82

11.1.5 Area 5 Roe's abalone fishery ... 83

11.1.6 Area 6 Roe's abalone fishery ... 83

11.1.7 Area 7 Roe's abalone fishery ... 84

11.1.8 Area 8 Roe's abalone fishery ... 84

11.2 Catch and Effort maps ... 85

Executive Summary

This report summarises the biology, demography, research and management relevant to abalone (*Haliotis* sp.) fisheries in Western Australia up to and including the 2011/12 season. It presents a comprehensive review of current stock assessment in Western Australian abalone fisheries. Many of the biological parameters have not been published previously and represent a significant body of work over a number of years.

Abalone fisheries operate in shallow coastal waters off the south-west and south coasts of Western Australia and are primarily dive and wade fisheries. The majority of catch is taken by the commercial fishery, however there is also a significant recreational fishery, particularly for *Haliotis roei*. Three species of abalone are targeted: greenlip abalone (*Haliotis laevigata*), brownlip abalone (*H. conicopora*), and roe's abalone (*H. roei*).

The Abalone Managed Fishery is managed primarily through output controls in the form of Total Allowable Commercial Catches (TACCs), set annually for each species in each area and allocated to licence holders as Individual Transferable Quotas (ITQs) allocated to specific management areas. The other major management tool is the legal minimum length. Fishery status is monitored using daily catch and effort logbooks, commercial fishery catch samples to estimate mortality, recreational field and phone-diary surveys, and fishery-independent dive surveys using traditional (transect-based) and digital video techniques.

Trends in both fishery-dependent (standardised CPUE) and fishery-independent surveys indicate that abalone fisheries have been sustainably managed since their inception in the early 1970's. Overall the commercial fishery takes 86% (~ 300 t) of the total catch, with 14% (~50 t) taken by the recreational sector. The fishery has undergone an Integrated Fisheries Management process to facilitate the allocation of catch shares between sectors. Catch shares have been finalised for the Perth metropolitan *Haliotis roei* fishery, with the sector allocation being 0.5 t customary (~1%), 36 t commercial (~47%), and 40 t recreational (~52%).

TACC assessment using performance indicators and decision rules based on long-term standardised CPUE trends were undertaken for the 2012/13 fishing year. Total TACC remained similar to the 2011/12 fishing year. Recreational catch is expected to increase in 2012, after a low harvest in 2011 catch due to poor weather conditions. Further development of TACC decision rules to include information on harvest rate, fishery-independent abundance estimates and sectoral catch allocations will provide greater certainty in the management regime.

Surveys of the Perth metropolitan roe's abalone stock have resulted in a predictive model for stock abundance, with the 17 – 33 mm size class (~Age 1) showing a clear relationship with the ≥ 71 mm size class (harvested size class), 4 years later. However recent anomalies in 2011 and 2012 predicted abundances bear further investigation.

In the case of greenlip abalone, fishery-independent surveys suggest that overall stock levels have been stable over the past 3 to 5 years, but some localised declines and increases in particular age classes (e.g. ≥ 147mm in the Town sub-area) require further investigation. Further work is needed in other areas such as the basic biology of brownlip abalone. There is currently limited information on growth for this species, and estimates of fishing mortality in this species have been based on growth assumptions derived from the literature.

Research into stunted greenlip stocks has clearly established the presence of 'stunting' in this species, both from an individual and a stock perspective. However, the research has also shown that growth and productivity of all greenlip stocks will lie somewhere in a large continuum

from the very stunted, where maximum size reached is less than 120 mm, to the fast growing areas, where maximum size reached is greater than 180 mm.

The yield-per-recruit and egg-per-recruit analyses demonstrated that the Area 2 fishery were optimally exploited with respect to egg conservation targets, however the Area 3 fishery would benefit with small yield increases from minor reductions in minimum size of fishing.

Overall, the assessments show that stock levels are currently stable and fishing is sustainable. This is in concordance with an Australia-wide review of abalone fisheries management (Mayfield et. al., 2012). Future research should focus on the following key areas: Improvements and refinement to the TACC decision rules, research on the biology and fishery of brownlip abalone, environmental effects on fishing and catch variability, development of population assessment models and bioeconomic evaluations of fishing policy, including economic yield-per-recruit, and assessment of increases in economic performance under different harvest scenarios

Current Fishery

1.1 Commercial Fishery

The Western Australian abalone fishery is a dive fishery, operating in shallow coastal waters off the south-west and south coasts of Western Australia. The fishery targets 3 abalone species: greenlip abalone (*Haliotis laevigata*), brownlip abalone (*H. conicopora*), and roe's abalone (*H. roei*). Greenlip and brownlip abalone are larger, deeper water species, which can grow to around 200 mm shell length, and are primarily restricted in distribution to the south coast (Figure 1). Roe's abalone are a smaller (growing to 100 mm) species found in commercial quantities from the South Australian border to Shark Bay, although they are not uniformly distributed throughout this range (Figure 2).

The principal harvest method is a diver working off 'hookah' (surface supplied breathing apparatus) or SCUBA using an abalone 'iron' to prise the shellfish off rocks – both commercial and recreational divers employ this method. Commercial abalone divers operate from small fishery vessels (generally less than 9 metres in length).

The Abalone Managed Fishery is managed primarily through output controls in the form of Total Allowable Commercial Catches (TACCs), set annually for each species in each area and allocated to licence holders as Individual Transferable Quotas (ITQs). ITQs are specific to management areas (Table 1). The TACC for the Greenlip / Brownlip fishery is administered through 16,100 ITQ units, with a minimum unit holding of 450 units required before a Managed Fishery License (MFL) can be granted (Table 1). The TACC for Roe's abalone is administered through 25,180 ITQ units, with a minimum unit holding of 800 units, although some Roe's abalone licences are permitted to operate below this minimum in recognition of historical fishing practices. The licensing period runs from 1 April to 31 March of the following year for all species and fishing grounds.

All fisheries are harvested under a Legal Minimum Length (LML). The LML for greenlip and brownlip abalone is 140 mm shell length, although the commercial industry fishes to self-imposed size limits of 153 mm, 147 mm and 145 mm in various parts of the main stocks (Table 1). Slow growing or 'stunted stocks' are also fished. These stocks have been shown to not grow to the current LML, and are fished at 120 mm under special exemptions (see section 5.2). Stunted stock fishing is strictly controlled to pre-arranged levels of catch and effort.

The LML for Roe's abalone is 60 mm shell length in most parts of the commercial fishery (Table 1). However, commercial LMLs of 75 mm and 70 mm apply in Area 1 (Western Australia/South Australia border to Point Culver) and Area 7 (Cape Bouvard to Moore River) respectively.

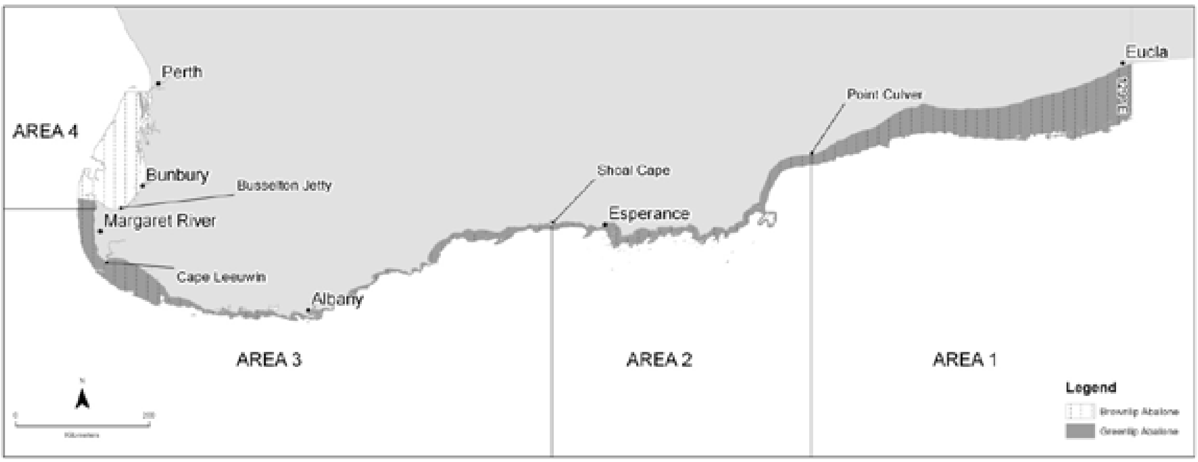


Figure 1. Management areas used to set quotas for the commercial greenlip brownlip fishery in Western Australia. Area 4 currently has no quota allocated

Figure 2. Map showing the management areas used to set quotas for the Roe's abalone commercial fishery in Western Australia.

Table 1. Management details relevant to commercial abalone fisheries in Western Australian. Commercial minimum lengths refer to voluntary minimum lengths imposed by commercial fishers

Species	Area	$No. of Fishery Licenses (MFLs)	#ITQs	*Current TACC (t) (2011/12)	*Current value of ITQs (kg)	Legal Minimum Lengths (mm)	Commercial Minimum Lengths (mm)
Greenlip	1	6	600	3.2	5.33	120	120
	2	6	6000	76.8	12.8	140	145
	3	8	7200	93.3	12.96	140	147 & 155
Brownlip	1	6	60	0.06	1.0	140	150
	2	6	1440	18.0	12.5	140	150
	3	8	800	18.0	22.5	140	150
Roe's	1	12	1980	5	2.52	60	75
	2	12	3600	19.8	5.50	60	75
	5	12	4000	20.0	5.00	60	60
	6	12	2400	12.0	5.00	60	60
	7	12	7200	36.0	5.00	60	70
	8	12	6000	0^{ϕ}	0	60	60
TOTAL				**315**			

$ The 12 MFLs in the Roe's abalone fishery generally have access across all Management Zones, whereas in the Greenlip / Brownlip fishery MFLs are restricted to individual management zones.

Individual Transferable Quota Units

* Whole weight (t) Greenlip and Brownlip TACC. The TACC (and ITQ) are legislated in meat weight, and were converted to whole weight with a multiplier of 2.667 for Greenlip and 2.5 for Brownlip.

$^{\phi}$ This Area is closed under a Section 43 notice so a TACC of zero is set for this area. See section 7.2.1 for more details.

1.2 Recreational Fishery

The recreational abalone fishery is divided into 3 zones: the Northern Zone and West Coast Zone are exclusively Roe's abalone fisheries, while the Southern Zone is predominantly the Greenlip / Brownlip recreational fishery, however Roe's abalone is also taken in this Zone (Figure 3). The recreational fishery harvest method is primarily wading and snorkeling, with the main focus of the fishery being the Perth metropolitan stocks (West Coast Fishery), although smaller amounts of greenlip and brownlip abalone are harvested on compressed air (SCUBA or hookah).

The recreational Roe's abalone fishery is managed under a mix of input and output controls. Recreational fishers must purchase a dedicated abalone recreational fishing licence. These licences are not restricted in number. Total number of licenses currently issued is 18,000 (Figure 4). Historically fishers could also purchase an "umbrella" fishing license, under which abalone could be fished (Figure 4), however this practice was discontinued from 2010.

The fishing season in the Northern and Southern Zones extends from 1 October to 15 May. The West Coast Zone is only open for 5 Sundays annually, and the time of fishing in 2006 was reduced from 90 to 60 minutes (between 7 a.m. and 8.00 a.m.), commencing on the first Sunday in November. A summer fishing season was introduced in 2011 with fishing commencing on the first Sunday of each month from November to March These restrictive management controls on the west coast are necessary to ensure the sustainability of an easily accessible (and therefore vulnerable) stock located adjacent to a population in excess of 1.6 million people (including Geraldton).

The combined daily bag limit for greenlip and brownlip abalone is five per fisher (formerly 10), and the household possession limit (the maximum number that may be stored at a person's permanent place of residence) is 20. For Roe's abalone, the minimum legal size is 60 mm shell length, the daily bag limit is 20 per fisher, and the household possession limit is 80.

a)

b)

Figure 3. Maps showing (a) the recreational fishing boundaries for abalone, and (b) the West Coast (Perth Fishery) zone, showing conservation areas within this zone.

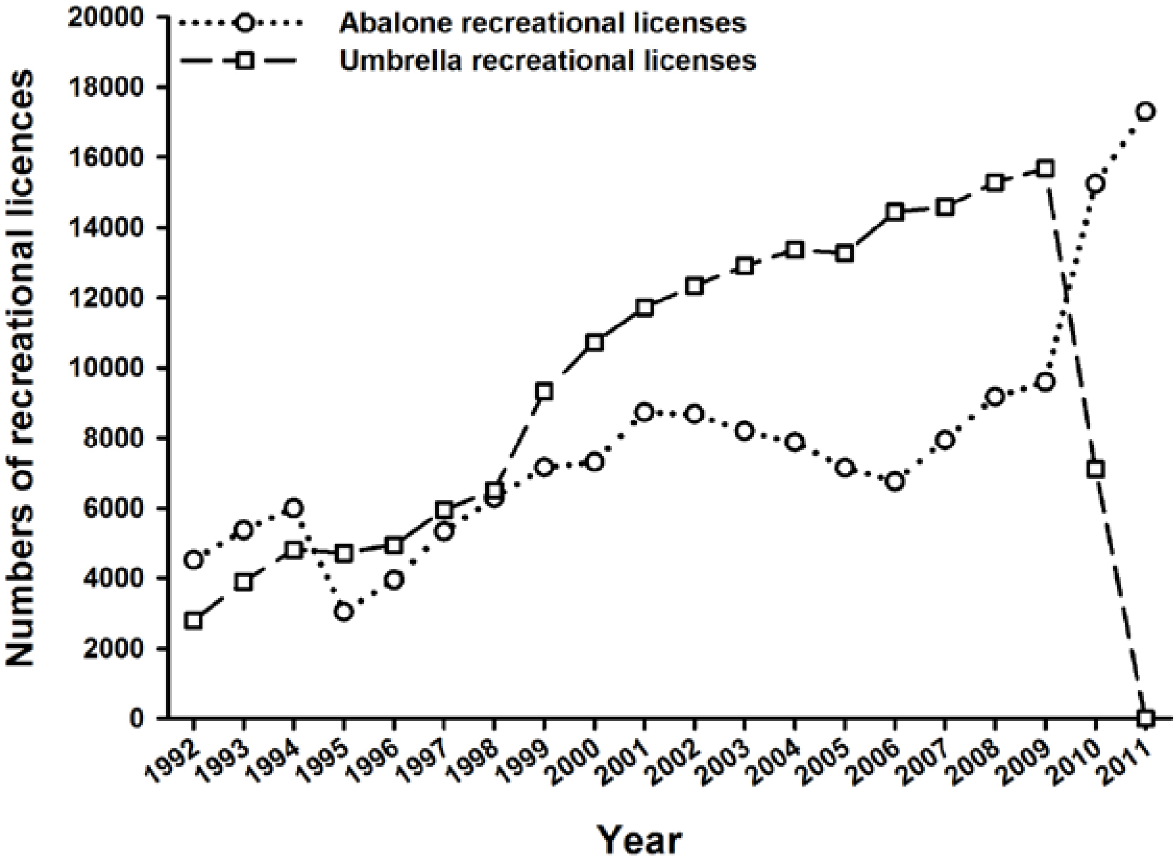


Figure 4. Number of recreational abalone licenses issued during the period 1992 to 2011.

1.3 *Illegal Fishery*

Quantity of illegal take depends on species. Overall, intelligence operations have revealed that greenlip abalone is the most desirable black market abalone and is easily sold and on sold; roe's abalone is of limited desirability, with some local black market trade in the Perth metropolitan area, and brownlip abalone is not highly sought and has a very limited black market.

Estimates are that at least 3 tonnes of greenlip abalone per year is taken for the black market on the South Coast. On the West Coast small quantities of excess possession limit metro roes abalone are taken overseas as hand luggage or baggage to Hong Kong, and Singapore.

2.0 Historical development of the fishery

2.1 Catch History

The abalone fishery in Western Australia is Australia's smallest, and fishing began more slowly than elsewhere because most of the main abalone producing reefs are found in isolated parts of the state. The exception to this is the roe's abalone fishery near Perth. Fishing of roe's abalone began in 1964, but was minimal and part-time until 1969. Emigration of divers from other states in 1970 resulted in a rapid expansion of catch to maximum of 450 tonnes before dropping back to current levels of between 300 and 350 tonnes (Figure 5a). Total catch has been stable since the early 1970s with an average tonnage around 350 tonnes.

The greenlip and brownlip abalone fisheries on the south coast are predominately commercial fisheries and have been that way since their inception in 1970. Greenlip abalone catches peaked at 270 tonnes in the first year of the fishery (1971) and oscillated between 150 and 270 tonnes during the 1970s and 1980s (Figure 5b). Catches dropped rapidly in 1990 to around 150 tonnes and have been at lower levels ever since, averaging around 190 tonnes (Figure 5b). Initially the catch was predominately greenlip, with small by catch of brownlip abalone, however since 1985 significant amounts of brownlip have been caught and it is now considered a separate fishery with catch showing increases in recent years (Figure 5b).

A similar historical pattern is seen in the roe's abalone fisheries. Commercial catches began earliest in this fishery, on the Perth metropolitan stocks in 1964, and then peaked at 170 tonnes in 1971, before declining to a relatively constant level of around 100 tonnes between 1980 and 2010 (Figure 5c). Recreational catch is significant in this fishery, currently comprising around 40% of the total catch (Hart et al., 2010). Recreational catch estimates are available since 1992, however considerable recreational catch also occurred in the 1980s. Recent years have seen an increasing recreational catch and total catch of roe's abalone in currently estimated to be around 160 tonnes (Figure 5c).

A more detailed analysis of catch and effort trends and finer spatial scales for individual species is found in section 11.2.

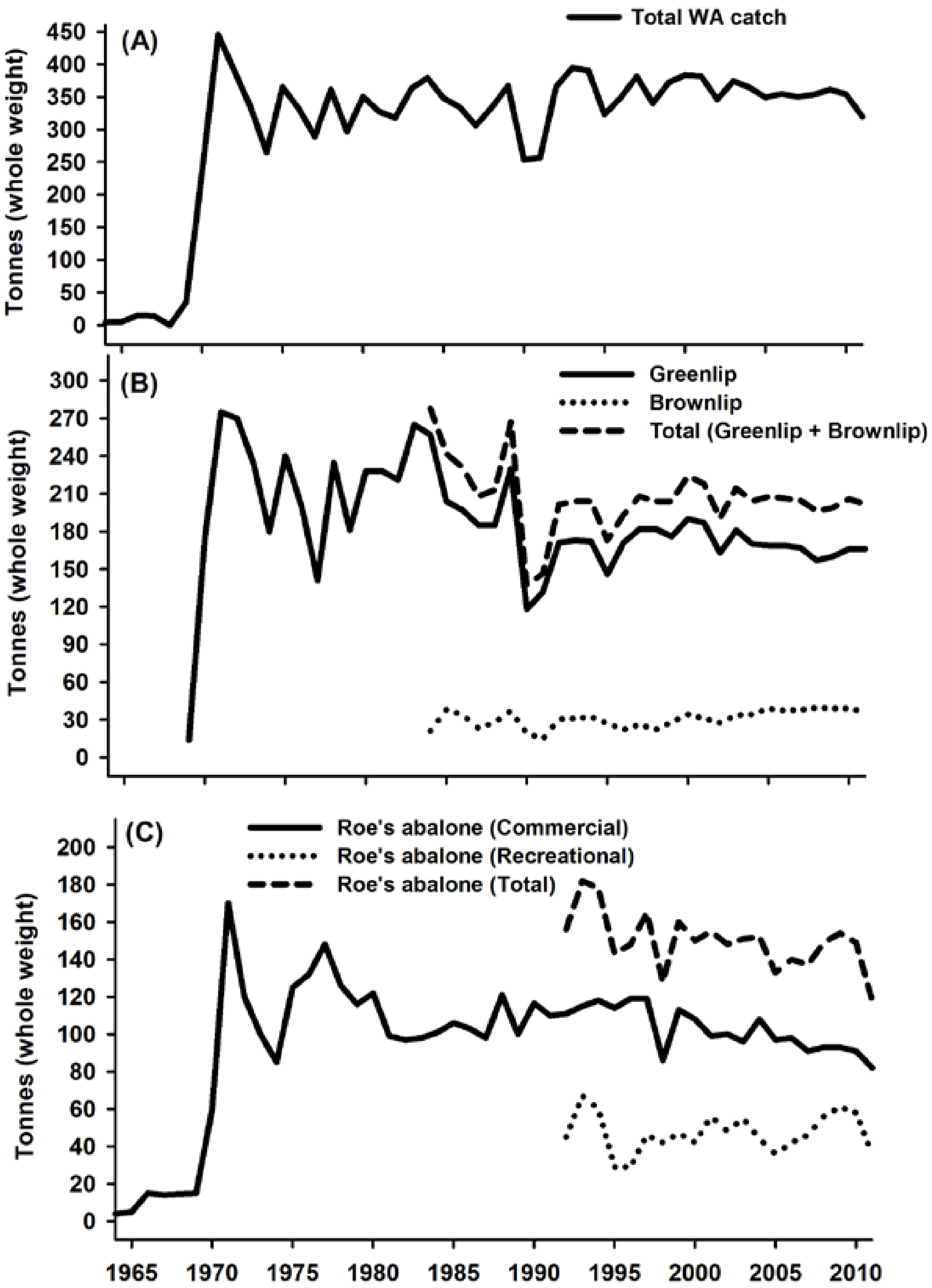


Figure 5. Historical catch estimates (tonnes whole weight) from abalone fisheries in Western Australia. (A) Total Catch, (B) Greenlip and Brownlip catch – commercial only, (C) Roe's abalone catch. Historical commercial catches (1964 to 1985) sourced from Prince and Shepherd (1992), and recreational catch (only estimated post 1991) averaged at 30 – 40% of total for roe's abalone. For greenlip and brownlip, recreational catch is minimal (3 – 4% of total; Hart et. al., 2010), and not included here.

2.2 Management History

Management in Western Australian abalone fisheries has followed a similar evolutionary path to many other fisheries, beginning with simple effort controls, developing into more complex catch controls and spatial management. A brief synopsis of the main significant events is summarised in Table 2, however the fishery has been very adaptive over its time and many changes have occurred. Only the major developments will be discussed here.

Commercial fishing began in 1964 when there were no controls and the fishery was open access. By 1971 rapid escalation of catch and license holders prompted the beginning of the first set of effort controls, primarily focused on the Perth metropolitan roe's abalone fishery. These included the setting of minimum size limits, license limitations and the beginning of spatial management with the use of rolling closures to protect and rest stocks (Table 2). These practices set the scene for the next decade. Formal spatial management was introduced in 1975 with the creation of three management zones (Zone 1, 2 and 3). The relationship between these zones and the current areas is shown in Figure 6. The new management arrangements were accompanied by catch and effort statistics provided on a monthly basis. The initial licenses were non-transferable and owner-operated, and this was designed to limit any further expansion in the fishery.

Daily bag limits were introduced into the Perth commercial fishery in 1978 and remained for 20 years. Size limits were initially a combination of minimum lengths and minimum meat weight, but by 1993, the emphasis on compliance and ensuring management regulations were enforceable resulted in the adoption of minimum length limits. Changes in size-limits have been an ongoing and regular management practice in these fisheries, as well as fishing area closures. For example, the Flinders Bay greenlip brownlip fishery in Zone 2 (Area 3) was regularly closed and opened, for periods of up to 2 years, between 1975 and 1996. This fishery has been particularly vulnerable because of its small size and ease of access, and has been intensively targeted by illegal fishing at certain periods in its history.

The next evolution in management was the period of catch controls, beginning in 1985 with the setting of a voluntary TAC (Total Allowable Catch) in the Zone 1 fishery. TACs were subsequently introduced to the Zone 2 fishery in 1986 and the Zone 3 fishery in 1988. In the greenlip brownlip fisheries these were initially non-transferable IQs (Individual Quotas), set at quite high levels. However, these were not deemed sustainable and TAC dropped substantially in 1990 in the greenlip brownlip fisheries, as evidence by a 40% drop in catch (Figure 5b). The TAC in the roe's abalone fishery (Zone 3) was a state-wide competitive quota, which caused a few localised depletion concerns, and IQs were eventually introduced into Zone 3 in 1993.

Recreational fishing controls were first introduced in 1980 in the Perth roe's abalone fishery, with a 2 month limited season from October to December. However by 1988 concerns with stock sustainability resulted in more restrictions; fishing was only permitted on weekends and public holidays, between 6 and 10 am. This fishery has subsequently under gone further restrictions, resulting in a 9 hour annual fishery in 1995, reduced to a 5 hour fishery in 2010 (Table 2). The fishery now also has a total allowable recreational catch (TARC), only the second fishery in WA to be allocated this under the Integrated Fisheries Management (IFM) initiative. Innovative ways to control this TARC are now being considered.

The next major management evolution of the commercial fishery management was the introduction of transferability, unitisation, and spatial TACs in 1999. These changes were particularly important for the roe's abalone fishery (the old Zone 3 fishery). Under the new regime, the spatial TACs (6 areas in total) enabled fishing effort to be more evenly spread across the fishery. Significant trading of quota units were undertaken between license holders wishing to fish in localised areas close to home.

Development of performance indicators and formal decision rules to assess annual TACs was introduced over the period 2005 – 2009 and these now underlie the main management functions relating to setting of a sustainable catch.

Table 2. Historical schedule of significant management action within Western Australian abalone fisheries

Year	Effort Controls									Catch Controls								Details
	Open access	Closures	Spatial management	License limitation	Size limits	Catch Monitoring	Limited entry	Bag limits	Recreational	TAC/IQs	Quota monitoring	Nominated operators	ITQs (transferable)	Spatial TAC	Performance indicators	TAC decision rules	IFM	
1964	■																	Initial fishing in Perth roe's abalone fishery. Open access.
1971		■	■	■	■													License limitation introduced. 36 non-transferable commercial licenses, reduced to 25 by 1975. Rolling closures begin in Perth fishery on approx. a 3 year rotation between North, Central, and South areas. System continues till 1982. Size limits (60 mm) introduced in roe's abalone fishery.
1972					■													Minimum size limit (100 mm) introduced for greenlip and brownlip fishery, corresponding to size at maturity.
1975		■	■		■	■												Formal spatial management introduced. Three zones created. Zone 1 (6 divers) and Zone 2 (8 divers) for the greenlip and brownlip fishery. Zone 3 (12 divers) for the roe's abalone fishery. Size limits for greenlip and brownlip fisheries changed to minimum weight of 113 g. Monthly catch and effort monitoring (CAES) introduced at the spatial scale of 1 degree (60 x 60 nautical miles). Flinders Bay (Zone 2) greenlip fishery closed for 2 years
1976							■											Limited entry (owner operated, non-transferable licenses) first introduced in Zone 2.
1978		■						■										Daily bag limit (100 kg) introduced for Perth commercial fishery. Remains in place till 1999 when the 36 tonne spatial TAC introduced. Flinders Bay (Zone 2) greenlip fishery closed for 18 months
1980		■			■				■									Size limits in Perth fishery increased from 60 to 70 mm. Flinders Bay (Zone 2) greenlip fishery closed for 2 years. Recreational fishery in Perth limited to a seasonal opening from mid-October to mid-December.
1985					■					■								Total Allowable Catch (TAC) introduced to Zone 1. TAC initially allocated as non-transferable IQ (Individual Quota). Size limit in greelip and brownlip fishery increased.
1986		■			■					■	■							TAC introduced to Zone 2. Flinders Bay (Zone 2) greenlip fishery closed for 2 years. Spatially delimited size limits introduced to Zone 2. Daily catch (quota) and effort monitoring introduced, initially in Zone 2.

Table 2 (continued). Historical schedule of significant management action within Western Australian abalone fisheries

Year	Effort Controls									Catch Controls								Details
	Open access	Closures	Spatial management	License limitation	Size limits	Catch Monitoring	Limited entry	Bag limits	Recreational	TAC/IQs	Quota monitoring	Nominated operators	ITQs (transferable)	Spatial TAC	Performance indicators	TAC decision rules	IFM	
1988																		State wide TAC introduced for Zone 3 (roe's abalone). Recreational fishing further restricted in Perth fishery. Only permitted on weekends and public holidays between 6 and 10 am.
1991 to 1996																		Experimental closures and rotational fishing undertaken by industry in Zone 2 greenlip fishery (Augusta region) to test effectiveness of reef-based management.
1992																		Nominated operators (i.e. lease divers) permitted in the fishery. Represents first step away from non-transferability. Daily access hours reduced from 4 to 2 hours on permitted fishing days in Perth recreational fishery.
1993																		IQs introduced in the roe's abalone fishery to reduce issues stemming from the competitive TAC. Minimum legal size changed from a meat weight (g) to shell length (mm) in all fisheries because of compliance concerns.
1995																		Permitted fishing days in Perth metro fishery reduced to 6 days in total during November / December creating a 9 hour annual fishery.
1999																		TAC unitised, quota made transferable (ITQs), and fishery divided into 8 new spatial units (Area 1 to Area 8) each with its own TAC. See Figure 6 for a comparison of "old" and "new" spatial areas.
2005																		Formal performance indicators introduced to monitor stock status and assist in TAC assessment process.
2006																		Permitted fishing hours in Perth metro fishery reduced to 1 hour per day resulting in a 6 hour annual fishery
2008																		TAC decision rules introduced. Integrated Fisheries Management (IFM), which determines sectoral catch allocations, introduced for the Perth roe's abalone fishery. Recreational fishery now has total allowable catch.
2010																		Permitted fishing hours in Perth metro fishery reduced to 5 days in total during November/Decemberr resulting in a 5 hour annual fishery
2011																		Permitted fishing days in Perth metro fishery changed from 5 consecutive weeks in November/December to a Summer season starting on the first Sunday of each month from November through March

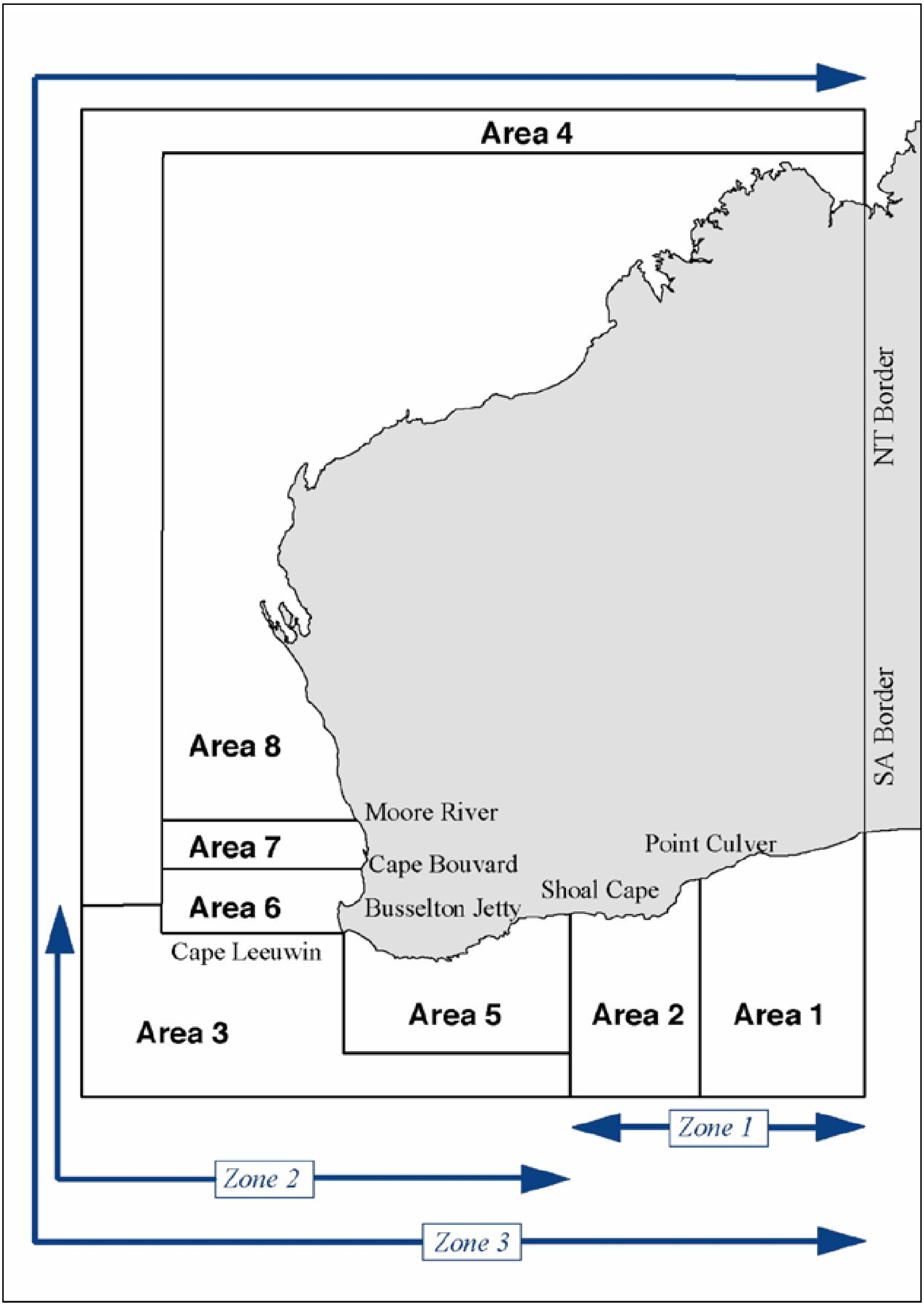


Figure 6. General map comparing old zonal arrangements (1975-1998; Zone 1, 2 & 3) and new area management areas (1999-2012+) of the commercial abalone fisheries of Western Australia

3.0 Abalone biology and life history parameters

Abalone are marine archaeogastropods (snails) with a worldwide distribution in tropical and temperate waters (Lindberg, 1992). All commercially targeted Western Australian species of abalone live on exposed, high-energy coasts and have evolved life-history characteristics to enable survival in this environment. General traits include: a muscular foot capable of providing solid attachment during periods of prolonged exposure; a feeding behaviour primarily focused on drifting algae dislodged by wave action, rather than actively grazing as do many other gastropods herbivores (Shepherd and Steinberg, 1992); broadcast spawning by separate sexes, synchronised by seasonal cue's such as change in water temperature and lunar periods, and a relatively short larval life-span of between 5 and 10 days to allow for quick settlement back into localised populations (McShane, 1992); use of specialised larval settlement substrate such as crustose coralline algae, and a relatively slow and long-lived life duration (McShane, 1992).

Managing harvest of these species requires detailed knowledge of the specific biology and habitat such as growth and mortality rates, length-weight relationships, and reproductive characteristics such as size-at-maturity and fecundity.

3.1 Greenlip abalone *(Haliotis laevigata)*

3.1.1 Growth

Growth of greenlip abalone in Western Australia varies significantly between populations. At the faster end, greenlip abalone populations reach an average maximum size of 175 mm (Table 3). At the lower end of the growth spectrum, stunted stocks show an average maximum size of 125 – 133 mm shell length, which is below the legal minimum length (Table 3). This is a difference in growth of between 12 and 38 mm yr^{-1} for an 80 mm animal in different areas.

All abalone exhibit large spatial heterogeneity in growth, with "stunted" populations occurring in all abalone fisheries (Wells and Mulvay, 1995). To ensure optimal and sustainable exploitation, populations with different growth characteristics require harvest strategies that account for this variability. Typically this is achieved via the use of spatially varying size-limits and TACCs matched to the productivity of the population (Mayfield and Saunders, 2008; Prince et al., 2008, Tarbath and Officer, 2003). In the case of *Haliotis laevigata*, comparisons of growth parameters from tag-recapture studies across Australia reveal a wide variability within and between fisheries (Figure 7).

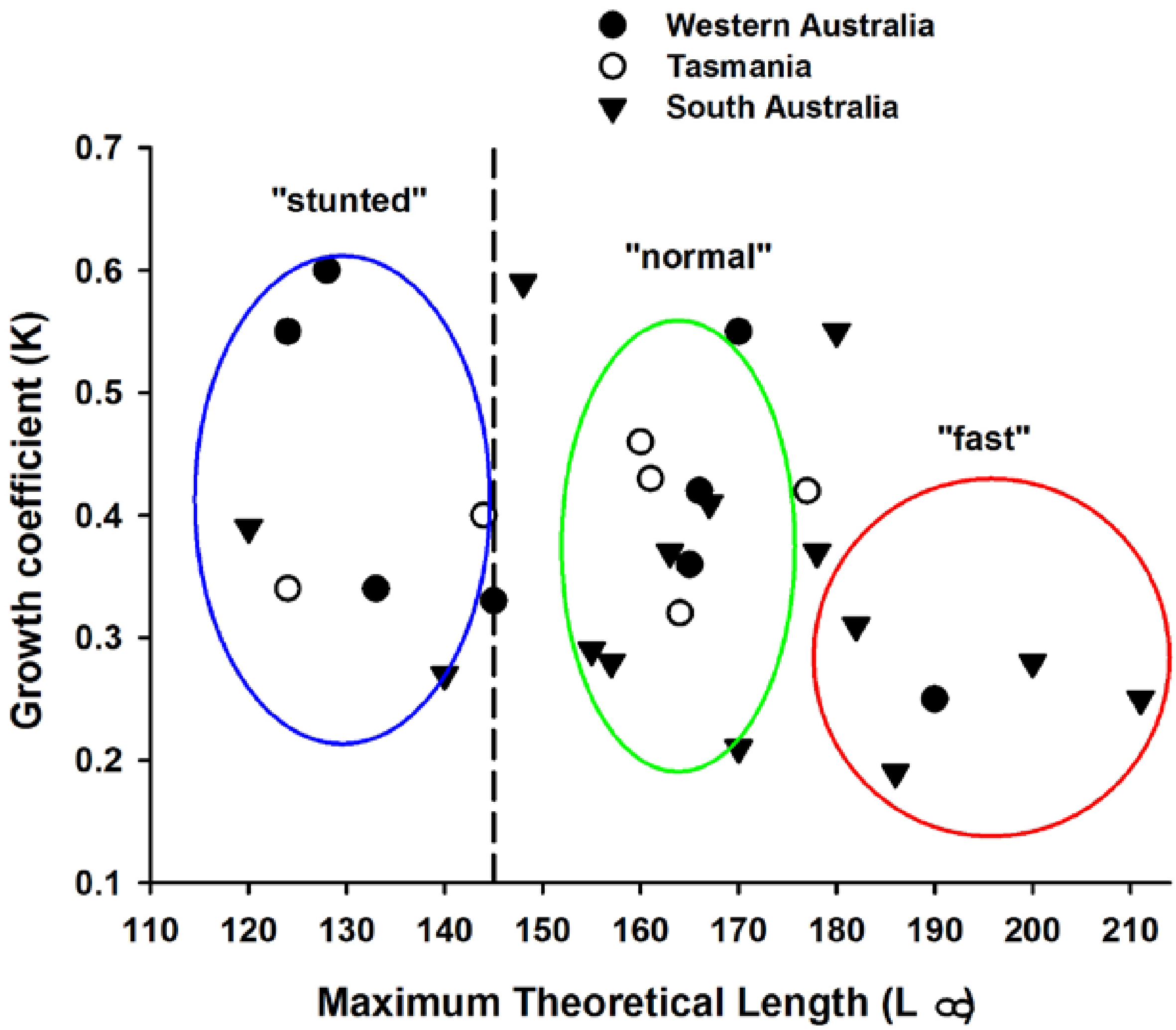


Figure 7. Von Bertalanffy growth parameters (K, L∝) from ***Haliotis laevigata*** populations within and between state fisheries in Australia. Data have been grouped into "stunted", "normal" and "fast" growth stocks in relation to the LML of 140 mmm (dashed line) for the Western Australian fishery. Growth parameters sourced from: this report (Table 3), Mayfield et al., (2003), Officer (1999), Shepherd and Hearn (1983), Shepherd et al. (1992), Wells and Mulvay (1995).

3.1.2 Natural mortality

Natural mortality (M) in adult greenlip abalone has been estimated between 0.15 and 0.4, depending on method and location (Table 3). For the most part M is assumed to be 0.25 (22% per annum) for WA's commercially fished population.

To obtain an estimate of fishing mortality from length-frequency data, growth assumptions were made to represent the entire stock in different areas (Table 3). These growth parameters provided the best fit for length-converted catch-curve estimates of Z and are a reasonable representation of average growth for the overall population. See section 5.1.5.

Table 3. Natural mortality and growth information for ***Haliotis laevigata*** from Western Australia. Growth is estimated from tag-recapture data and growth assumptions are made for model estimates of fishing mortality based on length-converted catch curves (see section 5.1.5) and yield-per-recruit analysis (see section 5.5).

Location	Natural Mortality (M)	Growth parameters (von Bertalannfy)*		Growth rate ($mm.y^{-1}$) for an 80 mm animal	Source
		K	L∝ (±SD)		
All	0.25				Unpublished data
South Australia	0.15 – 0.40				Mayfield *et al.* (2003)
Growth estimates from tag-recapture					
Augusta (Outback)		0.55	170 (14)	38	Hart *et al*. (1999)
Augusta (Flinders Bay)		0.36	165 (10)	34	Wells and Mulvay (1995)
Hopetoun (2 Mile Main stocks)		0.33	145 (14)	29	Unpublished data
Hopetoun (2 Mile stunted stocks)		0.34	133 (13)	12	Unpublished data
Station Island (Duke of Orleans Bay) – stunted		0.60	128 (12)	22	Unpublished data
Pt Malcolm (Israelite Bay) – stunted		0.55	124 (9)	18	Unpublished data
Growth parameters for length-converted catch curve and yield-per-recruit analysis					
West Coast (Augusta)		0.30	185	27	
South Coast (Area 3)		0.25	179	22	
Area 2		0.25	179	22	

* Growth parameters estimated using maximum likelihood (see Francis, 1988)

3.1.3 Length-weight relationships

Length-weight relationships for greenlip abalone in Western Australia are summarised in Figure 8. Relationships vary slightly between areas, for example a 160 mm animal at Flinders Bay, Augusta has an average meat weight of 230 g, compared to 186 g for the same-sized animal at Windy Harbour (Figure 8).

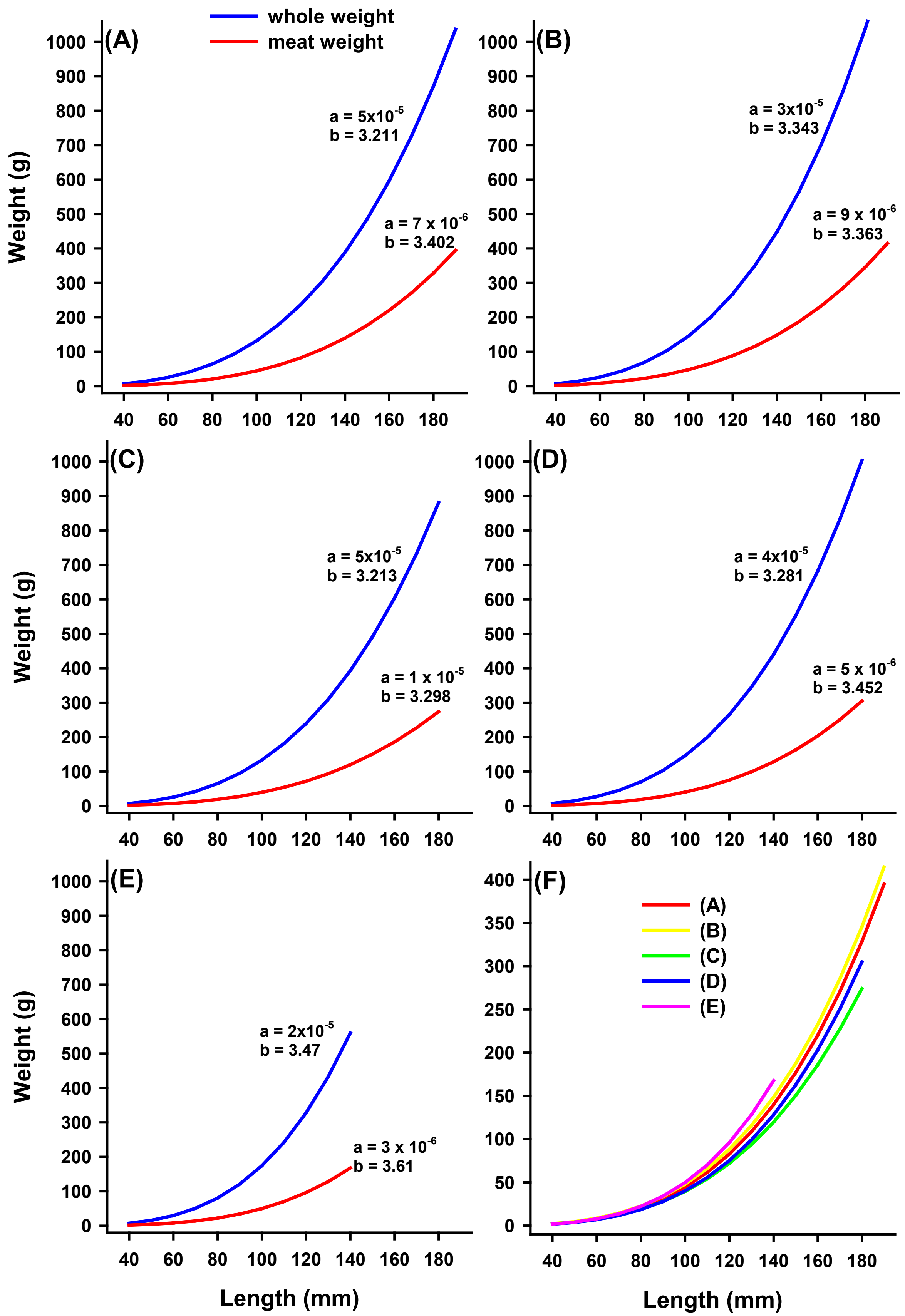


Figure 8. Length-whole weight (blue line), and length-meat weight (red line) relationships for ***Haliotis laevigata*** at 5 sites in Western Australia: A) Augusta (outback); B) Augusta (Flinders Bay); C) Windy Harbour; D) Hopetoun; E) Point Malcolm, F) comparison of length – meat weight relationships between areas. The equation is $W=aL^b$

3.1.4 Size-at-maturity and length-fecundity

Size-at-maturity and length-fecundity relationships for greenlip abalone in Western Australia are summarised in Table 4. Average size-at-maturity for females varies between 78 and 97 mm (Table 4), and appears to be primarily dependent on growth rate. Based on growth data, age-at-maturity is expected to be about 3 years, although there is some evidence that maturation is not entirely age dependent, and can be accelerated under optimal conditions (McAvaney et al., 2004). However there are generally at least 2 breeding years protected by the LML of 140 mm.

Table 4. Size-at-maturity and length-fecundity relationships for ***Haliotis laevigata*** at 6 sites in Western Australia. Length-fecundity equations are of the form $F = aL^b$, where F is fecundity (millions of eggs), and L is length (mm)

Location	Size at 50% maturity (mm)	Length-Fecundity parameters		Source
		a	b	
Augusta (fast)	97	1.00×10^{-6}	5.48	Hart *et al.* (2000)
Augusta (normal)	87	1.49×10^{-3}	4.29	Wells and Mulvay (1992)
Augusta (stunted)	78	1.39×10^{-4}	4.70	Wells and Mulvay (1992)
Hopetoun (normal)		6.91×10^{-4}	4.42	Wells and Mulvay (1992)
Hopetoun (stunted)	81			Wells and Mulvay (1992)
Cape Arid (normal)	88	4.95×10^{-5}	4.99	Wells and Mulvay (1992)
Cape Arid (stunted)	85	6.19×10^{-4}	4.42	Wells and Mulvay (1992)

3.2 Roe's abalone *(Haliotis roei)*

3.2.1 Growth and natural mortality

Estimates of natural mortality (M) of adult roe's abalone vary between 0.13 and 0.17, or between 12 and 16% per annum (Table 5).

Growth of roe's abalone varies significantly between populations. At the higher range, roe's abalone reach an average maximum size of 89 mm (Table 5). At the lower end of the growth spectrum, slow growing stocks show an average maximum size of 73 – 75 mm shell length (Table 5). This is a difference in growth of between 6 and 14 mm yr^{-1} for a 40 mm animal.

To obtain an estimate of fishing mortality from length-frequency data, growth assumptions were made to represent the entire stocks in different areas (Table 5). These growth parameters provided the best fit for length-converted catch-curve estimates of Z and are a reasonable representation of average growth for the overall population.

3.2.2 Length-weight relationships

Length-weight relationships for roe's abalone in Western Australia are summarised in Figure 9.

3.2.3 Size-at-maturity and length-fecundity relationships

Size-at-maturity and length-fecundity relationships for roe's abalone in Western Australia are summarised in Table 6. Size–at-maturity for females is around 40 mm shell length. Based on growth data, age-at-maturity is expected to be about 3 years, similar to greenlip and brownlip abalone. There are generally one or two breeding years protected by the LML of 60 mm.

Table 5. Natural mortality and growth information for ***Haliotis roei*** from Western Australia. Growth is estimated from tag-recapture data and growth assumptions are made for model estimates of fishing mortality based on length-converted catch curves (see section 4.4.2.2)

Location	Natural Mortality (M)	Growth parameters (von Bertalannfy)		Growth rate (mm.y^{-1}) for a 40 mm animal	Source
		K	L∝		
All	0.13 – 0.16				Unpublished data
Growth estimates from tag-recapture					
Waterman’s Reserve (North platform)		0.31	89	13	Hancock (2004)
Waterman’s Reserve (North subtidal)		0.40	83	14	Hancock (2004)
Waterman’s Reserve (South platform)		0.44	81	14	Hancock (2004)
Waterman’s Reserve (South subtidal)		0.34	86	13	Hancock (2004)
Shag Rock (Trigg Island)		0.42	73	12	Hancock (2004)
Three Bears (Margaret River)		0.20	75	6	Hancock (2004)
Bald Face (Kalbarri)		0.35	73	10	Hancock (2004)
Growth assumptions for length converted catch – curve analysis					
Gompertz parameters	**g**	**L∝**	**t0**		
Area 7 (Perth Metro)	0.57	88	2.2	16	
Area 6	0.45	83	2.2	13	
Area 7 (Perth Metro)	0.57	88	2.2	16	

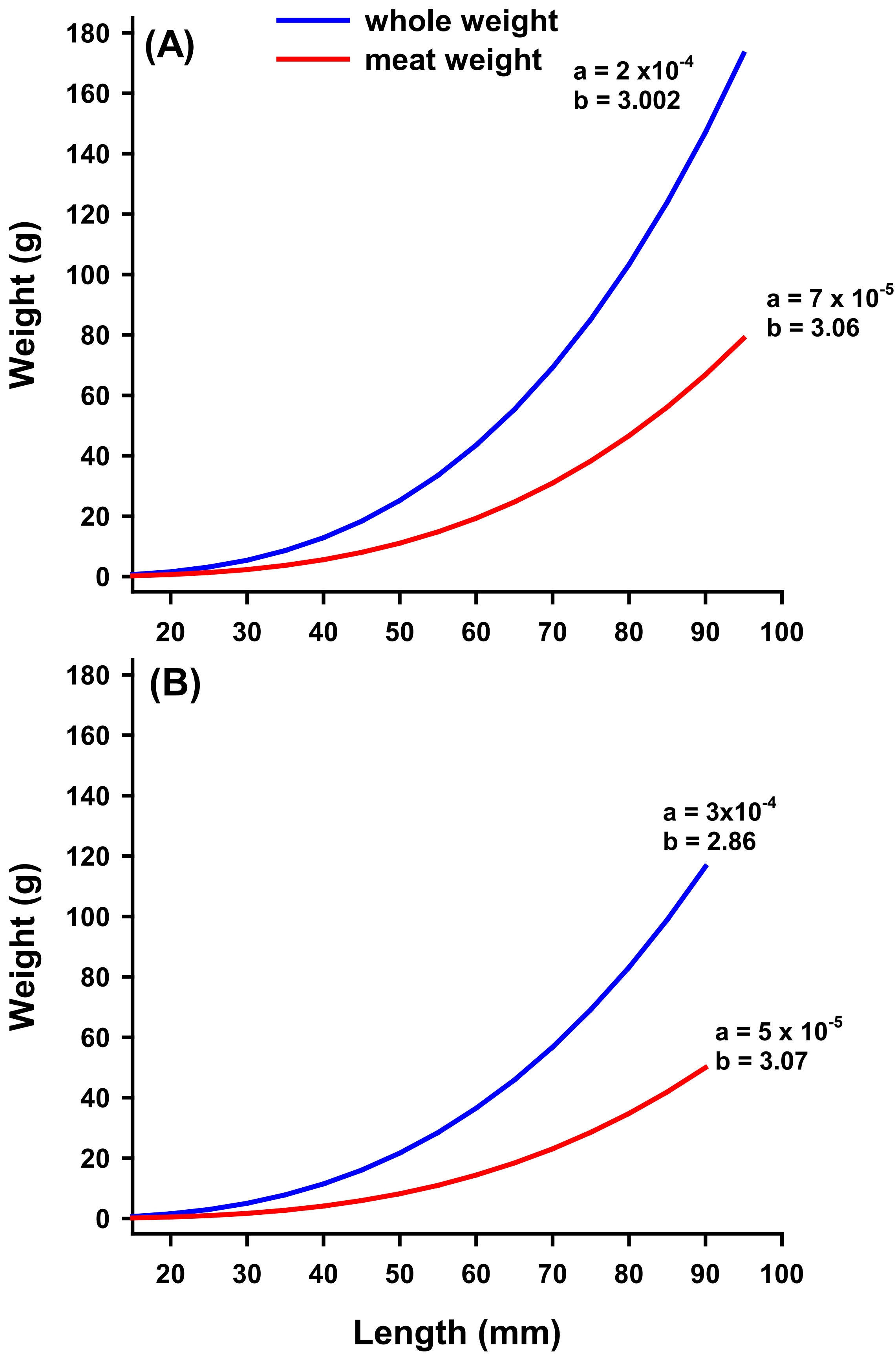


Figure 9. Length-whole weight (blue line), and length-meat weight (red line) relationships for ***Haliotis roei*** at 2 sites in Western Australia: A) Perth metro (Area 7), B) Cape Naturaliste – Cape Leeuwin (Area 6). The equation is $W=aL^b$

Table 6. Size-at-maturity and length-fecundity relationships for ***Haliotis roei*** at 2 sites in Western Australia. Length-fecundity equations are of the form $F = aL^b$, where F is fecundity (millions of eggs), and L is length (mm)

Location	Size at 50% maturity (mm)	Length-Fecundity parameters		Source
		a	b	
Perth (Waterman)	40	1.98×10^{-2}	4.52	Keesing (1984)
Perth (Marmion)*		9.00×10^{-8}	4.28	Unpublished data

* the fecundity parameters (a,b) for Marmion are for length-gonad weight equations of the form $GW = aL^b$, where GW is gonad weight (g).

3.3 Brownlip abalone *(Haliotis conicopora)*

3.3.1 Growth and natural mortality

Studies of natural mortality (M) of adult brownlip abalone in Western Australia have not been undertaken to date. M was assumed to be 0.25, based on data from blacklip abalone (*Haliotis rubra*) in the Western Zone of South Australia (Table 7).

Estimates of von Bertalanffy growth parameters from tag-recapture studies for brownlip abalone are provided in Table 7. To obtain an estimate of fishing mortality from length-frequency data, growth parameters from Hopetoun Oldfields stocks ($L\infty$ = 198 mm and K = 0.32) were applied (Table 7). These growth parameters provided the best fit for length-converted catch-curve estimates of Z and are a reasonable representation of average growth for the all populations.

Table 7. Natural mortality and growth information for ***Haliotis conicopora*** from Western Australia. Growth is estimated from tag-recapture data and growth assumptions are made for model estimates of fishing mortality based on length-converted catch curves (see section 5.1.5) and yield-per-recruit analysis (see section 5.5).

Location	Natural Mortality (M)	Growth parameters (Von Bertalannfy)		Source
		K	$L\propto$ (mm)	
All	0.25 (3+ animals)			Mayfield et al., (2003)
Growth estimates from tag-recapture				
Hopetoun Masons		0.32 (± 0.03)	183 (± 2.5)	Unpublished data
Hopetoun Oldfields		0.32 (± 0.05)	198 (± 6.3)	Unpublished data
Growth parameters (assumptions) for length converted catch – curve analysis				
All Stocks		0.32	198	

3.3.2 Length-weight relationships

Length-weight relationships for brownlip abalone in Western Australia are only preliminary estimates due to lack of information of smaller sized animal's. The equations for Cape Leeuwin are summarised in Figure 10.

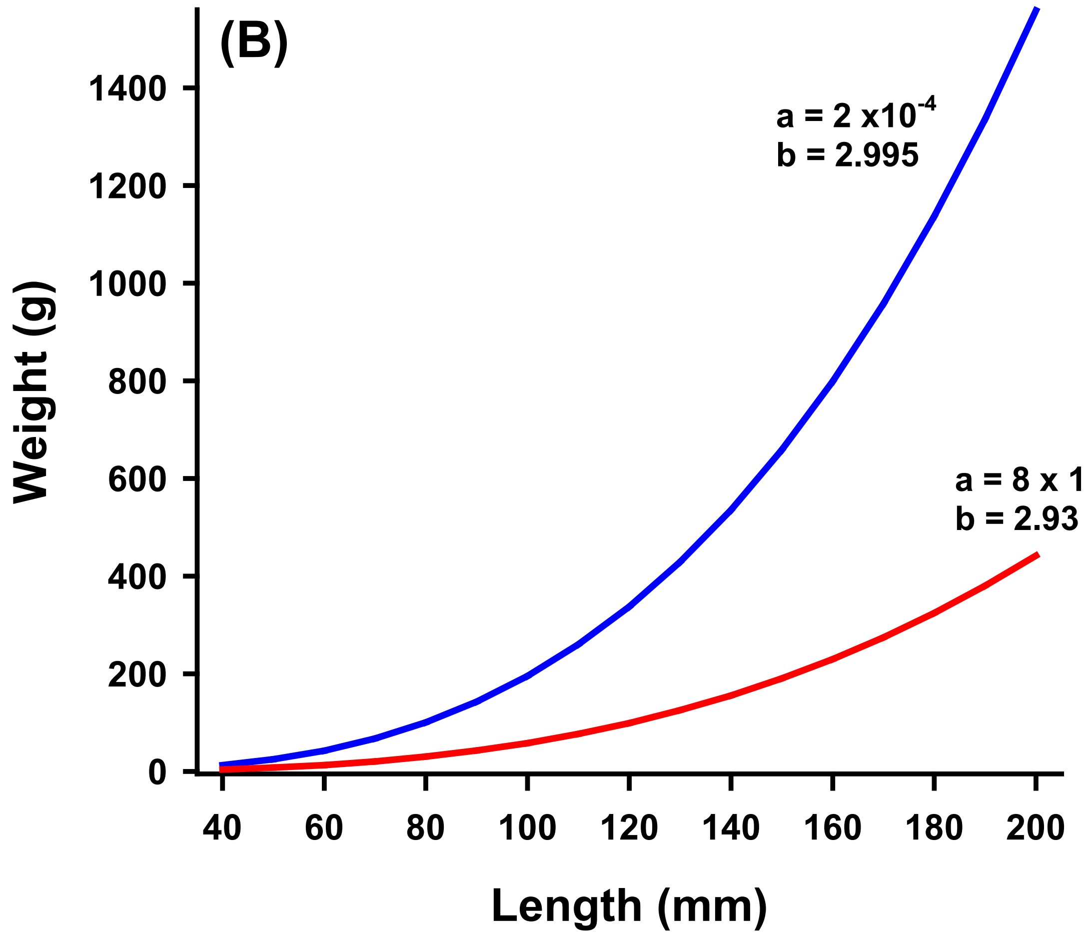


Figure 10. Length-whole weight (blue line), and length-meat weight (red line) relationships for ***Haliotis conicopora*** at Cape Leeuwin in Western Australia. The equation is $W=aL^b$.

3.3.3 *Size-at-maturity and length-fecundity relationships*

Size-at-maturity and length-fecundity relationships for brownlip abalone in Western Australia are summarised in Table 8. Size–at-maturity for females is around 120 – 125 mm shell length. Age-at-maturity is expected to be about 3 years, similar to greenlip and roe's abalone.

Table 8. Size-at-maturity and length-fecundity relationships for ***Haliotis conicopora*** at 2 sites in Western Australia. Length-fecundity equations are of the form $F = aL^b$, where F is fecundity (millions of eggs), and L is length (mm)

Location	Size at 50% maturity (mm)	Length-Fecundity parameters		Source
		a	b	
Augusta (Area 3)	125	1.34×10^{-2}	3.74	Wells and Mulvay (1992)
Cape Arid (Area 2)	120	1.69×10^{-3}	4.15	Wells and Mulvay (1992)

4.0 Research and assessment methodology

4.1 Commercial fisheries data collection

4.1.1 Monthly catch and effort logbooks (1975+)

Catch and effort information was collected on a monthly basis by divers submitting compulsory monthly catch returns to the Research Divisions CAES (Catch And Effort System). This system encompasses all fisheries in WA and the data is divided up into large grid systems (60 x 60 mile). Although it is not as detailed as the ACE (Abalone Catch and Effort) database, catch data has been entered in this system since the late 1970's, and it is a useful source of archival information.

4.1.2 Daily catch and effort logbooks

For each day's fishing, commercial divers record estimates of catch (kg), effort (hours) spent diving for abalone, and location fished within a 10 x 10 mile grid system (Section 11.2). The data is stored on a daily Catch and Disposal Record (CDR) that accompanies each daily catch, which is officially weighed at a licensed processors, and entered into the ACE (Abalone Catch and Effort) effort database at Regional Fishery Offices. In the greenlip and brownlip fisheries, the number of abalone caught is recorded, enabling estimates of mean weight of abalone from each day's fishing.

4.2 Recreational fisheries data collection

Current annual recreational catch and effort estimates are derived from an annual field survey (West Coast Zone / Perth metropolitan fishery), and an occasional telephone diary survey covering the entire state. The last year of the telephone diary survey was in 2007.

4.2.1 Field surveys – Perth metropolitan roe's abalone fishery

The field survey estimates the catch and effort from each distinct roe's abalone stock within the Perth fishery, and estimates are based on average catch (weight and numbers), catch rates (derived from 1,000 interviews in 2007), and fisher counts conducted by Fisheries Volunteers and research personnel from shoreline vantage points and aerial surveys (Hancock and Caputi, 2006). This method provides a comprehensive assessment of the 5-day metropolitan area fishery, but is too resource-intensive to be applied routinely outside of the Perth metropolitan area.

4.2.2 Weather conditions, license numbers and recreational abalone catch

Due to the constrained nature of the Perth recreational roe's abalone fishery (1 hour per day; 5 hours per annum), weather conditions are hypothesised to play a major role in determining the total amount caught. A weather condition index was developed for the fishery (Hancock and Caputi, 2006), however has not previously been used to investigate the annual variability in catch.

As a preliminary analysis, the daily weather condition index was quantified for each days fishing (n = 5), and the annual index was the mean of these. The effort in hours fished was also estimated, based on methodology described by Hancock and Caputi (2006).

Annual catch estimates were modelled with a multiple regression model incorporating the explanatory variables of weather condition index in year i (W_i), and effort (hours fished) in year i (E_i). The estimation model was as follows

$\log Catch_i = aW_i + b\log E_i + c + \varepsilon_i$

where a is the partial regression coefficient for W_i, b is the partial regression coefficient for E_i, c is the the intercept and $\varepsilon \sim N(0 , \theta^2)$.

4.2.3 Phone diary surveys – entire state

The telephone diary survey estimates the catch of all three species on a state-wide basis. In 2007, around 500 licence holders were randomly selected from the licensing database, with selection stratified by licence type (abalone or umbrella) and respondent location (country or Perth metropolitan area). The licence holders were sent a diary to record their fishing activity and were contacted every 3 months by telephone for the duration of the abalone season, or at the end of the season for those only involved in the Perth abalone season.

4.3 Fishery independent stock surveys

4.3.1 Research diver transect surveys

4.3.1.1 Greenlip and Brownlip abalone

A survey method developed for *Haliotis rubra* (Gorfine et al., 1998; Hart et al., 1997) was adapted for greenlip and brownlip abalone in Western Australia. Method development occurred over 2003 to 2005. The method involves repeated surveys at fixed sites representing all areas of the fishery. Survey sites were selected on the basis of known stock distributions and currently there are 85 stock survey sites in the Area 2 fishery and 116 in the Area 3 fishery, targeting a range of sites of different productivity (Table 9). The Arid and Augusta sub-areas are surveyed annually, and other sub-areas visited every 2 – 3 years. Another 28 sites have been surveyed and used for stock enhancement experiments (Hart et al., in press a, Hart et al., in press b), and a further 150 sites have been set up as baseline survey sites to examine the effects of proposed marine parks (Table 9). Further details for abalone surveys in proposed marine parks are found in Hesp et al., (2008).

Table 9. Fishery-independent survey sites in the greenlip and brownlip fishery.

Management Area	Sub-Area	Stock survey sites	Stock enhancement sites	Capes-Capes Marine Park sites	
2	Arid	27			
	Duke	12			
	Israelite	12			
	Town	16			
	West	18			
3	Albany	28			
	Augusta	29	28	150	
	Hopetoun	44			
	Windy Harbour	15			
TOTAL		**202**	**28**	**150**	**380**

At each site, 2 or 3 survey transects of 30 m^2 (30 x 1 m) divided into 1 m^2 quadrats are surveyed. Observers swim out a rope marked at 1m intervals and measure the abundance and size of greenlip and brownlip abalone within each 1m^2 quadrat. The area of suitable abalone habitat is also quantified according to criteria developed in Table 10 and utilised to obtain a density estimate. Suitable abalone habitat was defined as habitable surfaces (generally granite or limestone) of sufficient quality and area to allow effective attachment for abalone above 40mm shell length (1+ years). Younger juveniles are cryptic, while the larvae settle preferentially on non-geniculate coralline algae, and require different habitat and sampling requirements (Daume et al., 1999; McShane, 1995). Density estimates were obtained with the following equation:

Density = # abalone / m^2 of habitat.

Table 10. Habitat survey criteria for ***Haliotis laevigata***. Codes are applied to each 1m^2 quadrat within the larger sample unit (a 30m^2 transect). An estimate of the total area of habitat per 30m^2 transect is obtained by summing the midpoints for each quadrat.

Code	Habitat Area (m^2)	Midpoint (m^2)
0	0	0
1	0 – 0.1	0.05
2	0.1 – 0.2	0.15
3	0.2 – 0.3	0.25
4	0.3 – 0.5	0.4
5	0.5 – 1.0	0.75
6	>1.0	1.1

Density in *Haliotis laevigata* is analysed by five age classes for both stunted and primary stocks (Table 11). These correspond to approximate year classes prior to recruitment, plus recruited animals. Note that the size classes considered as recruit animals (147 mm+) in the primary stocks are higher than the legal minimum length of 140 mm, because they are first commercially harvested at these larger size classes. In the stunted stocks size classes considered as recruits are less than the LML because of much slower growth (see section 5.2).

Estimates of density trends for each sub area (Figure 12; Figure 13) were derived using a 3-factor (Year, Site, Diver) ANOVA model. The analysis was carried out in S_Plus®. A logarithmic transformation of raw data was undertaken to take into account the skewed distribution associated with density. The least squares mean of the factor Year was used to produce an index of density, standardised by site and diver, for each year.

Table 11. Size (mm) and age classes used in the analysis of greenlip abalone survey density.

Size class (Primary stocks)	Size class (Stunted stocks)	Age-class (approximate)	Description
< 90 mm (juveniles)	< 80 mm (juveniles)	1 – 3 years	Juvenile animals, not part of the breeding stocks
90 – 114	80 – 104	3+	Approximately 3 years of age, about 3 years prior to recruitment into the Recruits size-class
115 – 134	105 – 119	4+	Approximately 4 years of age, about 2 years prior to recruitment into the Recruits size-class
135 – 146	120 – 129	5+	Approximately 5 years of age, about 1 years prior to recruitment into the Recruits size-class
≥147	≥130	Recruits	Approximately 6+ years of age – animals recruited into the exploited population.

4.3.1.2 Roe's abalone

Size and density of roe's abalone in the Perth metropolitan fishery is measured annually at 13 indicator sites between Yanchep and Penguin Island. Eleven of these are fished while the other two are the Waterman's Reserve Marine Protected Area (MPA) and the Cottesloe Fish Habitat Protection Zone. Sites initially began in 1996 at 5 sites, with the full complement of 13 indicator sites available from 2011 onwards.

Surveys are carried out on two habitats, the reef platform and the sub-tidal habitat, which generally correspond to the recreational and commercial fisheries respectively. The methodology involves surveying fixed quadrats of 0.25 and 0.5 m^2 at each site and counting and measuring all animals within these quadrats (Figure 11). For further details of survey methodology, see Hancock (2004).

Estimates of density were derived using a 3-factor (Year, Location, Habitat) ANOVA model. The analysis was carried out in S_Plus®. A logarithmic transformation of raw data was undertaken to take into account the skewed distribution associated with density. The least squares mean of the factor Year was used to produce an index of density, standardised by location and habitat, for each year.

Figure 11. Research diver undertaking surveys for ***Haliotis roei*** in shallow water. The yellow vest contains an extra 15 kg of weight to counteract the swell.

Preliminary investigations on the predictive capacity of pre-recruit density estimates were also undertaken. Data on Age 1+ abundance (17 – 32 mm) were taken from the outer and middle platform habitats, and Age 5+ data (71 mm) was from all habitats. Regression analysis was applied using a 4-year lag between the juvenile and adult age classes.

4.3.2 Digital video surveys

Size and density of greenlip abalone are surveyed by commercial industry divers using a specifically developed video survey methodology for these species (Hart et al., 2008.). The reason for using industry divers is a cost-effective measure as many fishing sites are remote.

The method is being used primarily in the Area 2 greenlip abalone fishery. In the period 2008 to 2012, between 26 and 82 sites were surveyed per year by an industry diver using a random survey method.

The survey design is as follows. The Area 2 fishery is divided up into the 4 main sub-areas, described in Figure 12, and a minium sample size of 10 sites is required for each area, up to a maximum of 30. Whilst fishing in any given sub-area the commercial diver films one site per day, at the commencement of the 2nd dive, prior to harvesting the animals. This ensures a randomised site selection process. The procedure is to undertake a 10-minute (approx.) survey, filming each abalone in turn so that lengths for each animal can be later determined. The footage is sent back to the Research Division, where the images are extracted and counts of abalone density and estimates of length are undertaken using digital image analysis software. Full details of the methodology are summarised in Hart et al. (2008).

For each site, a total count of abalone is made over the timed survey (usually 9 – 12 minutes), and 30% of animals with sufficient image quality are randomly selected for length measurements. In sites where abundance is low, a minimum selection of 20 animals is made per site to enable a representative sample.

Shell length (in mm) is used to estimate mean length and population length-frequency. These data can also be used to estimate fishing mortality as per methods described in section 4.4.2. For abundance estimates, the length data is separated into approximate age groups described in Table 11. Abundance is estimated as number per minute searched. The time spent searching is total time minus filming and scooting time. Divers use a mechanised scooter to move between discrete habitats clusters, and this can be substantial part of the filming time that needs to be accounted for (see Hart et. al., 2008 for details).

4.4 Data analysis and stock assessment

4.4.1 Standardised catch per unit effort

Catch and effort data are analysed at pertinent spatial and temporal scales. Stock indicator variables include catch, effort, daily catch rate (CPUE), hourly catch rates, spatial distribution of fishing, average meat weights and lengths caught. Standardised indices of catch rates and meat weights are also estimated each year. The current standardised CPUE (SCPUE) model used takes into account technology and environmental effects on catching efficiency. Estimates of technology correction factors (GPS, Internet Weather Prediction) were established by Hart et. al., (2009), and applied to the raw CPUE data, prior to the GLM analysis. The GLM model is as follows:

$$Ln(CPUE + 1) = \mu + \beta_1(Year) + \beta_2(month) + \beta_3(subarea) + \beta_4(Diver) + \varepsilon$$

Minor variations and improvements on this GLM model are carried out periodically. See Hart et al., (2009) for more detailed information on the SCPUE model development and assumptions.

A description of the Area 2 and 3 sub-areas used in the SCPUE model for the greenlip and brownlip fisheries is provided in Figure 12 and Figure 13 respectively.

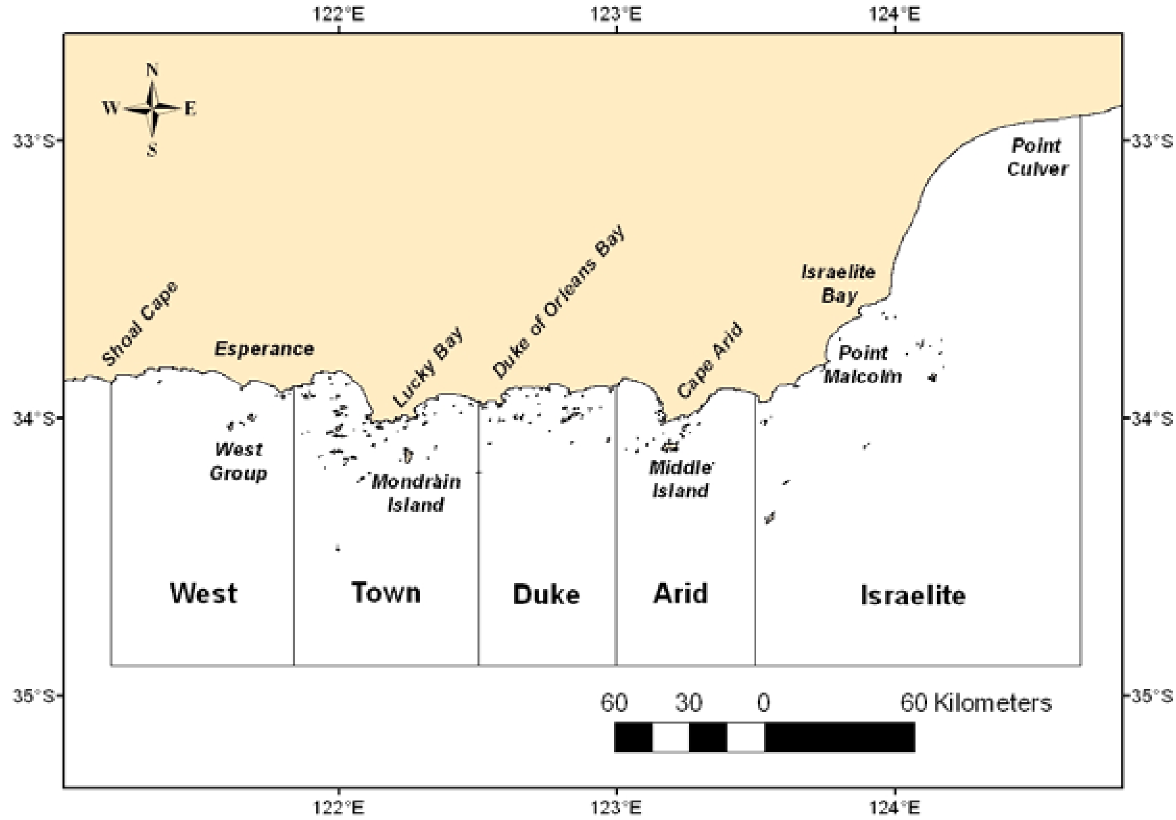


Figure 12. Map of Area 2 greenlip brownlip fishery with sub-area boundaries relevant to fishery assessment (West, Town, Duke, Arid, Israelite).

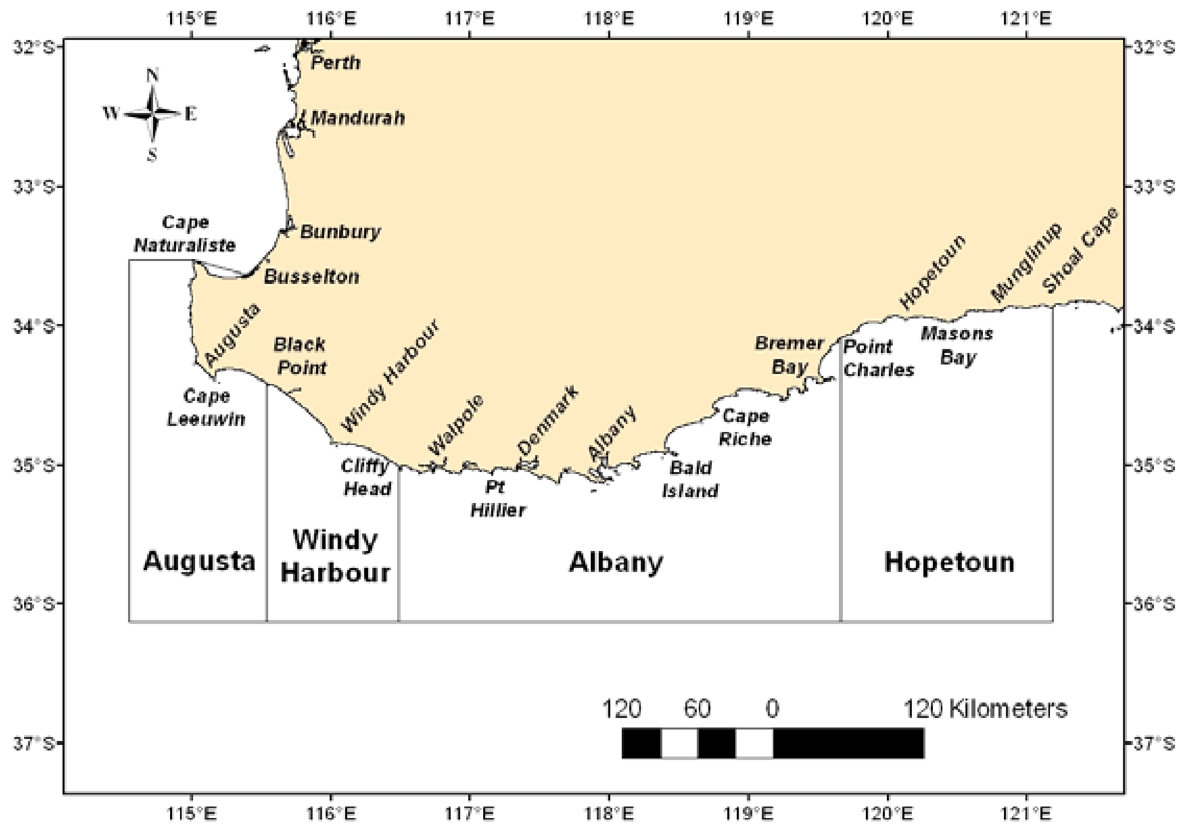


Figure 13. Map of Area 3 greenlip brownlip fishery with sub-area boundaries relevant to fishery assessment (Augusta, Windy Harbour, Albany, Hopetoun).

4.4.2 Fishing mortality

4.4.2.1 Data

Commercial greenlip and brownlip fishers provide a random sample of shells harvested from each days fishing and these are categorized into relevant sub-areas (Figure 12 and Figure 13). The current sampling protocol is 10 greenlip shells and 5 brownlip shells from each day of fishing, which is in accordance with a study by Andrew and Chen (1997) who concluded that the optimal sampling procedure was to maximise the number of diver-days from which samples were collected. Commercial divers also undertake digital video surveys on commercially fished reefs (see section 4.3.2), from which a random sample of abalone (~30% of the total) are selected and measured. The legal size animals from the video survey data are used to estimate fishing mortality where applicable.

This sampling provides length-frequency data to enable estimation of total mortality and fishing mortality. These datasets are used in the development of performance indicators and TACC assessment processes (see section 7), and to assess the changes in targeting practices between years.

Sampling statistics for estimates of fishing mortality are provided in Table 12.

Table 12. Length and morphometry sampling statistics for greenlip and brownlip abalone by year

Year	Area	Total # Divers	# Divers Participating	Greenlip samples	Brownlip samples
1995	3	8	7	2597	425
1996	3	8	8	7549	0
1997	3	8	1	1377	0
2004	2	6	5	1525	422
	3	8	8	2017	533
2005	2	6	5	1814	481
	3	8	4	3004	625
2006	2	6	0	0	0
	3	8	3	1102	292
2007	2	6	5	1494	465
	3	8	5	1763	436
2008	2	6	3	1086	271
	3	8	6	2031	952
2009	2	6	4	821	463
	3	8	7	3190	1140
2010	2	6	1	287	261
	3	8	8	2783	523
2011	2	6	1	232	103
	3	8	5	775	157

4.4.2.2 Estimation methodology

The large variation in growth of abalone (see Figure 7), coupled with the inability to estimate age with any degree of accuracy precludes the use of age-based estimation methodologies for ascertaining total and fishing mortality. Consequently a length-based catch-curve analysis method is used (Pauly, 1984). The main assumptions of this are that growth, recruitment and natural mortality parameters are constant from year to year. None of these assumptions are likely to hold strictly true, however they facilitate an estimate of relative fishing mortality that is comparable between years, and relatively robust to violations of the assumptions. For example, an increase in growth rates or recruitment under a constant catch is likely to shift the frequency of the median length-class upward, which would result in a reduction in fishing mortality estimates. The catch curve equation is of the form;

$$Ln\left[N_i\left(\frac{dl_i}{dt}\right)\right] = -Zt_i + b$$

where Z is total mortality, N_i is the number of abalone in length class i, dl_i/dt is the growth rate (mm year $^{-1}$) of length class i, and t_i is the relative age of length class i. Following an estimation of -Z from the slope of the equation, fishing mortality (F) = Z – M, where M is assumed to be 0.25 for the harvested size-classes.

An example of length frequency data from greenlip abalone fishing in 2010 and parameter values used in the catch curve analysis are summarised in Table 13. Note that the mode of the size distribution differs between spatial areas (Figure 18), which relates to different growth and selectivity. Full selectivity is not assumed until the modal size class.

Table 13. Length-frequency data (***Ni***) and catch-curve parameters used in the estimation of total (Z) and fishing (F) mortality in the Western Australian ***Haliotis laevigata*** fisheries. Data are from the 2010/11 fishing season.

Fishery	Length class midpoint (mm)	N_i	dl_i / dt	Relative age (t_i)	Ln[N_i(dl_i / dt)]
Area 3 South Coast	*von Bertalanffy growth parameters:* K = 0.25; L∞ = 179 mm				
	152.5	222	6.9	6.33	7.334
	157.5	254	5.5	7.08	7.242
	162.5	197	4.3	7.92	6.741
	167.5	81	3.0	9.17	5.493
	172.5	40	1.7	11.08	4.22
Area 3 West Coast	*von Bertalanffy growth parameters:* K = 0.30; L∞ = 185 mm				
	162.5	365	5.9	7.00	7.675
	167.5	303	4.6	7.83	7.240
	172.5	218	3.2	9.00	6.548
	177.5	109	2.0	10.67	5.385

4.4.3 Yield-per-recruit and egg-per-recruit analyses

Yield-per-recruit (YPR) and egg-per-recruit (EPR) analysis was undertaken for three greenlip abalone populations, Area 2, Area 3 South Coast, and Area 3 West Coast using the PREP model (Shepherd and Baker, 1998). The PREP (Per-Recruit Population Egg Production) model is an age-structured dynamic pool model based on Baranov's (1918) catch equation. Time steps in the model are monthly time-steps.

In the model the spawning potential of each age class cohort, based on the length-fecundity relationship, is summed from size at reproductive maturity to maximum age (16 years) for an unfished stock. This is the relative population egg production per recruit (PREP). Spawning potential of the fished stock under various levels of F is evaluated and expressed as a percentage of the spawning potential for the unfished cohort (%EPR).

The percentage yield per recruit (%YPR) is obtained in a similar manner. Firstly, the maximum biomass of the cohort attainable at optimum size at first capture and optimal F, for the relevant growth parameters and length-weight relationship, is estimated by iteration. Then the yield-per-recruit under various levels of F and size at first capture is summed over all age classes, and expressed as a % of the maximum possible yield (%YPR). The size-at-first capture is not the minimum legal length, but the size at which animals are actually harvested by the commercial fishery, which is higher than the LML.

4.4.3.1 Sensitivity analysis

Due to the variability in growth it was necessary to make assumptions of average growth. Growth and fecundity parameters assumed for the YPR and EPR analyses are summarised in Table 3 and Table 4 respectively. Sensitivity analyses to different growth parameters were also undertaken using the Augusta population as a test case, where a tagging study resulted in growth parameters of $K = 0.55$, and $L\infty = 170$ mm (Table 3).

4.5 Other Research Projects

4.5.1 Stock enhancement research *(Haliotis laevigata)*

A series of experiments on stock enhancement of greenlip abalone have been carried out in collaboration with industry divers since 2004. Preliminary analyses and research findings are summarised in Hart et al. (2007). In 2008 a further experiment was initiated at Flinders Bay, Augusta. This experiment involved the release of abalone at high density at 3 sites, with 11,000 animals of 20 – 30 mm (1+ age) released at an approximate density of 18 – 20 juveniles m^{-2}. The animals were bred from wild broodstock obtained from Augusta in November 2006. Control sites and effects of the enhancement on the habitat and other species are also being examined at part of this research.

In 2009, the Australian Seafood CRC (Cooperative Research Centre) awarded an externally funded research project. The project was called "Bioeconomic evaluation of commercial scale stock enhancement in abalone", with the objectives to undertake a comprehensive evaluation of the feasibility for stock enhancement in abalone over 2009 to 2012. Relevant publications from this work can be found in Hart et. al., (in press a; in press b; in press c).

4.5.2 Recovering a collapsed abalone stock through translocation

This project is in response to a catastrophic mortality of an abalone fishery in Western Australia due to an anomalous environmental event in the summer of 2010/11. During this event, termed a "marine heatwave" (Pearce et. al., 2011), sea surface temperature (SST) rose to lethal levels for this species (roe's abalone) and, coupled with deoxgenation of the water during an extended calm period, effectively wiped out an entire stock. The project arose following a complete closure of the fishery to protect any remaining stock and a desire by the industry to examine the possibility of assisted recovery.

The project has been funded by the Australian Seafood CRC (Cooperative Research Centre), meets the CRC's Future Harvest Theme Outcomes 1 and 2, and is entitled "CRC project 2011/762 Recovering a collapsed abalone stock through translocation." The study is a major collaboration between Industry partners WAFIC, who are providing $81,519 as a cash contribution, the Department of Fisheries WA, Flinders University South Australia, and the Seafood CRC. The objectives of this project are as follows:

1. To establish founder populations of roe's abalone in areas of mass mortality
2. To evaluate the genetic structure of existing and founder populations
3. To compare natural and assisted recovery rates of roe's abalone populations
4. To evaluate the genetic contribution of existing and founder populations to stock recovery

4.5.3 Brownlip abalone: Exploration of wild and cultured harvest potential

Brownlip abalone (*Haliotis conicopora*) is the largest and possibly fastest growing abalone species in Australia. It is a characteristically unique abalone species, reaching considerably larger maximum sizes (>230 mm), than greenlip (200 mm) and displaying very cryptic behaviour within an extremely limited habitat of caves and crevices. Due to its large size and high meat yield (approx. 35% greater meat weight per length than greenlip abalone) it is extremely suitable for the lucrative wild and brand new cultured or ocean grown, whole meat export markets.

Brownlip abalone currently comprises a small, but very valuable component of the commercial wild abalone fishery in WA (annual value: $1.6 million) and since 1998, annual catches have risen by 25% to over 40 tonnes. This increase in demand has caused a necessity to further explore the brownlip abalone wild, ocean grown and cultured harvest potentials. There is currently however, limited information on habitat, growth and mortality of wild populations and the understanding of aquaculture systems and growth rates. The objectives of the project are as follows:

1. Determine the growth and natural mortality of wild brownlip abalone populations.
2. Determine growth rates and mortality of cultured brownlip abalone.
3. Habitat identification to determine release mortality, growth, survival and recapture parameters for potential brownlip abalone stock enhancement.
4. Develop fishing size limits and optimal market sizes based on size distribution and growth to examine the harvest potential of the total industry

The project has been funded by the Fisheries Research and Development Corporation (FRDC).

4.5.4 Marine Park Abalone surveys: Cape Leeuwin – Cape Naturaliste

In 2007, a series of abalone surveys were undertaken in areas proposed as sanctuary zones in the proposed Capes-Capes marine park as well as control areas. These areas were designed to estimate total abalone biomass in the sanctuary zones, to provide more information on what quantity of catch might be foregone as a result of the closure of abalone fishing in these zones. These survey sites will be visited on a periodic basis following the implementation of the Marine Park. Further details are available in Hesp et al., (2008).

5.0 Greenlip and Brownlip Abalone

5.1 Commercial fisheries

5.1.1 Total Catch, effort and CPUE

In 2011 the greenlip/brownlip catch was 202 tonnes whole weight (Table 14), which was similar to the 2010 catch of 205 t. The Area 1 (Nullarbor fishery) exploratory quota remained at 1.2 t but was not fished in 2011.

The greenlip catch of 165.9 t whole weight from a total quota of 173.3 t, was very similiar to the 2010 catch of 165.6 t. The brownlip catch of 36 t whole weight for the 2010 season was 8% lower than the 2010 catch of 39 t, and represents 91% of the quota of 39.9 t (Table 14).

Total fishing effort on the main stocks in 2011 was 1,224 days. This was 2% higher than in 2010 (1,196 days).

Catch per unit effort: The commercial divers' standardised catch rates (SCPUE) are the principal indicator of the abundance of legal-sized abalone and are assessed annually.

In 2011, the SCPUE for the combined greenlip stocks was 35 kg whole weight per hour (Table 14). This was a decrease from the 2010 value of 37 kg per hour.

Table 14. Greenlip and brownlip abalone catch and effort by quota period

Quota period[2]	Greenlip TAC kg whole weight	Greenlip caught kg whole weight (all stocks)	Brownlip TAC kg whole weight	Brownlip caught kg whole weight[4]	Combined catch kg whole weight	Diver days (main stocks only)[3]	Greenlip standardised CPUE (kg whole weight) per diver hour
1989		229,619	–	36,977	266,596	1,324	
1990	126,500	118,395	–	19,118	137,514	696	
1991	148,500	132,194	–	14,658	146,852	816	
1992	192,500	170,608	–	30,404	201,012	1,120	37
1993	197,450	173,397	–	31,153	204,550	1,238	37
1994	200,750	171,820	–	32,222	204,042	1,337	36
1995	187,264	145,467	–	27,061	172,528	1,087	32
1996	189,750	171,337	–	21,932	193,269	904	40
1997	207,350	182,317	–	26,297	208,614	1,059	35
1998	200,750	181,810	–	22,197	204,006	1,031	36
1999	184,023	175,765	28,000[5]	28,047	203,812	922	39
2000	194,691	189,511	34,875	34,179	223,690	1,029	41
2001	194,691	187,459	33,075	31,091	218,550	1,002	37
2002	194,691	166,828	33,075	27,458	194,286	1,027	34
2003	202,521	180,730	37,453	33,449	214,179	1,144[3]	33
2004	190,520	170,385	35,000	34,196	204,581	1,154[3]	34
2005	171,755	169,285	38,500	38,745	208,030	1,252	31
2006	171,755	168,752	39,750	37,265	206,017	1,161	31
2007	171,755	166,647	39,750	38,660	205,307	1,139	34
2008	163,220	157,224	41,900	39,515	196,739	1,144	34
2009	171,301	160,156	41,900	39,050	199,206	1,205	34
2010	171,221	165,558	41,900	39,006	204,564	1,196	37
2011	173,355	165,927	39,950	36,274	202,201	1,224	35

1. Data source: quota returns.
2. The length of quota period has varied with management changes, and for simplicity has been recorded against the nearest calendar year.
3. Effort (diver days): main stocks are separated from stunted stocks, which are subject to controlled fishing regimes and not directly comparable.
4. Greenlip conversion factor (meat weight to whole weight) is 2.667. Brownlip conversion factor for meat weight to whole weight is 2.5.
5. Brownlip allocations not fixed across Areas 2 and 3 (ex-Zone 1 and 2) prior to 1999. Brownlip TAC fixed for the first year in 1999.

5.1.2 Catch, CPUE and meat weights by subregion

The greenlip-brownlip fishery consists of three main management zones (Area 1, 2, and 3; Figure 1), however 99% of the catch comes from the Area 2 and Area 3 fisheries. Trends in catch, CPUE, and average size (meat weight) of greenlip abalone caught in the subregions of the Area 2 and Area 3 fisheries are provided below. See Figure 12 and Figure 13 for maps of the subregions.

5.1.2.1 Area 2 fishery

The Area 2 greenlip fishery is divided up into 5 main subregions. The two most important regions are Town and Arid (Figure 14), collectively providing an average of 6.1 and 7.6 tonnes respectively of the historical catch. Average catch in the other regions was 3.3 (West), 5.5 (Duke), and 4.0 tonnes (Israelite) (Figure 14). Trends in the catch, catch rate, and meat weight indicators have been stable over the last 20 years, although significant oscillations have occurred.

A larger size limit is fished in the West populations, as indicated by the higher average meat weight of 192 g, compared to the Town (178 g), Duke (181 g), Arid (181 g) and Israelite (187 g). Average catch rate is very similar between areas, varying only 2 kg/hr between the lowest (West – 14 kg/hr) and highest (Arid – 16 kg/hr).

5.1.2.2 Area 3 fishery

The Area 3 greenlip fishery is divided up into 4 main subregions. The most important region is Augusta (Figure 15), providing an annual average of 18 tonnes of the historical catch. Average catch in the other regions was 4 (Windy), 2 (Albany), and 11 tonnes (Hopetoun) (Figure 15). Trends in the catch, catch rate, and meat weight indicators have been stable over the last 20 years, although significant oscillations have occurred in the Augusta and Hopetoun populations.

A larger size limit is fished in the Augusta population, as indicated by the higher average meat weight of 244 g, compared to the Windy (192 g), Albany (193 g) and Hopetoun populations (195 g; Figure 15). Average catch rate is also highest in Augusta (19 kg/hr), and similar between Windy (14 kg/hr), Albany (15 kg/hr), and Hopetoun (15 kg/hr).

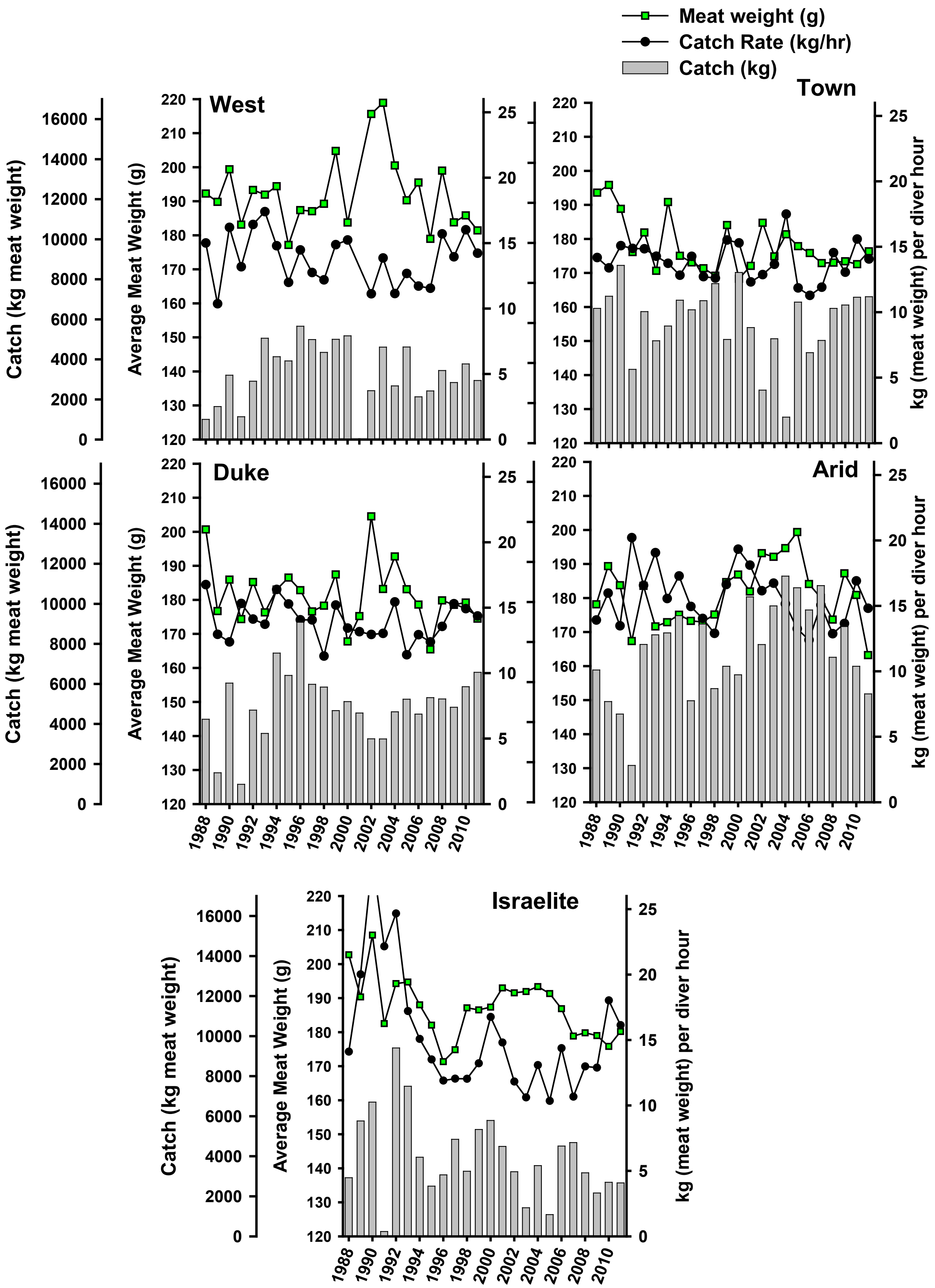


Figure 14. Catch, raw CPUE (kg / day) and average meat weight (g) of greenlip abalone caught in the 4 main sub-regions of the Area 2 greenlip fishery. No catch data available prior to 1987 for the subregions.

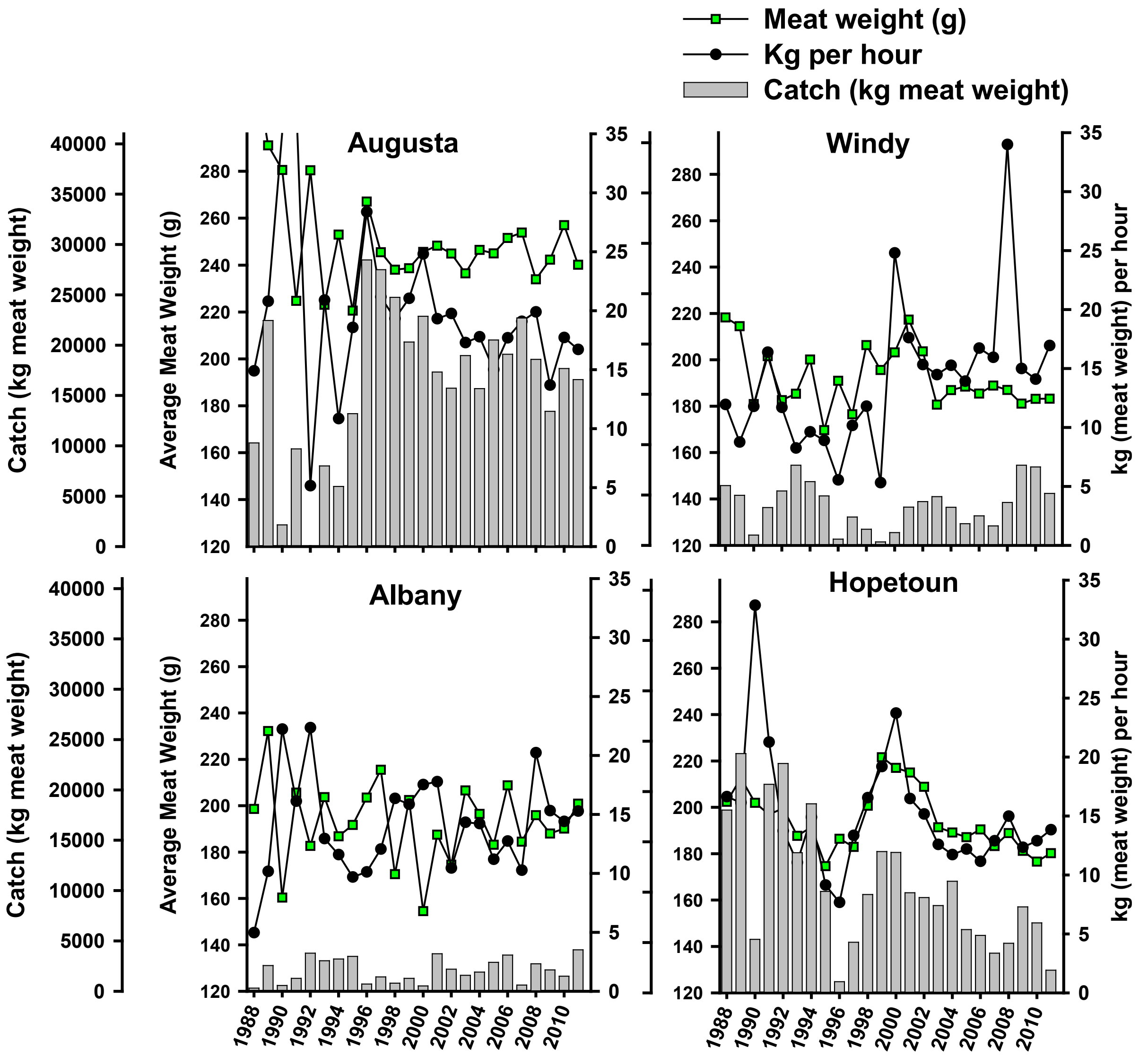


Figure 15. Catch, raw CPUE (kg / day) and average meat weight (g) of greenlip abalone caught in the 4 main sub-regions of the Area 3 greenlip fishery. No catch data available prior to 1987 for the subregions.

5.1.3 Standardised CPUE

Standardised CPUE in the two main greenlip abalone fisheries are currently mid-range of the long-term historical trend, which appears to be relatively stable (Figure 16). The Area 2 fishery showed a 7% increase from 2007 to 2011, while Area 3 fishery had stable catch rates in this period (Figure 16).

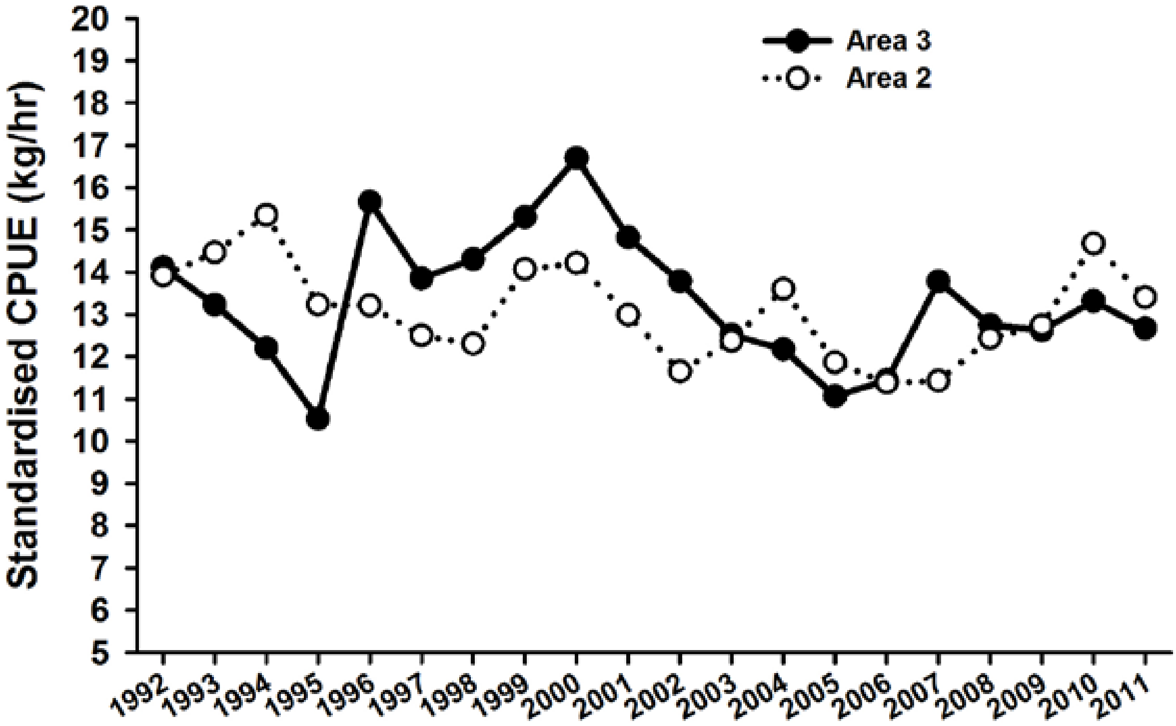


Figure 16. Standardised meat weight CPUE (kg/hr) of ***Haliotis laevigata*** in Area 2 and Area 3.

5.1.4 Average meat weight and length-frequency of catch

Average meat weight of greenlip abalone in Area 2 decreased from 2002 to 2011, and is currently at its lowest historical level (Figure 17). In Area 3, average meat weight dropped from 2007 to 2009 however shell length has been stable between 2004 and 2011 (Figure 17). Overall, a larger size-range and average size is caught in the Area 3, compared to the Area 2 fishery (Figure 18). In the Area 3 fishery, 60% of the catch is greater than 160 mm shell length, whereas in the Area 2 fishery, only 25% of the catch is above 160 mm (Figure 18).

Average meat weight and length of brownlip harvested in the Area 2 fishery decreased between 2004 and 2011 and are currently at a low level compared to historical averages (Figure 19). In the Area 3 fishery average meat weight and shell length of brownlip abalone has generally been stable with the exception of 2011, which saw a large drop in average meat weight from 2010, but this decline was not reflected in mean length, which remained stable (Figure 20).

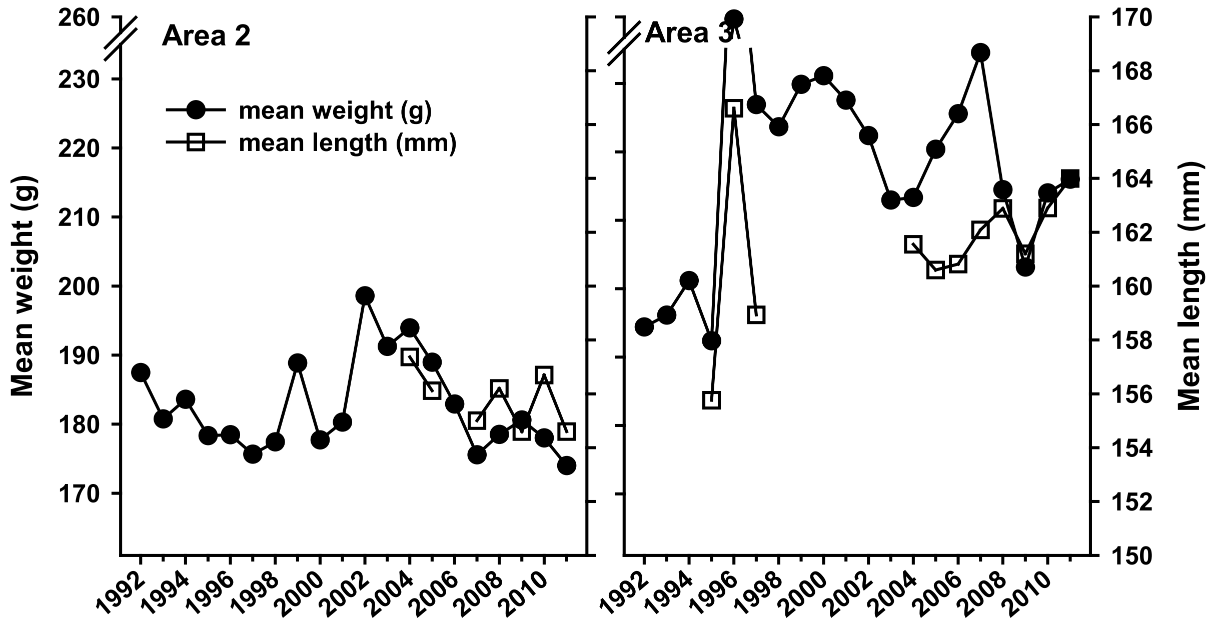


Figure 17. Mean meat weight (g) and shell length (mm) of ***Haliotis laevigata*** harvested from the Area 2 and Area 3 fisheries.

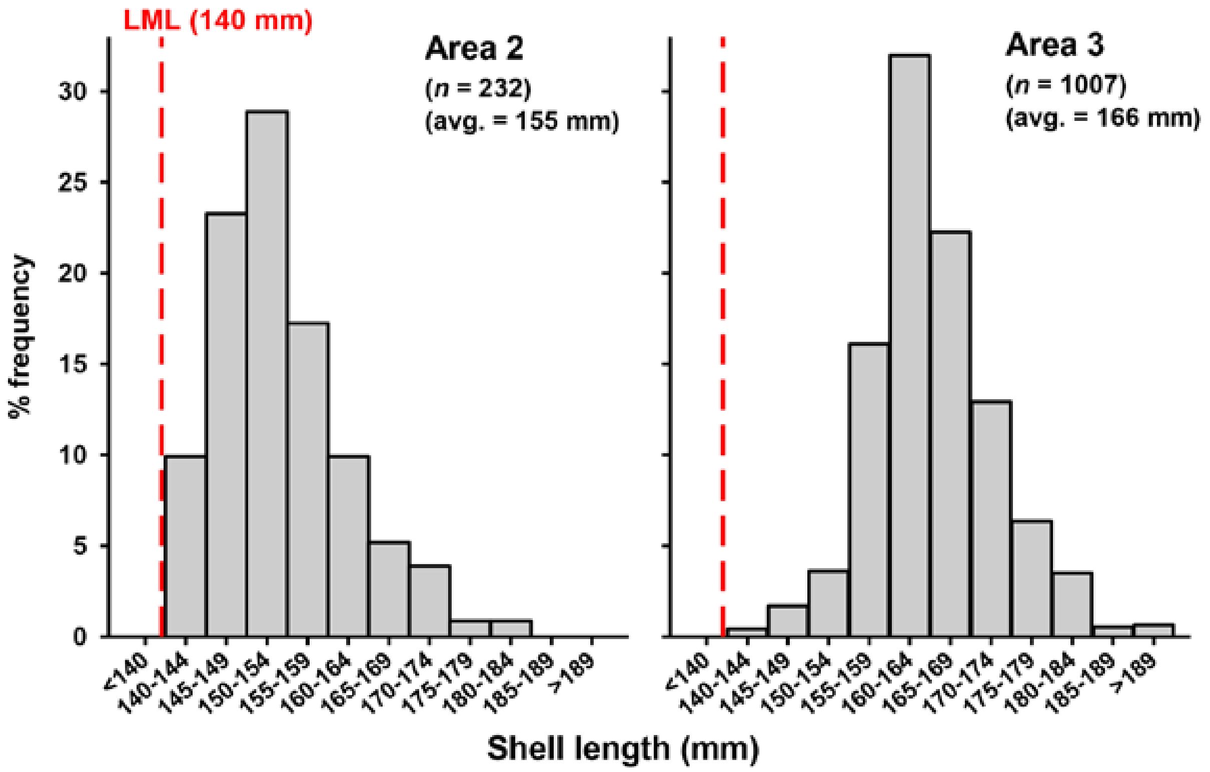


Figure 18. Size-frequency of the catch of ***Haliotis laevigata*** from the Area 2 and Area 3 fisheries during 2011. Legal minimum length is 140 mm.

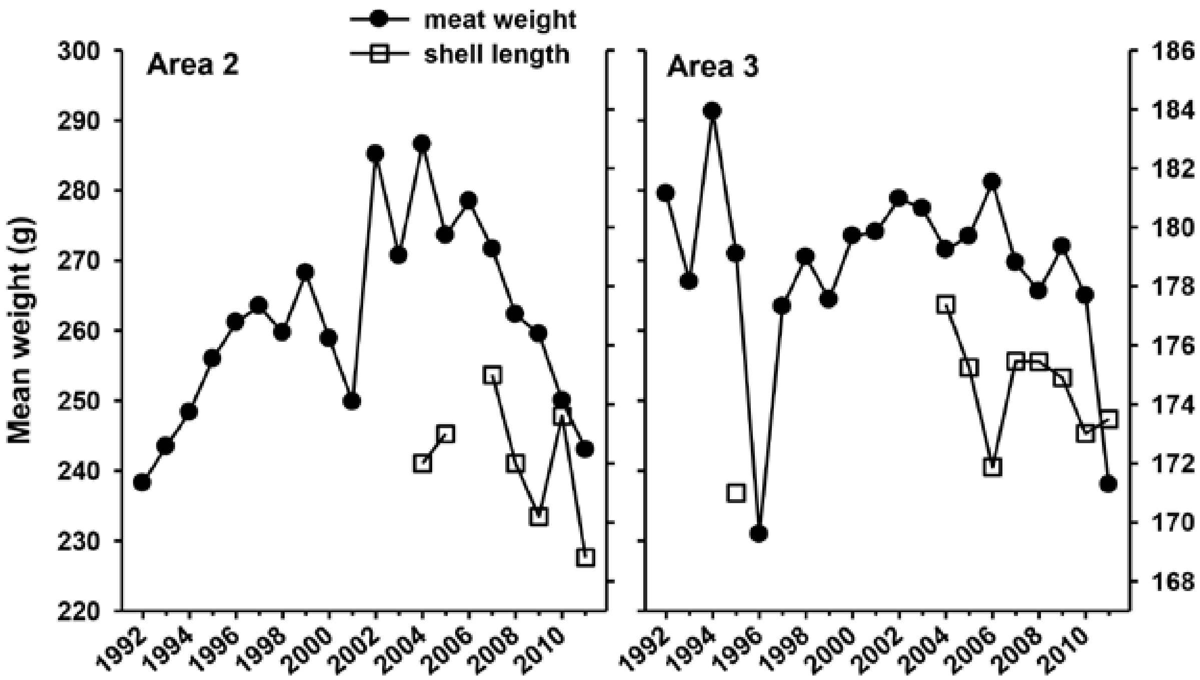


Figure 19. Mean meat weight (g) and shell length (mm) of ***Haliotis conicopora*** in the Area 2 and Area 3 fisheries.

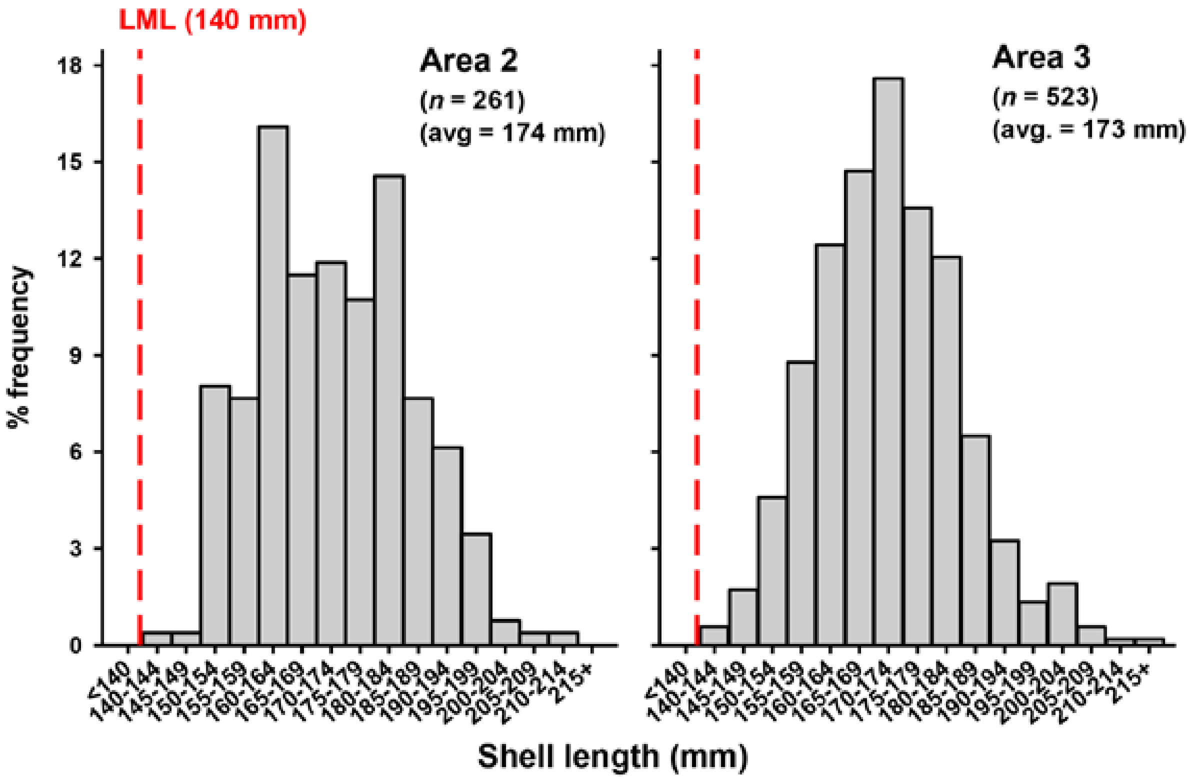


Figure 20. Size-frequency of the catch of ***Haliotis conicopora*** from the Area 2 fishery and Area 3 fishery in 2010. Sufficient data is not available for 2011. Legal minimum length is 140 mm.

5.1.5 Fishing mortality

Fishing mortality declined significantly in the Area 3 greenlip fishery between 2007 and 2008, particularly on the South Coast (Figure 21a), but then increased again over 2009 to 2011. In the Area 2 fishery it decreased only slightly over the same time period. In the brownlip fisheries, fishing mortality declined in Area 2 in 2004 and has since been relatively constant in both areas (Figure 21b).

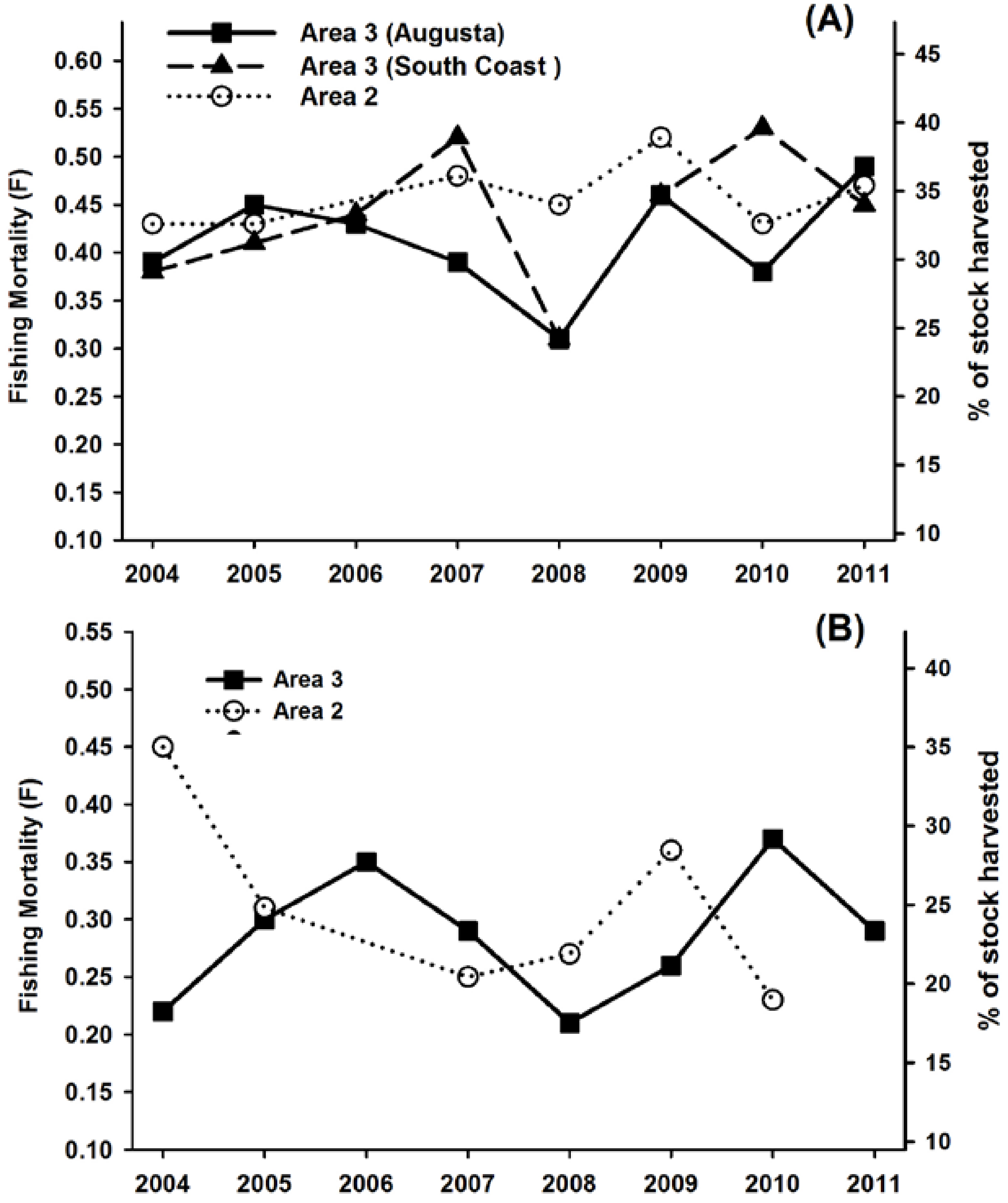


Figure 21. Fishing Mortality (F) for greenlip (a) and brownlip (b) abalone. Estimates of F apply only to harvest size animals, and are derived from catch-curve analysis using length-frequency data. See section 4.4.2 for methods.

5.2 Stunted stocks

5.2.1 Stunted individuals

Typical indicators of stunting in individual abalone include the shape of the shell, usually deeper, shorter and/or possibly bowed at the ventral margin (Figure 22e and f). Stunted animals usually have increased growth in depth rather than length, reducing the length-width ratio and producing a more rounded shell (Figure 22b and c). Shells can be thick and unusually heavy or light, thin and weakened by boring organisms. The ventral surface of the shell can have distortions, blistering, uneven texture and spiracles can be filled in or a spiracle channel may have formed (Figure 22d). Stunted animals generally have more encrusting animals on the back of the shell, and the ventral surface of the shell may have staining and the nacre can lack lustre (Figure 22d). Quantitative morphometric indicators that depict stunting in commercial shell samples of abalone have been developed (Saunders et al., 2009).

5.2.2 Stunted populations

Abalone that fail to reach their full growth potential have traditionally been considered stunted. However as shown in Figure 7, the full growth potential varies considerably within and between regions and habitats. Stunted populations have been described as: populations whose individuals grow slowly and/or grow to a smaller maximum size in comparison with other populations (Shepherd, 1988; Wells and Mulvay, 1995). Also stunted populations have been hypothesised to have wider, heavier, and deeper shells for a given length, in comparison to their faster growing conspecifics (Worthington et al., 1995).

To obtain a practical working definition for stunted greenlip stocks in Western Australia, stock structure from in-water stock surveys (see section 4.3.1) was compared with growth parameters from mark-recapture studies at representative populations. Overall, 92% ($r^2 = 0.92$) of the variability in the mean growth parameter ($L\infty$) could be explained by the variability in mean length of the population measured from fishery independent surveys (Figure 23).

Based on these results and the equation in Figure 23, we applied a working definition of "stunted" stocks as those populations where the maximum theoretical length is less than 140 mm. This equates to a mean population length, as measured by in-water stock surveys, of less than 115mm (Figure 23).

Figure 22. Comparison of slow (stunted) and fast growing *H. laevigata* shells from Hopetoun, Western Australia: **a** & **b.** Fast growing shell (longer) and slow growing shell (shorter) with very similar heights (age and maturity). **c.** Variable heights of slow growing shell, old deep-cupped shells to shallow young shell. **d.** Thick shells that lack lustre with blistering and discoloured ventral margins is typical of old slow growing animals, however healthy shells with a good lustre are also common. **e, f** & **g.** Typical slow growing stunted shells with irregular growth causing distortions in the shape of the shells (greater width and height). **h.** Ventral view of shells from animals of the same age but with significantly different growth.

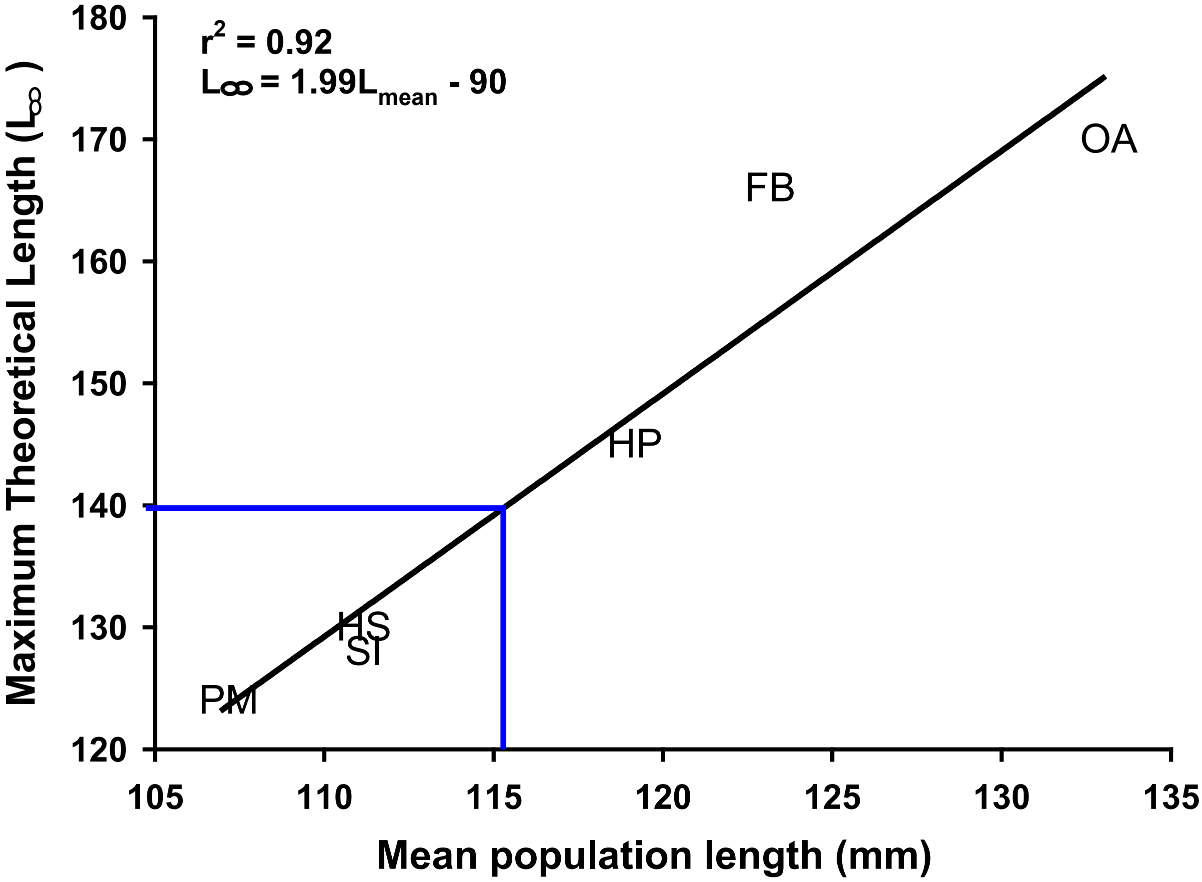


Figure 23. Maximum theoretical length (L∞) of ***Haliotis laevigata*** in Western Australia as a function of mean length of populations measured from in-water stock surveys (see section 4.3.1). Populations are: Point Malcolm (PM); Station Island (SI), Hopetoun stunted (HS), Hopetoun Primary (HP), Flinders Bay, Augusta (FB), Outback Augusta (OA). L∞ estimated from tag increments using maximum likelihood method (Francis, 1988), with the exception of FB, which was sourced from Wells and Mulvay (1995).

5.2.3 Stunted stock surveys

Densities of stunted stocks have remained fairly constant over time (Figure 24). Mean total density in stunted stocks (2 – 3 per m^2) are slightly lower than found in primary stocks (3 to 4 per m^2; see Figure 25 and 27.

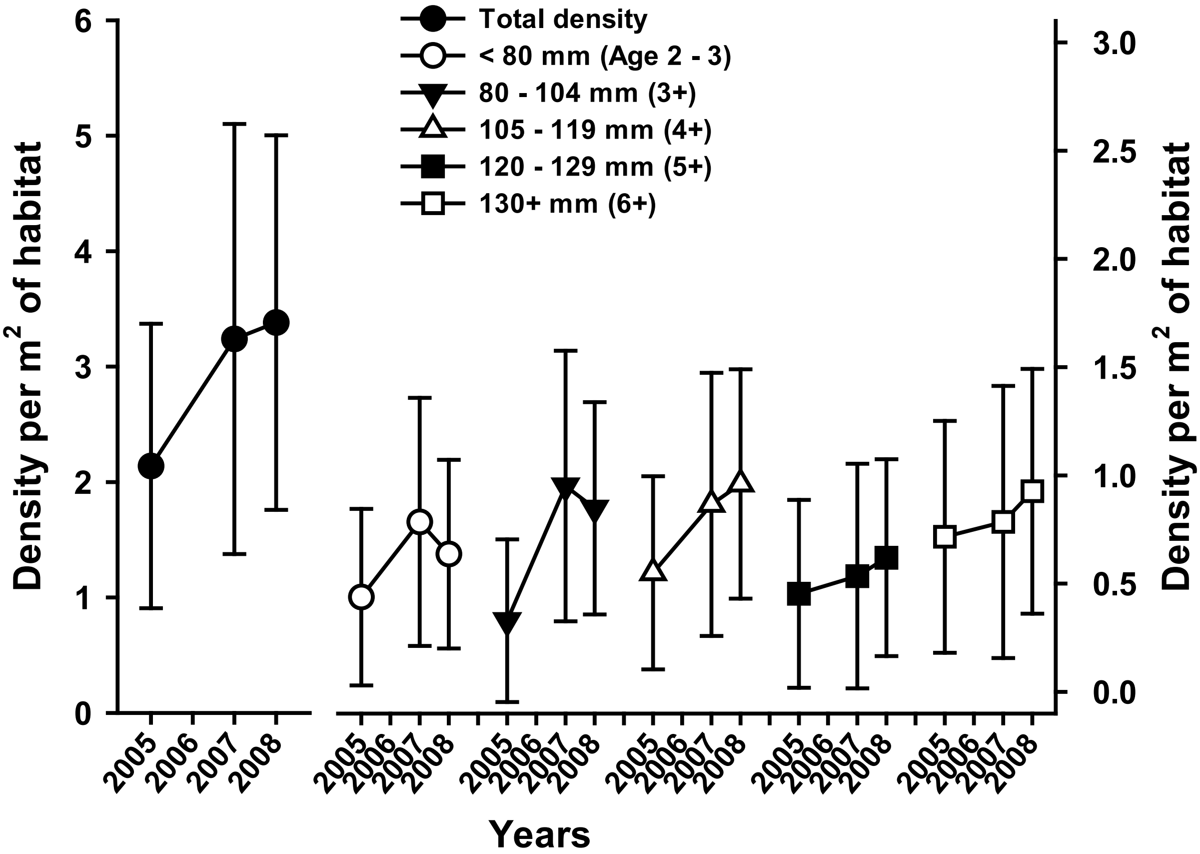


Figure 24. Densities (± 95% CL) of stunted stocks of ***Haliotis laevigata*** from research surveys for each size/age class in Western Australian fishery. Data are least-squares mean density and age groupings are approximate only. The right vertical axis is relevant for the total density and the left axis for the individual length classes.

5.2.4 *Managing harvest from stunted stocks*

Stunted stocks are fished as a unique fishing episode (called a “fishdown”). A TACC, legal minimum size (Table 15), and duration of fishing, usually about 2 weeks, are set for each episode, and the remainder of the commercial fishery is closed for that period. This controls the harvest and simplifies the compliance task of policing an appropriate size-limit.

From 1998 to 2011, 78 t of catch was taken from stunted stocks, usually at a legal minimum length of 115 – 120 mm (Table 15). Average weight of individual animals was around 110 – 130 g, compared to 180 – 230g for normal commercial stocks (Figure 17).

Table 15. Location, population data, and fishery statistics of stunted stocks of ***Haliotis laevigata*** fished in Western Australia

Location	*Mean shell length (mm)	No. of fishing episodes	Mean TACC (kg)	LML (mm)	Total Catch (kg)	Average weight (g)
Augusta	107	3	2,000	130	7,100	140
Hopetoun	109	7	3,700	115	19,800	128
Cape Arid	108	3	5,700	115	14,200	125
Israelite Bay	104	8	4,600	115 – 120	33,800	106
Area 1		5	1,200	110 – 120	4,000	99
TOTAL					**78,900**	

* from fishery-independent stock surveys

5.3 Recreational fisheries

5.3.1 Catch, effort and CPUE

The estimated recreational catch of greenlip and brownlip abalone in 2007 was 8 tonnes, which comprised around 3.5% of total catch (Table 16). This is similar to the 2006 estimate. It is possible that there were species identification issues between brownlip and greenlip as the brownlip catch in 2004 and 2006 appears high relative to the greenlip catch. Total effort (11,200 days) and average CPUE (1.4 abalone per day) for the greenlip brownlip fishery in 2007 was similar to 2006, which had a total effort of 10,800 days and an average CPUE of 1.4 abalone per fisher day (Table 16). No telephone diary surveys were undertaken in 2008 – 2011.

Table 16. Summary of telephone diary surveys of recreational effort (fisher days), catch rate (abalone per fisher day) and catch (tonnes whole weight) for the greenlip and brownlip abalone fisheries in 2004, 2006, and 2007

Location	Year	Effort	Greenlip		Brownlip	
			Catch Rate	Catch (tonnes)	Catch Rate	Catch (tonnes)
West Coast	2004	10,100 (6,500–13,600)	0.6	4 (2–6)	0.4	3 (1–5)
	2006	8,000 (4,700–11,300)	0.3	2 (0–3)	0.4	3 (0–5)
	2007	6,300 (3,800 – 8,800)	0.7	3 (0–6)	0.1	<1 (0–1)
South Coast	2004	2,700 (1,700–3,700)	2.4	2 (1–5)	<0.1	<1 (0–1)
	2006	2,800 (1,600–3,900)	1.6	2 (0–4)	0.5	1 (0–2)
	2007	4,900 (1,700–8,000)	1.8	4 (0–8)	0.2	<1 (0–1)

5.4 Fishery-independent stock surveys

5.4.1 Research Diver Transect Surveys

5.4.1.1 Area 2

An analysis of data from fishery-independent surveys of greenlip stocks in Area 2 was available for the first time in 2011. Mean total density varied between sub-areas, ranging from 3 and 8 m^{-2} but did not vary significantly over time, with the exception of Arid (Figure 25), where it decreased between 2006 and 2008, but increased again to 2012.

Regarding harvest-sized densities (147+ mm), the only sub-area to experience significant change in density was the Duke region, where density declined by 50% between 2007 and 2009 (Figure 25). No recent survey data is available, however the CPUE analysis for Duke showed an increasing trend between 2004 and 2009 (Figure 14), and a slight decline since then (Figure 14). Significant changes in density were also observed for the < 90 mm size class at Town, and the 91 – 114 mm size class at West, but the density was oscillating, not heading in one direction (Figure 25).

Size-frequency of stocks shows a significant difference in average size of animals between the different sub-areas (Figure 28). For example, both the Augusta and Albany regions have a significantly higher average size of animal, with a greater proportion of animals in the exploited size-classes (Figure 28), compared to the Hopetoun and Windy Harbour regions. All areas show good recruitment of animals below the minimum legal length.

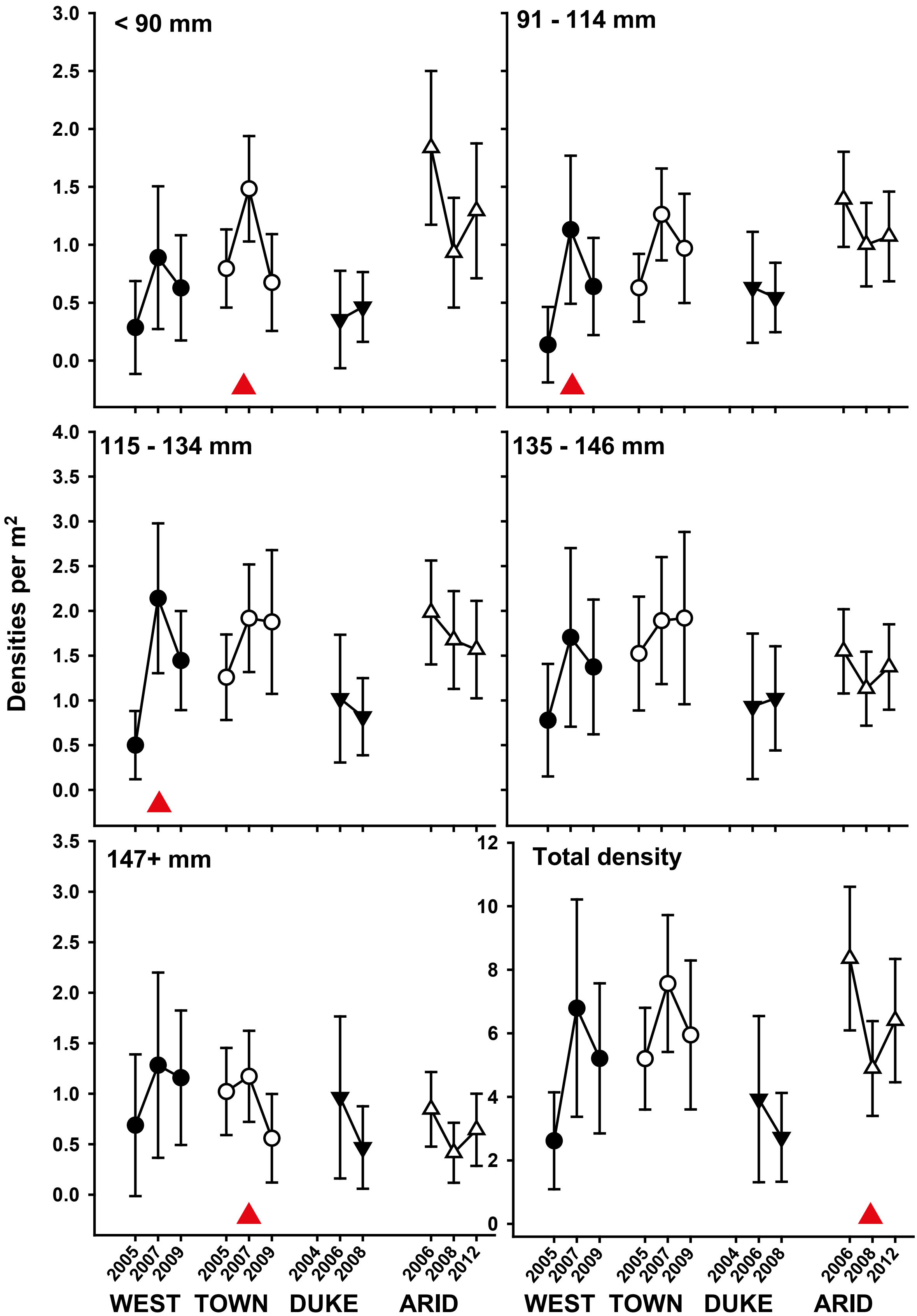


Figure 25. Densities (± 95% CL) of ***Haliotis laevigata*** over time and subarea in the Area 2 fishery. Sub-areas are West, Town, Duke and Arid and approximate age classes are 2 – 3 (< 90 mm); 3+ (91 – 114 mm); 4+ (115 – 134 mm); 5+ (134 – 144 mm); 6+ (≥ 147 mm). ▲ = significant effect of year ($p < 0.05$)

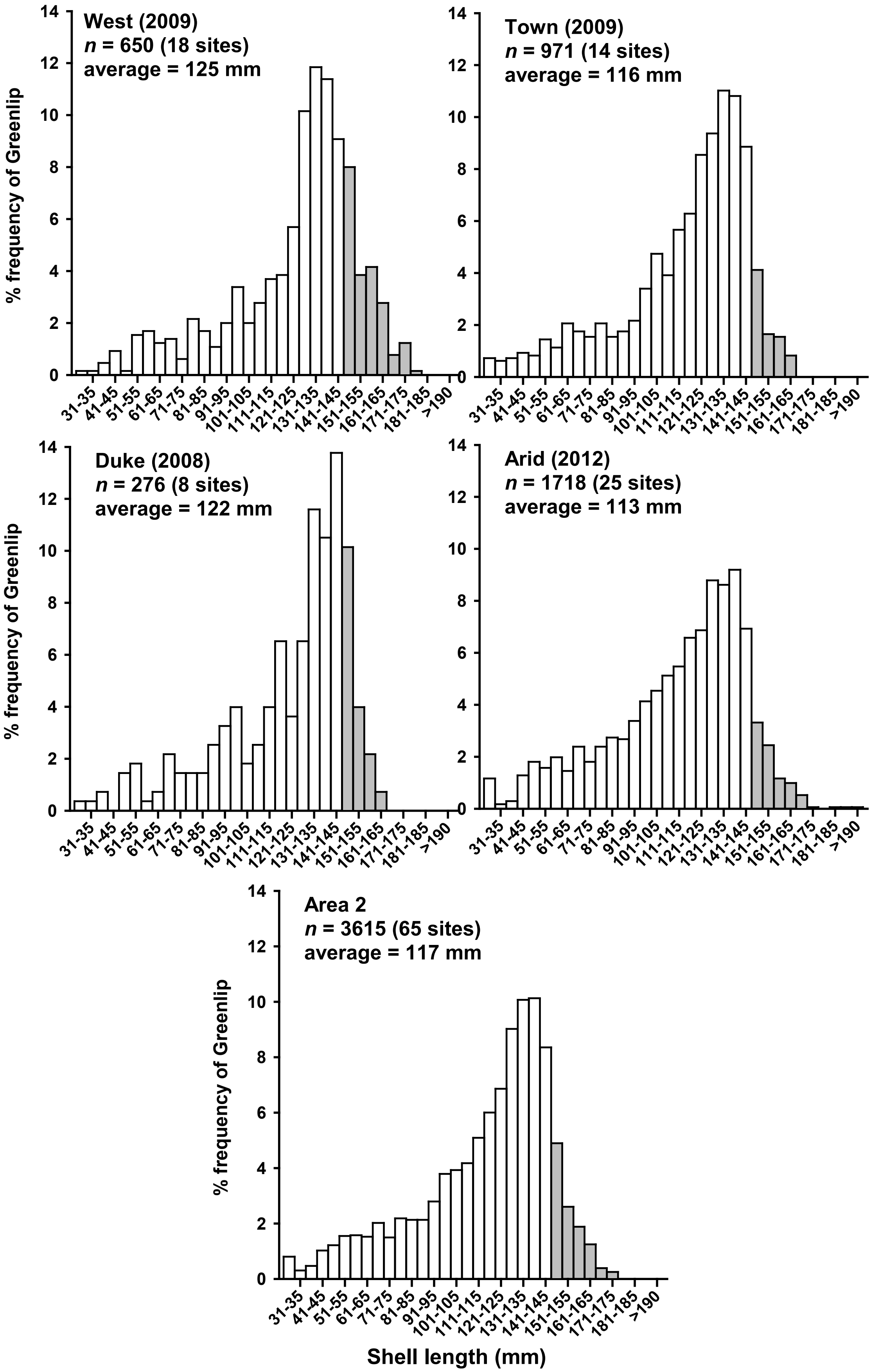


Figure 26. Size-frequency and average size (mm) of ***Haliotis laevigata*** from different sub-areas and the whole Area 2 fishery. Shaded area indicates the exploited size-classes (see Figure 18).

5.4.1.2 Area 3

An analysis of data from fishery-independent surveys of greenlip stocks was available for the first time in 2011. Mean total density varied between sub-areas, ranging from 2 and 6 m^{-2} but did not vary significantly over time (Figure 27).

Regarding harvest-sized densities (147+ mm), the only sub-area to experience significant change in density was the Augusta region, where density declined by 50% between 2004 and 2008, but remained constant until 2010 (Figure 27). The SCPUE trends oscillated during this time, showing a 10% decline between 2004 and 2005, but then a 30% increase to 2008, where it has remained relatively (Figure 16). Significant increases in juvenile density (< 90 mm and 91 – 114 mm size classes) were observed at Augusta between 2004 and 2010 (Figure 27), but densities in other sub-areas did not alter significantly. The exception was Windy Harbour (Windy), where a significant decline in density of juveniles (< 90 mm) was observed between 2007 and 2012.

Size-frequency of stocks shows a significant difference in average size of animals between the different sub-areas (Figure 28). For example, both the Augusta and Albany regions have a significantly higher average size of animal, with a greater proportion of animals in the exploited size-classes (Figure 28), compared to the Hopetoun and Windy Harbour regions. All areas show good recruitment of animals below the minimum legal length.

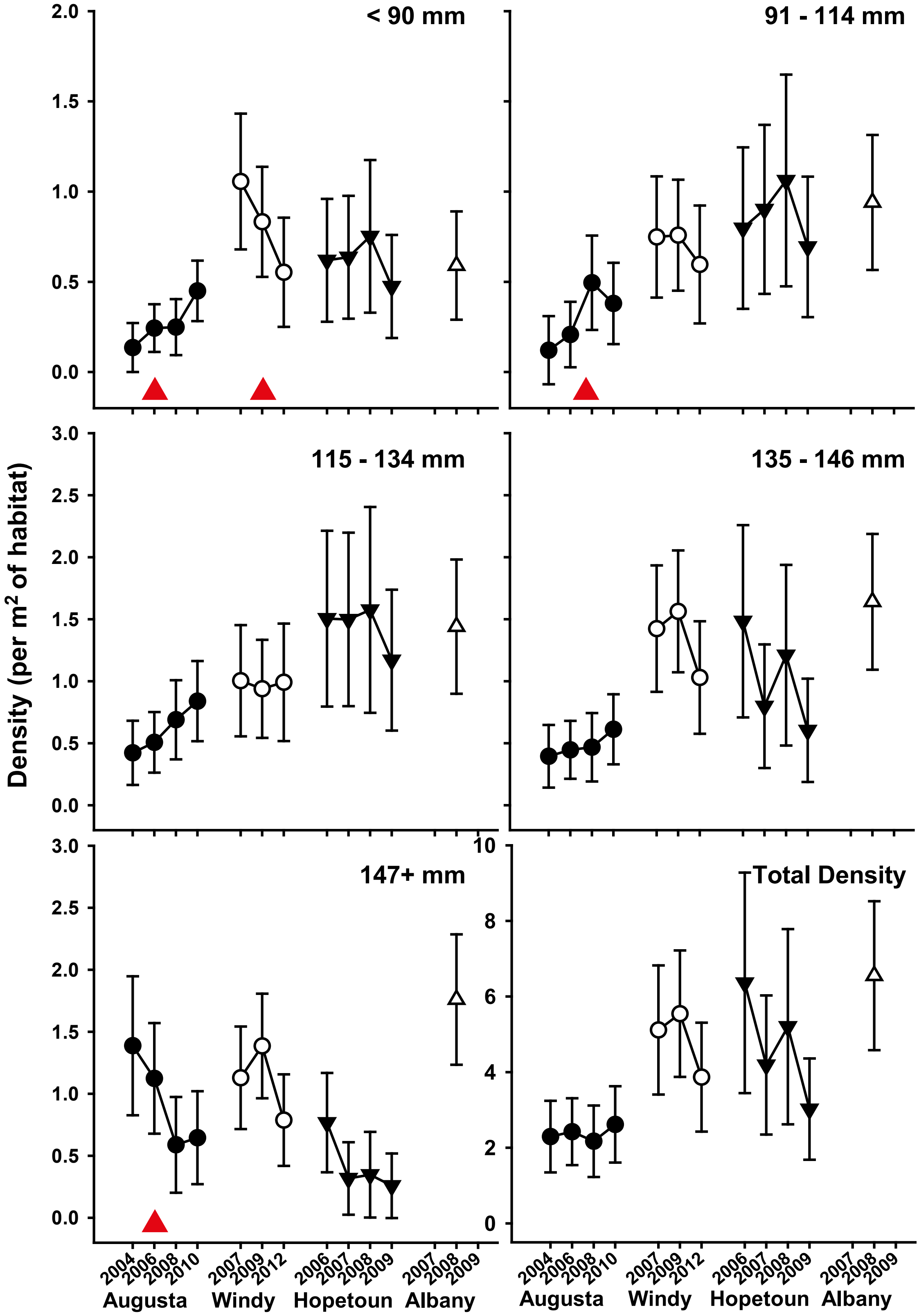


Figure 27. Densities of ***Haliotis laevigata*** over time and sub-area in the Area 3 fishery. Sub-areas are Augusta, Windy, Hopetoun and Albany (see Figure 13) and approximate age classes are 2 – 3 (< 90 mm); 3+ (91 – 114 mm); 4+ (115 – 134 mm); 5+ (134 – 146 mm); 6+ (≥ 147 mm). ▲ = significant effect of year ($p < 0.05$)

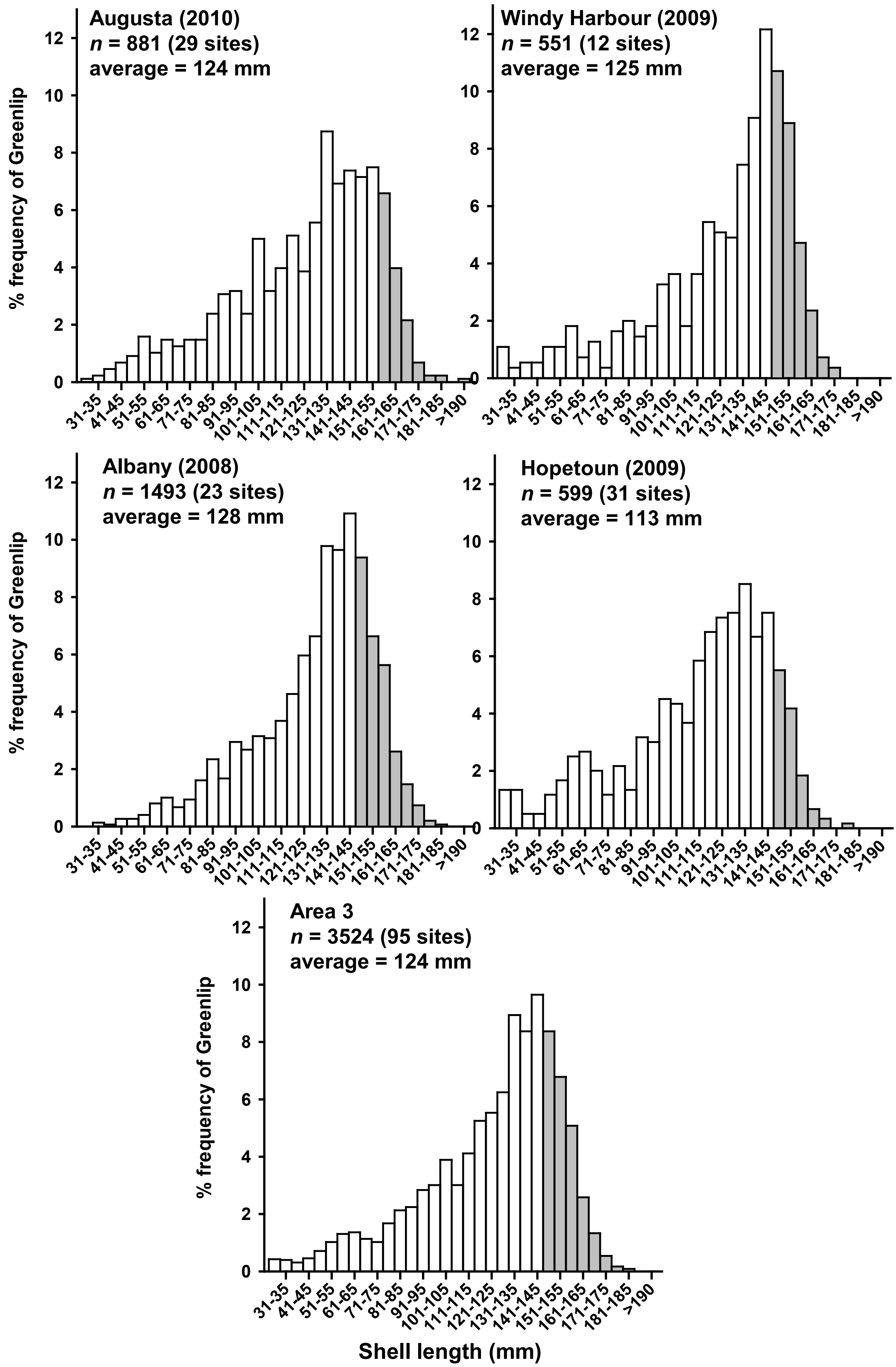


Figure 28. Size-frequency of ***Haliotis laevigata*** from different sub-areas and the whole Area 3 fishery. Shaded area indicates the exploited size-classes (see Figure 18).

5.4.2 Digital video surveys

Digital video surveys of greenlip abalone in Area 2 showed no change in mean abundance over time, with the exception of the 115 – 134 mm size class, which increased at Arid between 2010 and 2011, and the harvestable size class (147 mm+) in the Town sub-region, which declined between 2008 and 2012 (Figure 29).

Size-frequency data from the DVI surveys show a relatively stable size-structure with consistent recruitment (Figure 30). Approximately 20 – 25% of the population is vulnerable to exploitation, and there is substantial information on pre-recruit size and age classes (Figure 30).

Overall, the DVI surveys are still in the experimental stage, however in the Area 2 fishery appear to be providing a useful survey of abundance and size structure.

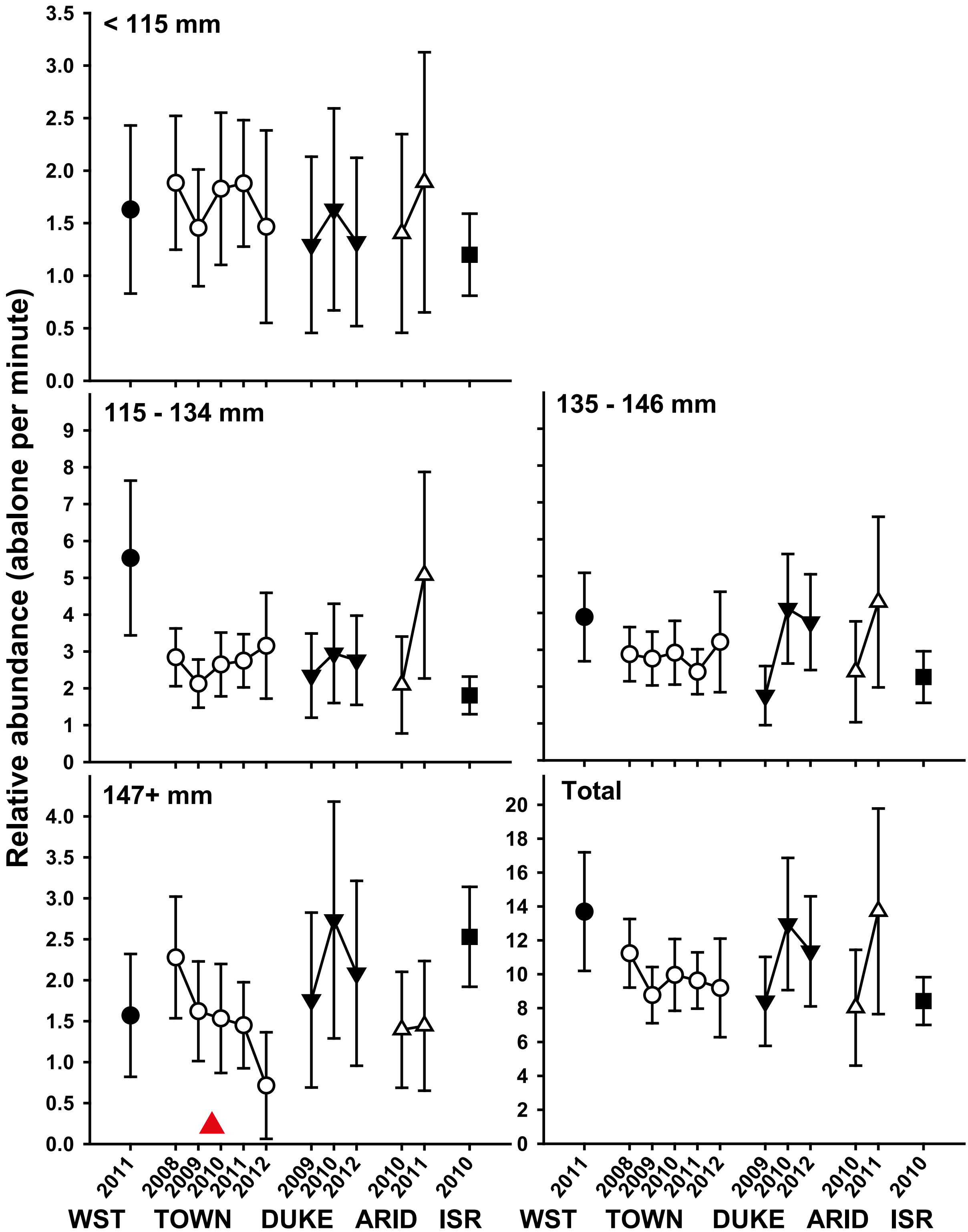


Figure 29. Mean abundance (± 95% CL) of different size classes (mm) of ***Haliotis laevigata*** in sub-areas of Area 2 as surveyed by digital video between 2008 and 2011. Sub-area codes are: WST – West, ISR – Israelite. For map of locations see Figure 12. ▲ = significant effect of year ($p < 0.05$)

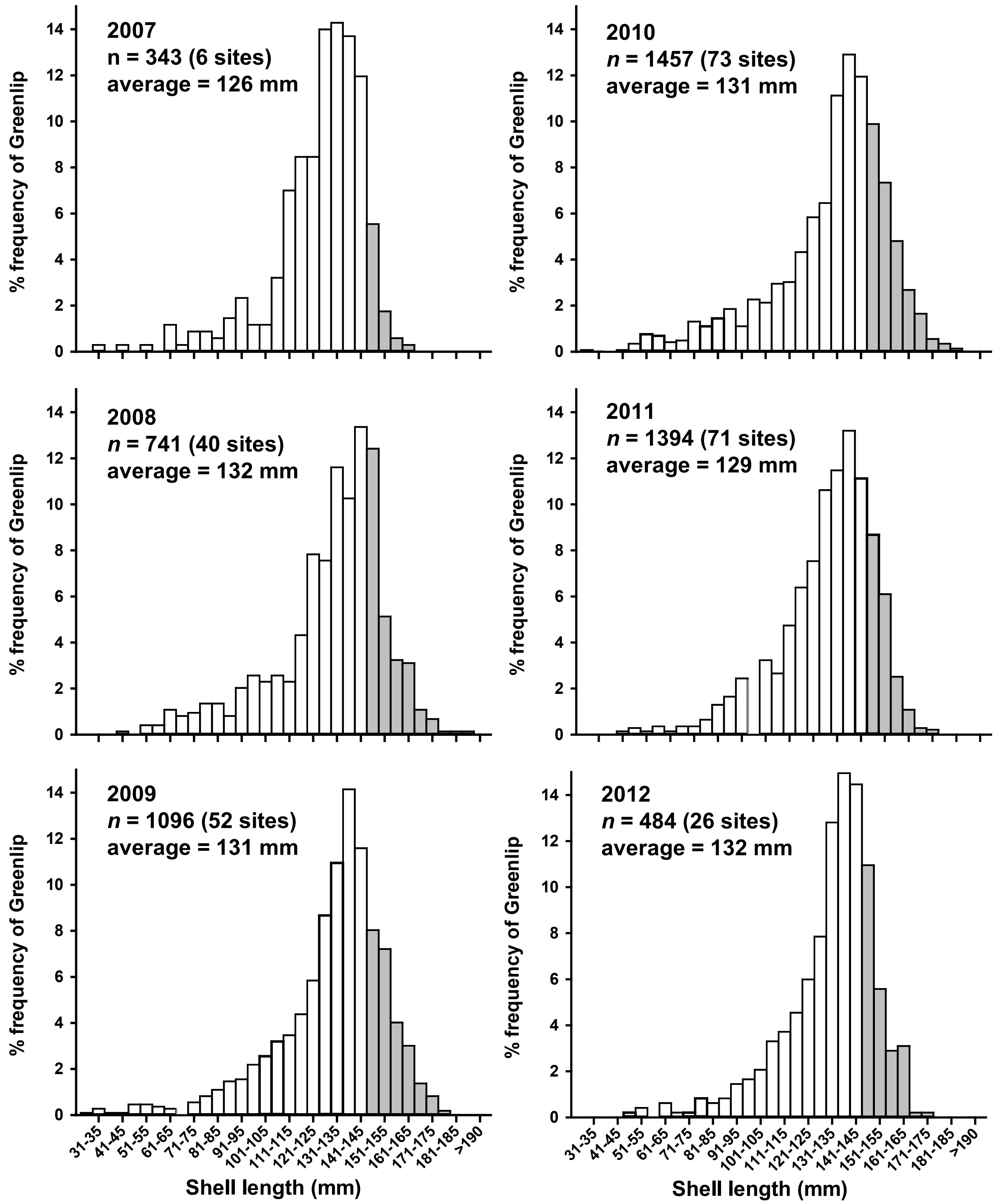


Figure 30. Size-structure of ***Haliotis laevigata*** in the Area 2 fishery, as captured by digital video surveys. Shaded areas indicate abalone of harvestable size (≥ 145 mm).

5.4.3 Discussion: FIS trends and limitations

These results represent the first analyses of fishery-independent survey methodology for *Haliotis laevigata* stocks in Western Australia. Looking at the transect surveys, total densities varied significantly between sub-areas, ranging from around 6 to 8 per m^2 of habitat in the Arid region of the Area 2 fishery (Figure 25) to around 2 per m^2 in the Augusta region of the Area 3 fishery (Figure 27). This is indicative of different levels of fishing intensity and productivity throughout the fishery. Size-frequency data supports this variability, for example in the Augusta region, 31% of the stock is ≥147 mm (Figure 28), compared to the Arid region where only 10% of the stocks are ≥147 mm (Figure 26). Coupled with the known variability in growth, these data suggest that regionally focused harvest and management controls are likely to be the optimal way for maintaining a sustainable fishery.

Densities over time appear relatively consistent, however significant declines in density of harvestable animals (147+ mm) was detected in two sub-areas, Town in Area 2, and Augusta in Area 3 between 2006 and 2010. In particular, the decline in densities of 147+ mm animals within the Town subregion was detected by two methods; the fixed-site transect surveys (Figure 25), and the random site digital video surveys (Figure 29). Although occurring at slightly different temporal scales (2007 to 2009 for the transect surveys and 2008 – 2011 for the video surveys) due to different sampling regimes, it highlights a potential issue because this sub-area supplies 25% of the Area 2 catch. Significant declines in the CPUE in these sub-areas were not observed over this time period, and fishing mortality oscillated with no obvious upward or downward trend. Fixed site transect surveys have not been conducted in these areas since 2009 (Town) and 2010 (Augusta), however are planned in 2013.

With only a few temporal data points, the conclusions for most areas are preliminary at this time, and extra surveys are being planned to strengthen the analysis. Once a reasonable time series of data has been established, the surveys will be used to set additional performance indicators for the fishery to complement the standardised CPUE of the fishers.

Overall, the research and DVI surveys provide an indication of pre-recruit abundance, which is not contained in the SCPUE trends. This will be valuable information for an early detection of any significant changes in recruitment patterns that may occur with climate variations.

5.5 Yield-per-recruit and egg-per-recruit analyses

5.5.1 Modelling under assumed growth parameters

Under the current minimum size fished of 142 mm, greenlip abalone populations in the Area 2 fishery have reached the maximum yield-per-recruit possible under the criteria of maintaining stocks above the 50% virgin egg conservation threshold (Figure 31). If the minimum size fished is dropped to 135 mm, a slightly higher yield per recruit is possible under current fishing mortality rates, however egg conservation would fall under the threshold (Figure 31), and the longer term sustainability of the fishery may be at risk.

This situation contrasts with the Area 3 fishery. For example, in the South Coast stocks (Albany, Hopetoun, Windy Harbour), the minimum size fished of 145 mm is resulting in egg-conservation levels above the threshold of 50% (Figure 32). The model showed that a modest increase in yield could be sustained by a fishing at a smaller minimum size fished of 140 mm, and that this would still result in egg conservation levels of around 50% of virgin. Similarly for the Augusta stocks, current levels of fishing mortality are producing around 70% of maximum yield-per-recruit at the current minimum size of 153 mm (Figure 33). Yield could be increased by 10% simply by moving to a smaller minimum sized fished of 143 mm, and egg conservation levels of 40% of virgin would still be attained (Figure 33). To determine an optimum level of fishing it is also important to assess the relative value of different size abalone and undertake a value-per-recruit analysis.

5.5.2 Sensitivity analysis: varying growth parameters

The sensitivity analyses for the Augusta population, using a different growth curve, produced a similar result to the main analysis. Namely that current levels of fishing mortality are producing around 70% of maximum yield-per-recruit at the current minimum sized fished of 153 mm (Figure 34), and that the egg conservation threshold is well exceeded. Yield could be increased by 5 to 10% by moving to a smaller minimum sized fished of 143 mm, whilst still maintaining egg conservation levels of 40% (Figure 34).

The main assumptions of YPR and EPR models of constant growth, mortality and recruitment are not likely to hold true from year to year, and consequently there needs to be a cautious interpretations of their estimates. Nevertheless, the sensitivity analysis did not contradict the overall conclusion, namely that a small lowering of size-limits may be beneficial to the Area 3 fishery without compromising egg conservation targets. However, even if these targets were not met under smaller minimum sizes, the implementation of TACC decision rules that use estimates of fishing mortality will ensure that appropriate reductions in catch quotas can be implemented in response to the exceeding of egg conservation targets (see section 7.3 for further details).

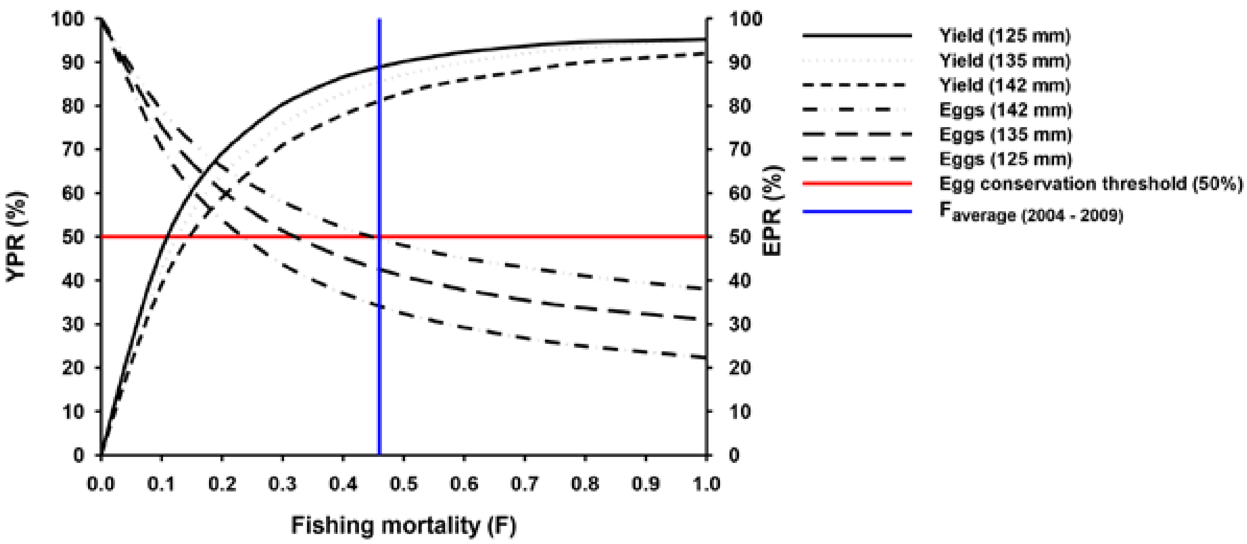


Figure 31. % YPR and % EPR versus fishing mortality fate for the Area 2 ***Haliotis laevigata*** populations, for the current minimum length of fishing (142 mm), as well as a 135 mm minimum length. Red line is the egg conservation threshold for these stocks (see section 7.3.1), and blue line is the current average fishing mortality over the period 2004 – 2008 (see Figure 21)

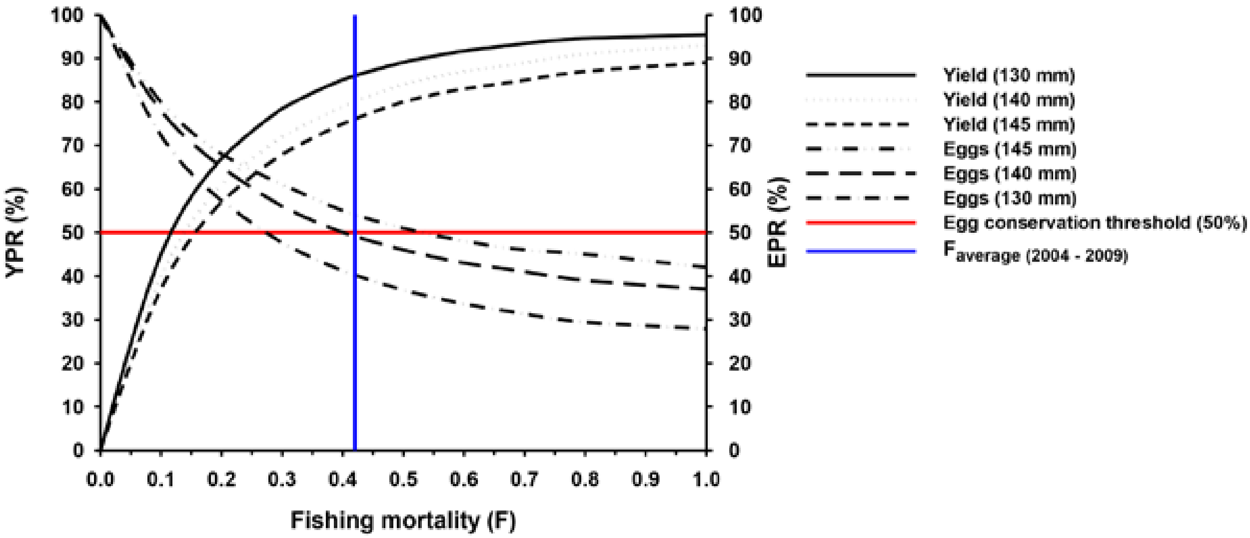


Figure 32. % YPR and % EPR versus fishing mortality for the South coast stocks (Albany, Hopetoun, Windy Harbour) of the Area 3 ***Haliotis laevigata*** fishery, under the current minimum length of fishing (145 mm), as well as a 140 mm minimum length. Red line is the egg conservation threshold for these stocks (see section 7.3.1), and blue line is the current average fishing mortality over the period 2004 – 2008 (see Figure 21).

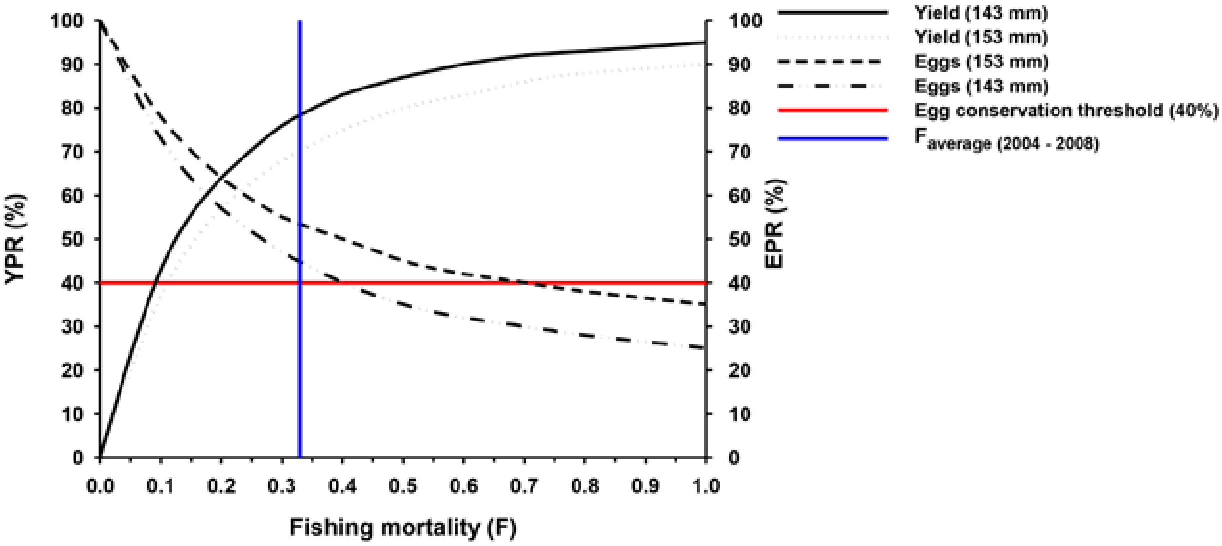


Figure 33. % YPR and % EPR versus fishing mortality fate for the West coast stocks (Augusta) of the Area 3 ***Haliotis laevigata*** populations, for the current minimum length of fishing (153 mm), as well as a 143 mm minimum length. Red line is the egg conservation threshold for these stocks (see section 7.3.1), and blue line is the current average fishing mortality over the period 2004 – 2008 (see Figure 21). Assumed growth parameters are K =0.3; L∞ = 185 mm.

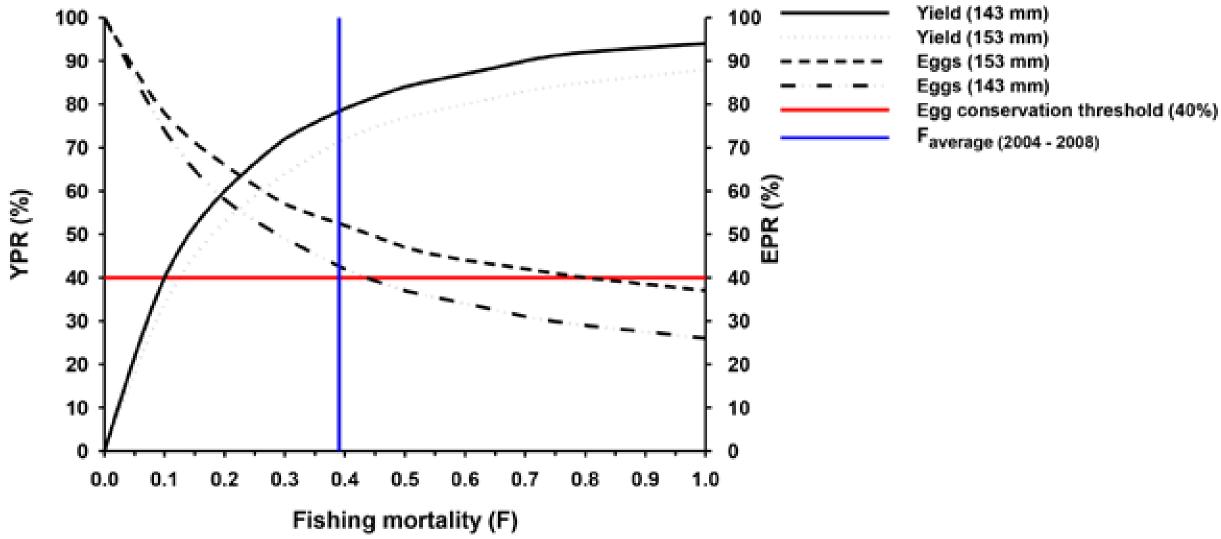


Figure 34. Sensitivity analysis: % YPR and % EPR versus fishing mortality rate for the West coast stocks (Augusta) of the Area 3 ***Haliotis laevigata*** populations, for the current minimum length of fishing (153 mm), as well as a 143 mm minimum length. Red line is the egg conservation threshold for these stocks (see section 7.3.1), and blue line is the current average fishing mortality over the period 2004 – 2008 using the adjusted growth parameters (K = 0.55, L∞ =170). In comparison, growth assumptions for model outputs in Figure 33 are K = 0.30, L∞ =185.

6.0 Roe's Abalone

6.1 Commercial fisheries

6.1.1 Catch, effort and CPUE

The TACC for the 2011 quota year was 92.8 t whole weight for Roe's abalone. The 2011 catch of 81.6 t whole weight (Roe's Abalone Table 1) was 10 tonnes lower than 2010 and about 90% of the TACC (Table 17). It was also the lowest catch in over 20 years. The overall TACC was not caught because Area 1 was not fished in 2011 and catches in Area 5 were below the TACC (75% of TACC caught) due to unfavourable weather.

Total TACC is not usually caught in the Roe's abalone fishery because of weather-related issues and the fact that TACC in the marginal regions of the fishery (Area 1) is mostly an exploratory quota.

Area 8 of the fishery also experienced catastrophic mortality of abalone due to an anomalous environmental "marine heatwave" event in the summer of 2010/11 (Pearce et al. 2011). The area was closed to fishing prior to the commencement of the 2011 commercial season.

Total effort for dedicated Roe's abalone divers in 2011 was 426 diver days, 25% lower than last year's effort of 567 diver days (Table 17). The effort in 2011, which was the lowest in over 20 years, resulted from a combination of lower quota being set, and closure to the Area 8 fishery (that traditionally required between 100 and 150 days).

6.1.2 Standardised CPUE

Standardised CPUE represents the best available long-term abundance index. The SCPUE for dedicated Roe's abalone divers in 2011 was 30.7 kg/hr, which was slightly higher than the 2010 catch rate (Table 17), and the third highest in over 20 years.

The Area 7 fishery has sustained the highest SCPUE, and this has been relatively stable since 1992. SCPUE in all other fisheries has oscillated up and down with no particular long-term trend. The exceptions include the Area 2 fishery where SCPUE had experienced an overall declining trend, which has reversed in recent years (Figure 35) and the Area 8 commercial fishery (Northern Region for recreational), which has been closed to all fishing to promote stock recovery following mass mortality.

Table 17. Roe's abalone catch and effort[1] by quota period with raw and standardised catch per unit effort (SCPUE).

Quota period[2]	Roe's TACC kg whole weight[3]	Roe's caught kg whole weight	Diver days[4] (Roe's divers only)	Raw CPUE (roei divers) kg per day)	SCPUE (kg per hour)
1990	105,000	116,447	936	112	
1991	101,000	109,489	832	118	
1992	105,000	111,341	735	134	27.3
1993	128,000	115,281	832	123	29.4
1994	125,960	117,835	908	113	27.7
1995	125,960	114,501	1,047	98	25.5
1996	125,960	118,715	1,004	106	28.8
1997	126,790	118,738	855	120	30.2
1998	93,960[5]	86,425	695	108	27.9
1999[6]	119,900	112,949	659	149	29.5
2000	115,900	107,735	647	144	28.7
2001	107,900	99,174	685	126	30.0
2002	107,900	100,471	700	125	28.6
2003	110,900	96,005	723	118	29.0
2004	110,900	107,593	736	126	28.0
2005	112,700	96,496	672	131	31.3
2006	112,700	98,370	625	136	33.2
2007	109,700	90,750	585	132	28.5
2008	106,700	93,197	580	133	28.6
2009	101,800	92,838	554	140	29.0
2010	101,800	91,418	567	134	29.5
2011	92,800	81,607	426	157	30.7

Notes

1. Data source: quota returns.
2. The length of quota period has varied with management changes and, for simplicity, has been recorded against the nearest calendar year.
3. Standard conversion factors for meat weight to whole weight for Roe's abalone were 2.5 prior to 2000 and 3.0 from 2000.
4. Effort (diver days) for dedicated Roe's divers only.
5. Reduced quota for a 6-month season.
6. In 1999, fishing restrictions (100 kg daily catch limit) in the Perth metropolitan area were lifted. This had the immediate effect of doubling the catch rate (kg/day) in that area.

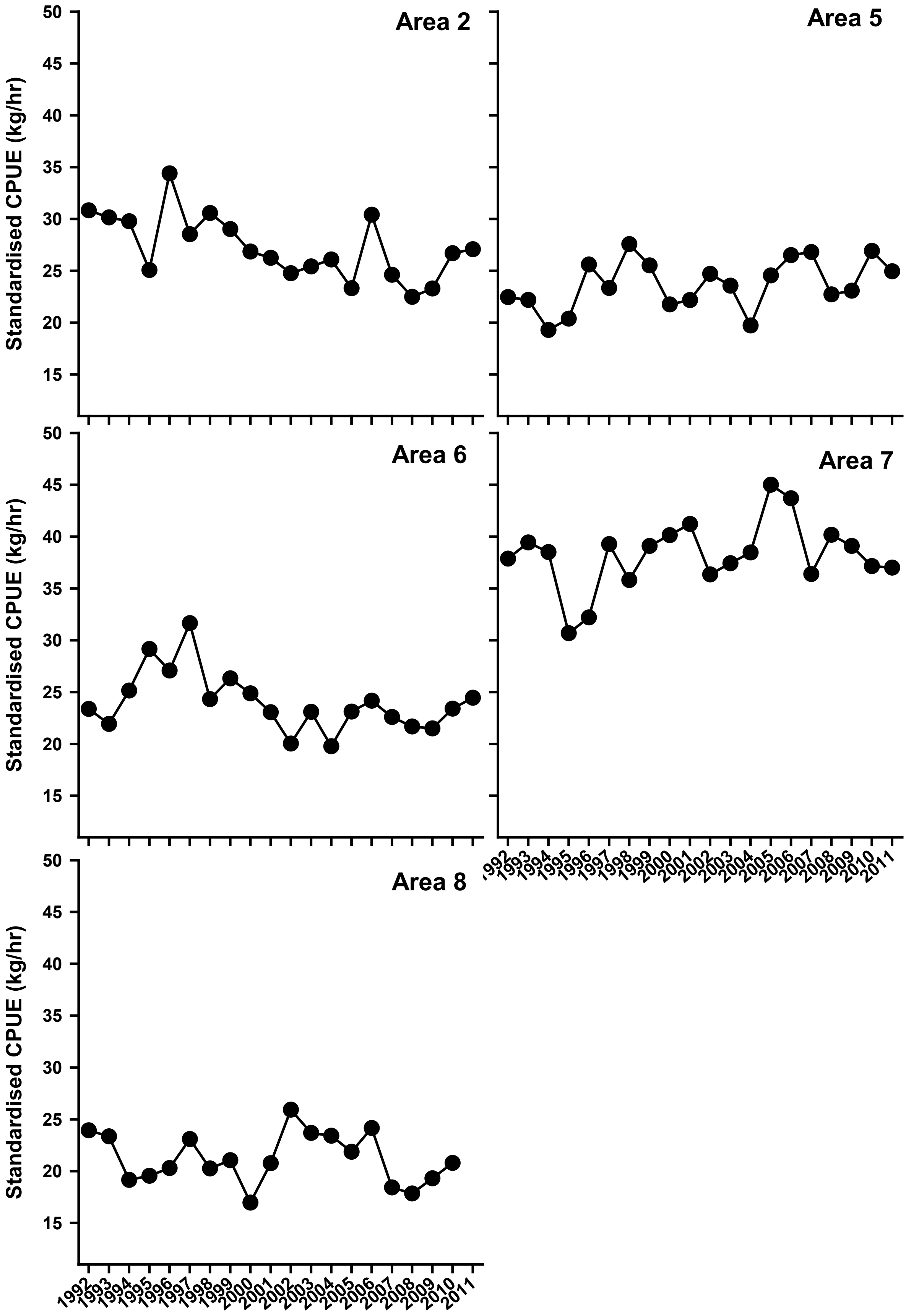


Figure 35. Standardised CPUE of ***Haliotis roei*** from the six fishery management areas from 1992 to 2009.

6.2 Recreational fisheries

6.2.1 Catch, effort and CPUE

Estimated catch of Roe's abalone from the Perth metropolitan area in 2011 was 22 t, as estimated from the field survey (Table 18). This is a 96% decrease of the catch achieved in 2010, caused by a combination of decreases in effort and catch rates as a result of poor weather conditions and meat weights (Table 18).

Catch estimates of Roe's abalone from the phone diary surveys in 2007 were 24.0 t in the Perth metro fishery, 9.0 t in the West Coast Fishery, and 5.3 t in the South Coast Fishery (Table 19). These estimates are similar to the 2006 telephone diary survey estimates. The phone diary estimates for the Perth metro are well below the field estimates in 2006 and 2007.

Recreational fishing represented about 22 – 36% of the total (commercial and recreational) Roe's abalone catch across the state in 2007. This is similar to the 2006 estimate of 21 – 34% of the total catch. Assuming catch from the South Coast fishery remained similar in 2011, it was estimated that recreational fishing produced 31% of the total Roe's abalone catch in 2011.

Effort in the Perth fishery in 2011 was 11,396 hours, which was a 37% decrease on 2010 effort of 18,010 hours (Table 18). Effort in 2011 was also 24% lower than the 10-year historical average of 14,951 hours. This was primarily due to the poor weather conditions affecting fisher participation. Weather conditions were rated as being the second worst in well over a decade of fishing (Figure 36).

Effort estimates for state-wide recreational abalone fishing from the 2007 telephone diary survey were 13,400 days in the Perth metropolitan area, 6,300 days on the west coast (excluding the Perth metropolitan area), and 4,900 days on the south coast (Table 19). Total effort has slightly declined from 30,000 days in 2004 to 24,600 days in 2007 (Table 19).

6.2.2 Weather conditions and recreational catch

Recreational catch in the Perth metropolitan region between 1999 and 2011 was significantly influenced by both effort (E_i; $p = 0.002$) and weather conditions (W_i; $p = 0.01$) in that year (i). The goodness-of-fit (R^2) to the predictive relationship was 0.79, and the relationship itself was as follows:

$$\log Catch_i = -0.183 W_i + 0.731 \log E_i - 2.946 + \varepsilon_i;\ R^2 = 0.79$$

Figure 36 shows that catch decreases linearly with an increase in the weather condition index, but the effort is also equally important in the final catch estimate.

Table 18. Summary of effort (fisher hours), catch rate (abalone per hour), catch (number of abalone and tonnes whole weight) and mean whole weight (g) for the Perth recreational Roe's abalone fishery, from annual field surveys

Year	Field Survey				
	Effort (hours)	Catch rate	Catch (number)	Catch (tonnes)	Mean weight (g)
1999	16,449	23	383,600	35.3	92
2000	15,818	21	330,300	30.2	91
2001	17,727	27	481,300	44.1	92
2002	18,127	22	401,500	36.0	90
2003	17,963	26	442,400	42.6	96
2004	14,614	24	342,900	31.7	93
2005	12,328	21	262,700	24.3	92
2006	10,435	29	297,000	30.2	101
2007	12,433	28	338,000	34.4	102
2008	14,490	29	420,000	44.4	106
2009	19,718	27	517,000	48.6	94
2010	18,010	26	468,000	43.9	94
2011	11,396	23	266,202	22.4	84

Table 19. Summary of telephone diary surveys of effort (fisher days), catch rate (abalone per fisher day) and catch (tonnes whole weight) for the Roe's abalone recreational fisheries in 2004, 2006, and 2007.

Location	Year	Effort (± Range)	Roe's	
			Catch Rate	Catch (t)
Perth Metro[1]	2004	17,200 (14,000 – 20,500)	17.8	28 (25 – 31)
	2006	12,600 (9,900 – 15,500)	18.2	23 (20 – 26)
	2007	13,400 (10,500 – 16,200)	17.6	24 (19 – 29)
West Coast[1] (excl. Metro)	2004	10,100 (6,500 – 13,600)	11.0	10 (7 – 14)
	2006	8,000 (4,700 – 11,300)	14.7	12 (7 – 17)
	2007	6,300 (3,800 – 8,800)	14.1	9 (6 – 12)
South Coast[2]	2004	2,700 (1,700 – 3,700)	6.2	2 (1 – 3)
	2006	2,800 (1,600 – 3,900)	6.3	2 (1 – 2)
	2007	4,900 (1,700 – 8,000)	10.8	5 (1 – 9)

1. Both areas are within the West Coast bioregion.
2. Survey area is South Coast bioregion (i.e. east of Black Point).

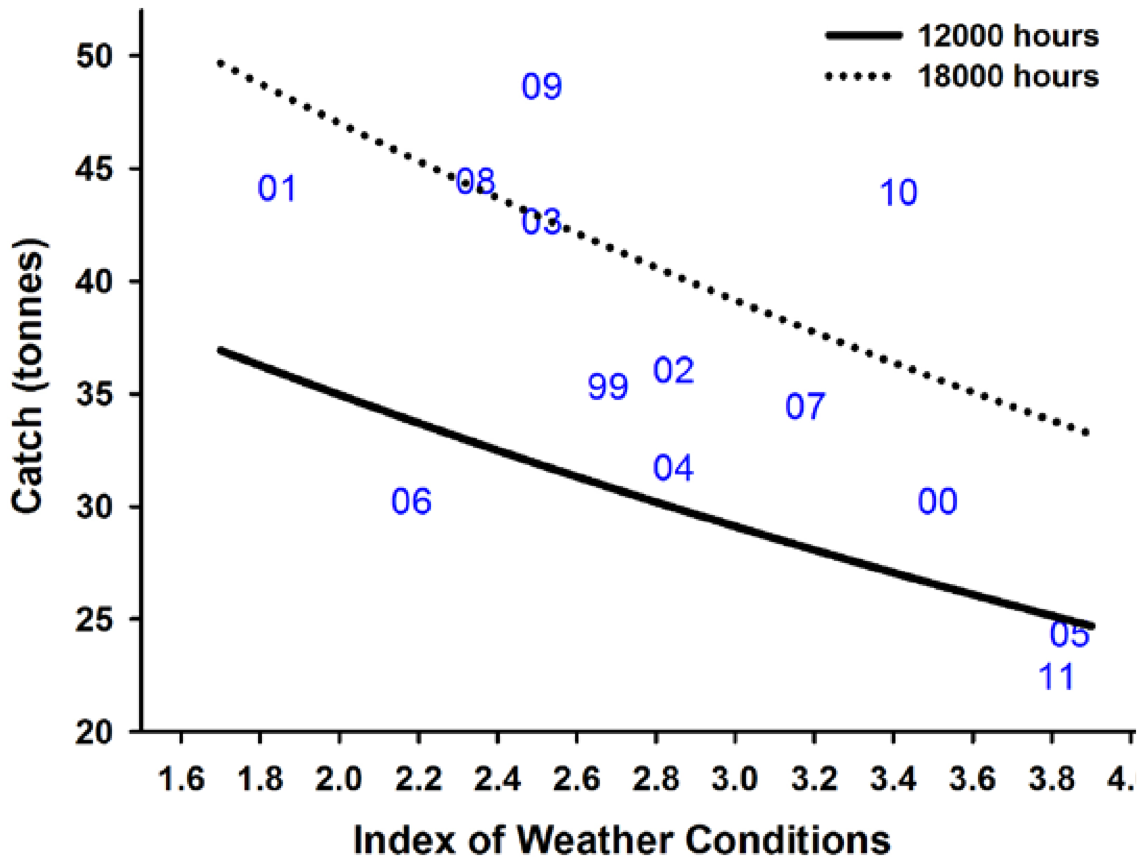


Figure 36. Catch of ***Haliotis roei*** in the Perth recreational fishery as a function of weather conditions (low index=good conditions for fishing) and varying effort. To show the effect of effort, two effort trajectories (12,000 and 18,000 hours) have been plotted. Table 18 provides the actual effort for each year of harvest. Symbols indicate years, e.g. 01 = 2001. For details of the weather condition index, see Hancock and Caputi (2006).

6.3 Fishery-independent stock surveys

6.3.1 Research Diver Surveys

Densities of individual age classes of *Haliotis roei* in the Perth metropolitan fishery have significantly changed over time (Table 20; Figure 37). The 51 – 60 mm size class (Age 3+), shows a significant increasing trend between 2006 and 2012, but the ≥ 71mm class shows the opposite trend (Figure 37). In early 2012 the proportion of animals ≥ 71mm was very low (Figure 38), around 5%.

The approximate age classes for *Haliotis roei* have been determined using a growth curve developed by Hancock (2004). To determine the accuracy of these age classes, correlations were carried out between densities of successive age classes from 0+/1+ to 4+/Recruits with a 1-year lag. Statistically significant correlations between 2+/3+ (r = 0.93) and 3+/4+ (r = 0.75) were detected, but not for other successive age classes. This may be due to a combination of selectivity, particularly for 0+ age class, the recruit class consisting of multiple year classes, and/or inaccurate assigning of size to age, however the significant correlations suggested a predictive ability in the density surveys, and further work was carried (see section 6.3.2).

Table 20. GLM results for the effect of Year, Habitat, and Location on densities of different size and age classes of ***Haliotis roei*** in the Area 7 fishery in Western Australia. Data has been ln (x+1) transformed.

Source of variability	d.f.	MS	F	P	MS	F	P
		0+ (< 17 mm)			1+ (17 – 32 mm)		
Year	15	11.9	7.42	<0.001	2.59	1.98	0.01
Location	10	12.2	7.59	<0.001	29.5	22.6	<0.001
Habitat	1	207.2	128.7	<0.001	103.6	79.3	<0.001
Residual	823	1.61			1.31		
		2+ (33 – 50 mm)			3+ (51 – 60 mm)		
Year	15	2.53	2.44	0.002	4.29	4.11	<0.001
Location	10	43.3	41.8	<0.001	77.9	74.9	<0.001
Habitat	2	257.3	247.9	<0.001	411.1	394.7	<0.001
Residual	1191	1.04			1.04		
		4+ (61 – 70 mm)			Recruits (^{3} 71 mm)		
Year	15	3.48	2.69	<0.001	8.67	6.8	<0.001
Location	10	85.5	66.2	<0.001	67.8	52.8	<0.001
Habitat	3	352.7	273.1	<0.001	89.1	69.4	<0.001
Residual	2201	1.29					

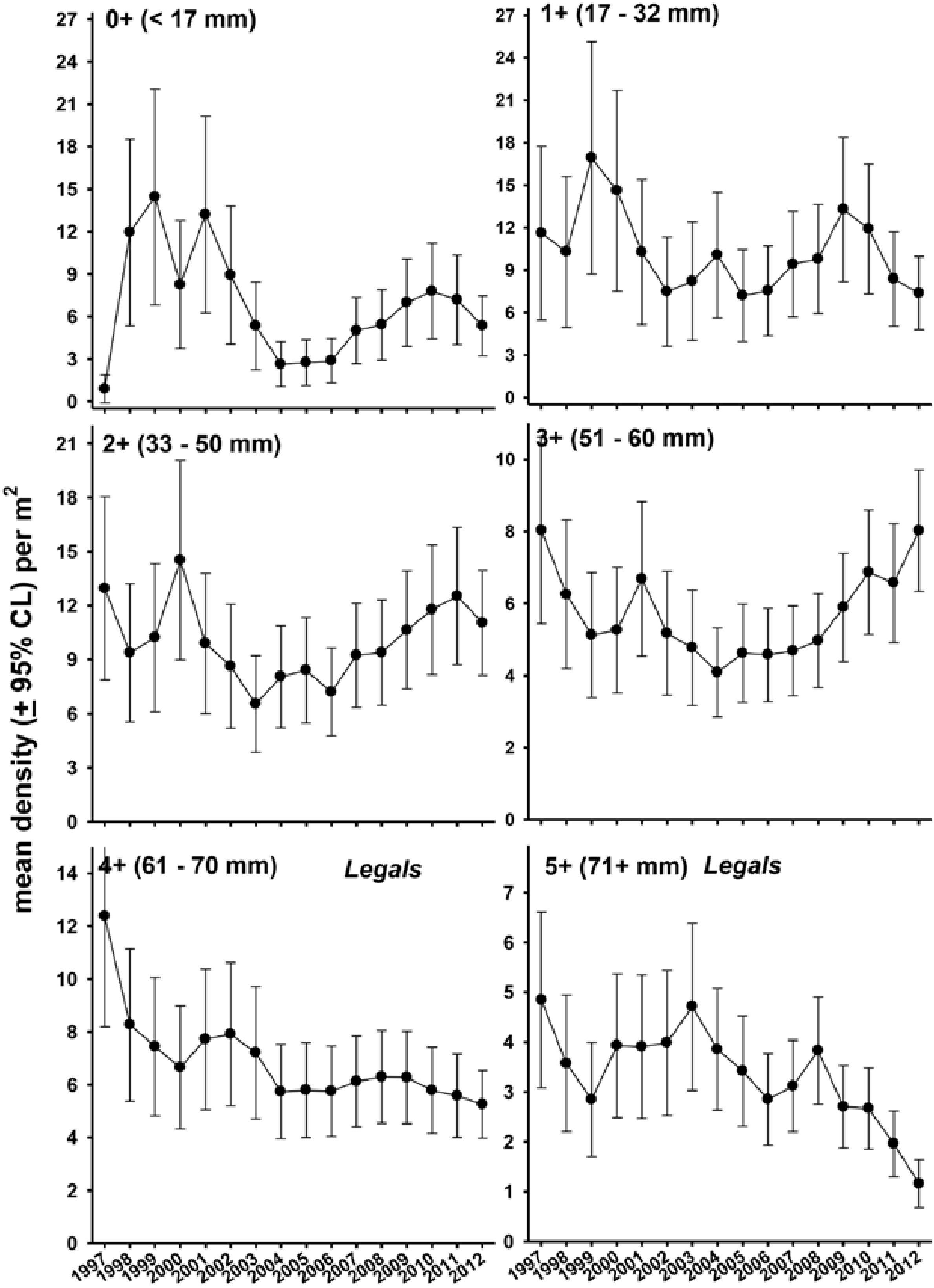


Figure 37. Density trends in Age 0+ (1 – 16 mm), Age 1+ (17 – 32 mm), 2+ (33 – 50 mm), 3+ (51 – 60 mm), 4+ (61 – 70 mm), and recruited (71+ mm) ***Haliotis roei*** in the Area 7 fishery.

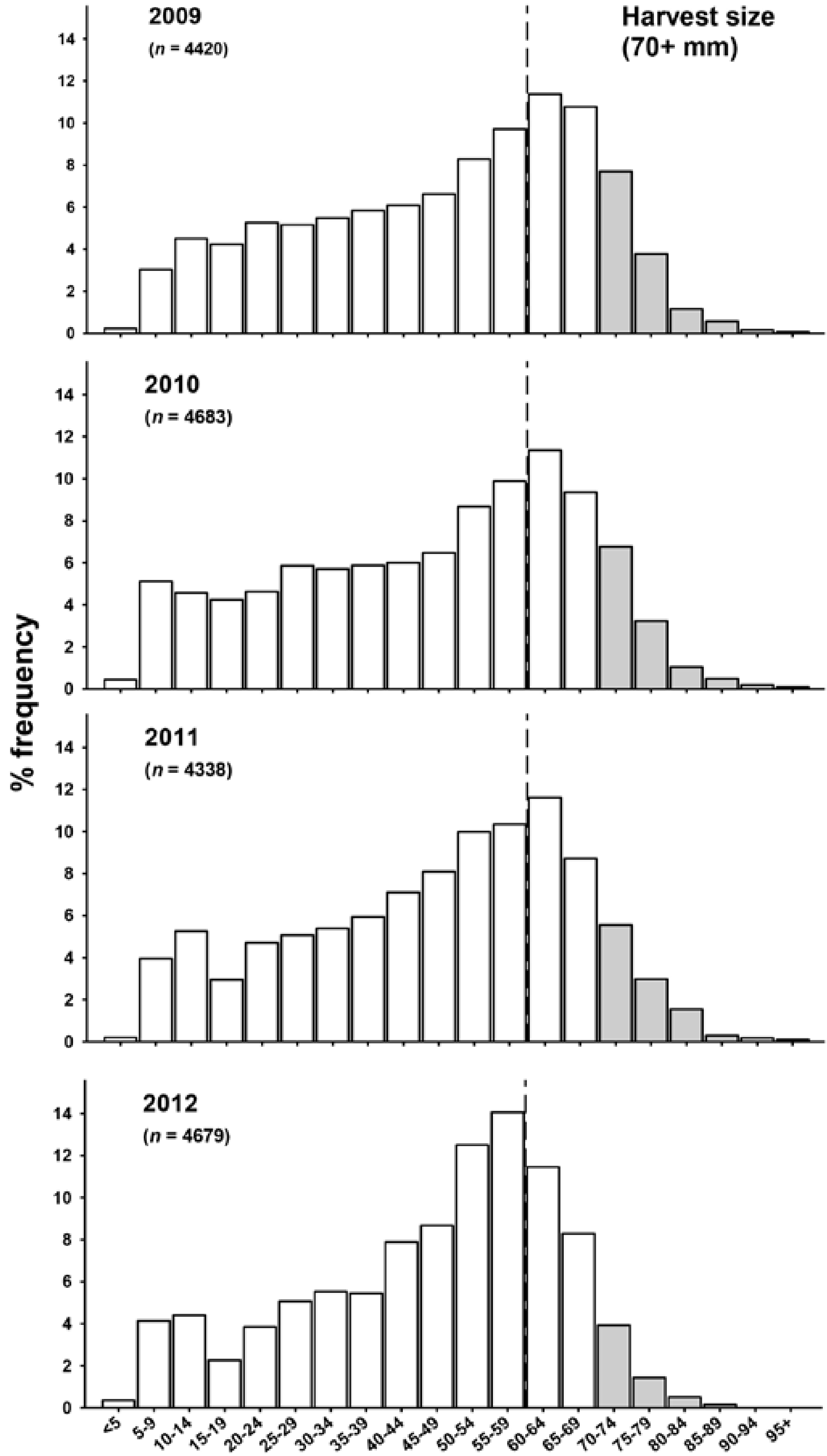


Figure 38. Size-frequency (mm) of ***Haliotis roei*** in the Peth fishery from 2006 to 2012. Shaded areas indicated size targeted by the fishery. Dotted line is the legal minimum length (60 mm).

6.3.2 Predicting future Haliotis roei stock densities

Between 2001 and 2010, density of *Haliotis roei* recruits (≥71 mm or 5+ age) on the reef platform was predicted by density of 1+ animals, 4 years earlier with a model fit (r^2) of 0.85 (Figure 39). There was also a significant correlation of 1+ density with standardised CPUE of the commercial fishery (r = 0.75: p = 0.05), except this occurred at a 6 year lag, not a 4 year lag. The commercial fishery only targets larger animals, primarily greater than 75 mm, hence it is feasible that their target age--class is primarily 7+ year old animals, which would explain the greater time-lag for the correlation. This area of research needs further investigation.

The density of the ≥71 mm size class in 2011 and 2012 was not predicted well by this model, and these years stand out as clear anomalies (Figure 39). The reasons for this are not ascertained as yet, however the main hypothesis is mortality of larger individuals caused by elevated water temperatures and associated deoxygenation experienced during the marine heat wave of the 2010/11 (Pearce et al., 2011) and 11/12 austral summers, and sub-lethal effects of elevated temperatures on growth, i.e. a slowing or cessation of growth. Investigations are continuing.

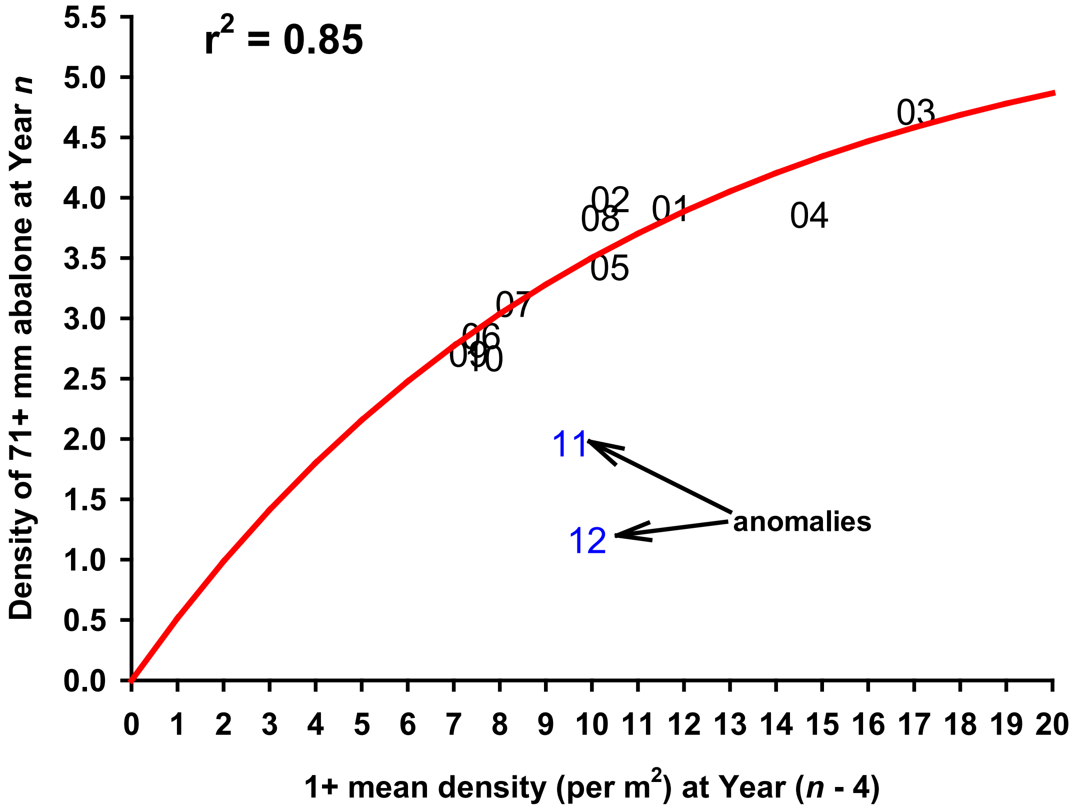


Figure 39. Predictive equation for density of harvest sized ***Haliotis roei*** (≥ 71 mm) on reef platforms only (Habitat 1 & 2) in Year ***n***, as a function of density of age 1+ animals, lagged by 4 years (Year ***n*** - 4). Equation is ***y*** = 5.014[1 – exp(-0.114 ***x***)]. Symbols are year ***n***, e.g. 08 = 2008.

7.0 Performance Indicators and TACC Assessment

7.1 Methodology

Development of performance indicators and TACC decision rules in the Western Australian abalone fishery is an ongoing process. Progress to date includes indicators based on commercial fishery catch rates (Hart et al., 2009), and research into harvest rates (section 7.3.1). The general protocol is to vary the allowable catch up or down around a sustainable long-term TACC (defined in Table 21), based on the relationship between the performance indicators and the biological reference points (Figure 40). The adjustment of TACC (both quantity and direction) is made according to pre-defined decision rules (Table 22). Colour codes denoting the decision rules for TACC adjustment in Western Australia's commercial abalone fisheries are summarised in Table 23.

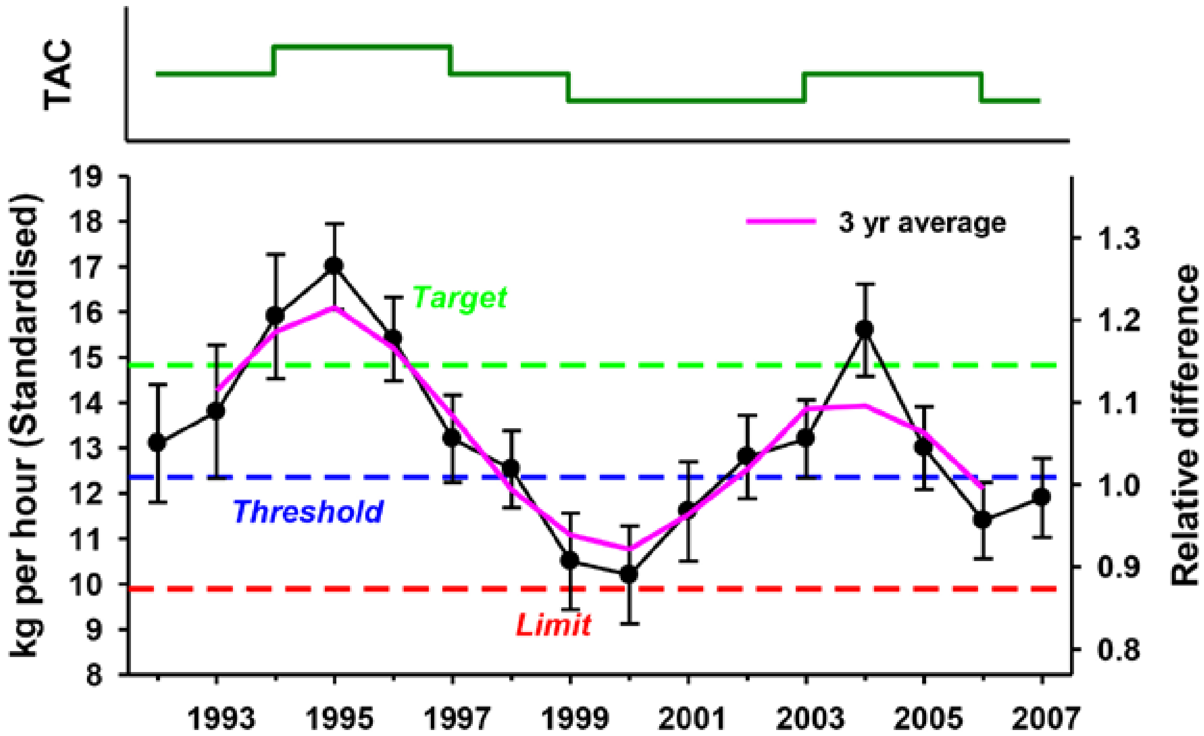


Figure 40. Example of performance indicator using a 3-year moving average (pink line) and biological reference points (Target, Limit, Threshold) for a hypothetical abalone fishery, and a schematic of how TACC would vary over time. Yearly data are standardised CPUE (± 95% CLs), and relative differences (to the threshold BRP) are on the right axis.

Table 21. Biological Reference Points (BRPs) and sustainable TACCs for management areas and species in the Western Australian abalone fisheries. The values of BRP relative to the Threshold level set at 1 are shown in brackets)

Area	Species	Threshold Reference Year	Sustainable TACC (t) 2011	Biological Reference Points		
				Threshold Value* (kg/hr)	Limit value (20% below Threshold)	Target value (20% above Threshold
2	*H. laevigata*	2005	30.0[#]	11.87 (1.0)	9.49 (0.8)	14.24 (1.2)
3	*H. laevigata*	2004	35.0	12.18 (1.0)	9.74 (0.8)	14.62 (1.2)
2	*H. roei*	1995	19.8[@]	25.07 (1.0)	20.05 (0.8)	30.08 (1.2)
5	*H. roei*	1993	20.0	22.19 (1.0)	17.75 (0.8)	26.62 (1.2)
6	*H. roei*	1993	12.0	21.93 (1.0)	17.54 (0.8)	26.31 (1.2)
7	*H. roei*	1998	36.0	35.80 (1.0)	28.64 (0.8)	42.96 (1.2)
8	*H. roei*	1998	0.0**	-	-	-

[#] *H. laevigata* TACC in meat weight;

[@] *H. roei* TACC in whole weight

* Current threshold value (as of February 2012), however will vary with future updates of the SCPUE model, and new values will be reported each year.

** Area 8 closed indefinitely due to environmentally induced mass mortality (Pearce et. al., 2011)

Table 22. Management decision rules in relation to defined biological reference points (BRPs) for Western Australian Abalone Fisheries. See Figure 40 for the relationship between the performance indicator and biological reference points.

BRPs	Description	Decision Rule
Target	20% above Threshold	Minimum of 10% TACC increase if PI is above the target BRP
Threshold	upper end of the bottom 30% of the historical variability in the PI	a) Maintain TACC at long-term sustainable level if PI is above threshold and below target BRP b) 10% TACC decrease (below long-term sustainable level) if PI is below threshold and above limit BRP
Limit	20% below Threshold	Minimum of 30% TACC decrease if PI is below limit BRP

Table 23. TACC decision rules for Western Australian Abalone Fisheries. These operate in relation to defined performance indicators (see Table 24).

Colour Code	TACC Decision
	Minimum of 30% TACC decrease
	10% TACC decrease below long-term sustainable levels
	Maintain TACC at long-term sustainable levels
	Minimum of 10% TACC increase above long-term sustainable levels

7.2 2012/13 TACC Assessments

The 2012/13 TACC decisions using the current decision rule framework are summarised in Table 24. The performance indicator (PI) was above the threshold value in all fisheries that were assessed. Using the Area 2 greenlip fishery as an example of the process, Table 24 shows that the performance indicator (PI) had a value of 13.6, which was above the threshold value (11.87). Consequently the decision rule concluded a blue result, i.e. that TACC should be set at the long-term sustainable level (30.0 t). After industry consultation on stock status, and examination of the outcome of new harvest control rule that incorporate egg conservation targets achieved though fishing mortality indicators (section 7.3.2), a precautionary approach was adopted for Area 2 and TACC maintained at 28.8 t. A graphical summary of PI trends in all fisheries is provided in section 11.1.

The basis for setting of brownlip abalone quota is less formalised than greenlip abalone, and is currently under review as part of an external project (see section 4.5.3). The procedure at present is based on an examination of historical trends in catch and meat weight, and feedback from industry. Quota reductions were taken in the 2011/12 season due to concerns over declining meat weights (see Figure 19).

The decision rule framework provides a level of certainty to the TACC process; in particular what changes could be expected under different scenarios. However the final decision on quotas is not entirely based on its outcomes, as the data used in the decision rule is not without uncertainty. Stakeholder input into the assessment process is an integral part of the decision-making process.

7.2.1 Fishery closures

The Area 8 roe's abalone commercial fishery (see Figure 2), and the northern section of the recreational abalone fishery (see Figure 3) have been closed under a section 43 order and no TACC is recommended for 2012/13. In the summer of 2010/11, the abalone stocks in Kalbarri region suffered a devastating mortality as result of a sustained period of elevated water temperatures, now being termed the "2011 marine heatwave" off Western Australia (Pearce et. al., 2011). Both commercial and recreational abalone fisheries have been closed to protect any remaining animals and promote natural recovery. The severe extent of the mortality (>99.9% in most places) means that natural recovery is unlikely within the next 10 years. A research project has been funded to evaluate the possibility of assisted recovery using restocking techniques (see section 4.5.2).

Table 24. Performance Indicator (PI), threshold reference point (Threshold), decision rule (Result), and TACC for the 2012/13 fishing year. Colour codes are summarised in Table 23.

Species	Area	PI	Threshold	Result	Sustainable TACC (t)	11/12 TACC	12/13 TACC
Greenlip	2	13.60	11.87		30.0	28.8	28.8
	3	12.87	12.18		35.0	35.0	35.0
Roe's	2	25.69	25.07		19.8	19.8	19.8
	5	24.98	22.19		20.0	20.0	20.0
	6	23.11	21.93		12.0	12.0	12.0
	7	37.76	35.80		36.0	36.0	36.0
	8	N/a			0		
Brownlip	2	N/a				7.9	7.2
	3	N/a				8.0	7.2

7.3 Future developments

7.3.1 Egg Production and Fishing Mortality performance measures

Using an egg production model (PREP) to examine fishing mortality and egg production levels in populations of varying productivity, Shepherd and Baker (1998) showed that the amount of egg production necessary to maintain sustainable spawning stock levels is negatively related to population productivity. Smaller populations require a higher % of virgin (no fishing) egg production to be conserved to ensure sustainable fishing, which translates to a lower fishing mortality. Consequently, the PREP model was used to develop preliminary fishing mortality reference points sufficient to maintain sustainable egg production in Western Australia's greenlip abalone fisheries.

To illustrate the process, virgin egg conservation levels of 40% (Limit BRP), 45% (Threshold BRP), and 50% (Target BRP) were investigated in a hypothetical fishery with a LML of 140 mm (Figure 41). These egg conservation targets resulted in F reference points of 0.7 (Limit), 0.53 (Threshold) and 0.4 (Target). Model assumptions for the egg conservation estimates are shown in the figure caption (Figure 41).

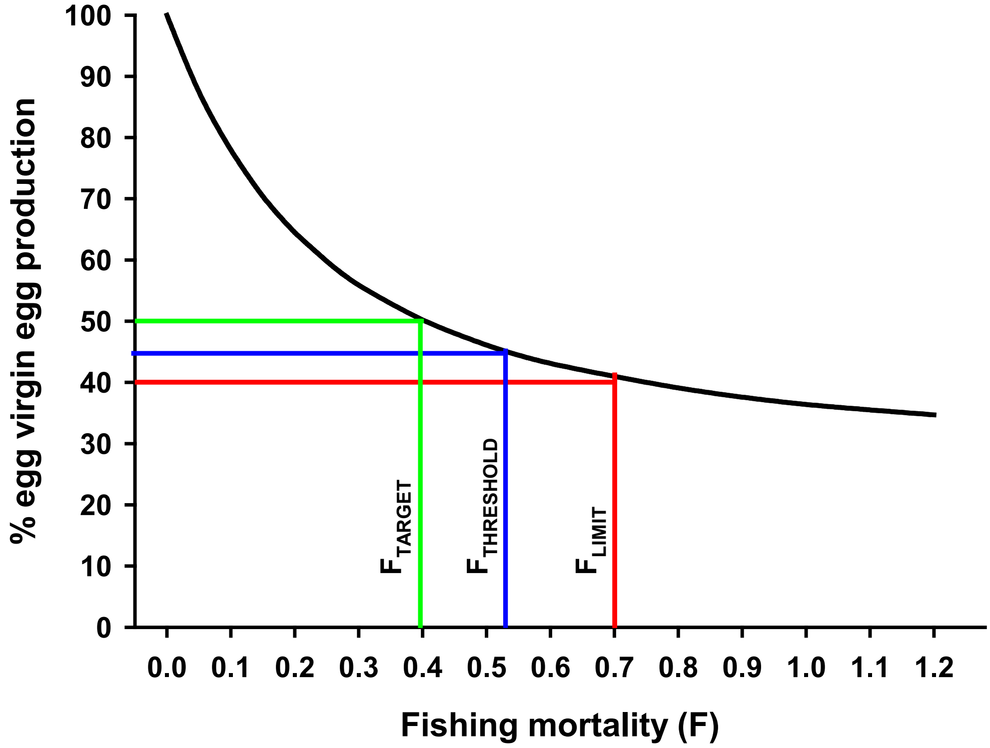


Figure 41. Relationship between fishing mortality (F) and % of virgin egg production conserved for a hypothetical greenlip abalone population fished at legal minimum length of 140 mm, under the following growth parameters (L∞=179 mm, K = 0.25). The model assumes constant recruitment, natural mortality (***M***) according to $\boldsymbol{M}_L = \boldsymbol{M}_1/\boldsymbol{L}$ (were L is length in cm, and $\boldsymbol{M}_L$ is 2.7 – Hart et. al., in press c), and length-fecundity parameters from Cape Arid (Table 4).

Fishing mortality reference points for Western Australian abalone fisheries were estimated using the PREP model, and are summarised in Table 25. Preliminary egg production targets in the south coast (Area 2 and Area 3) greenlip fisheries are more conservative than in the West Coast fishery. This is because the south coast fishery is made up of many smaller populations, i.e. the average catch (over 20 years) from each 10 x 10 mile spatial recording grid is 1.2 t (meat weight), compared to 5.7 t on the west coast. Smaller populations require a higher level of egg conservation (Shepherd and Baker, 1998). Ultimately the egg conservation target is a judgement on the level of risk a particular population can handle, or that fishery management is willing to take. Theoretical studies have indicated that egg conservation targets of 35 – 40% of virgin will be sufficient protection of the breeding stock for most, but not all, fisheries (Zhoue et al., 2012; Clark 2002).

Table 25. Preliminary fishing mortality (F) reference points (limit, threshold, target) necessary to achieve sustainable levels of egg production in Western Australian greenlip abalone fisheries.

Area	BRPs	Egg production target (% of virgin egg production)	Modelled size-at-first harvest (mm)	F#
South Coast (Area 2)	F_{Limit}	40	145	0.57
	$F_{Threshold}$	45	145	0.42
	F_{Target}	50	145	0.33
South Coast (Area 3)	F_{Limit}	40	147	0.77
	$F_{Threshold}$	45	147	0.54
	F_{Target}	50	147	0.40
Augusta (West Coast)	F_{Limit}	35	150	0.52
	$F_{Threshold}$	40	150	0.40
	F_{Target}	45	150	0.33

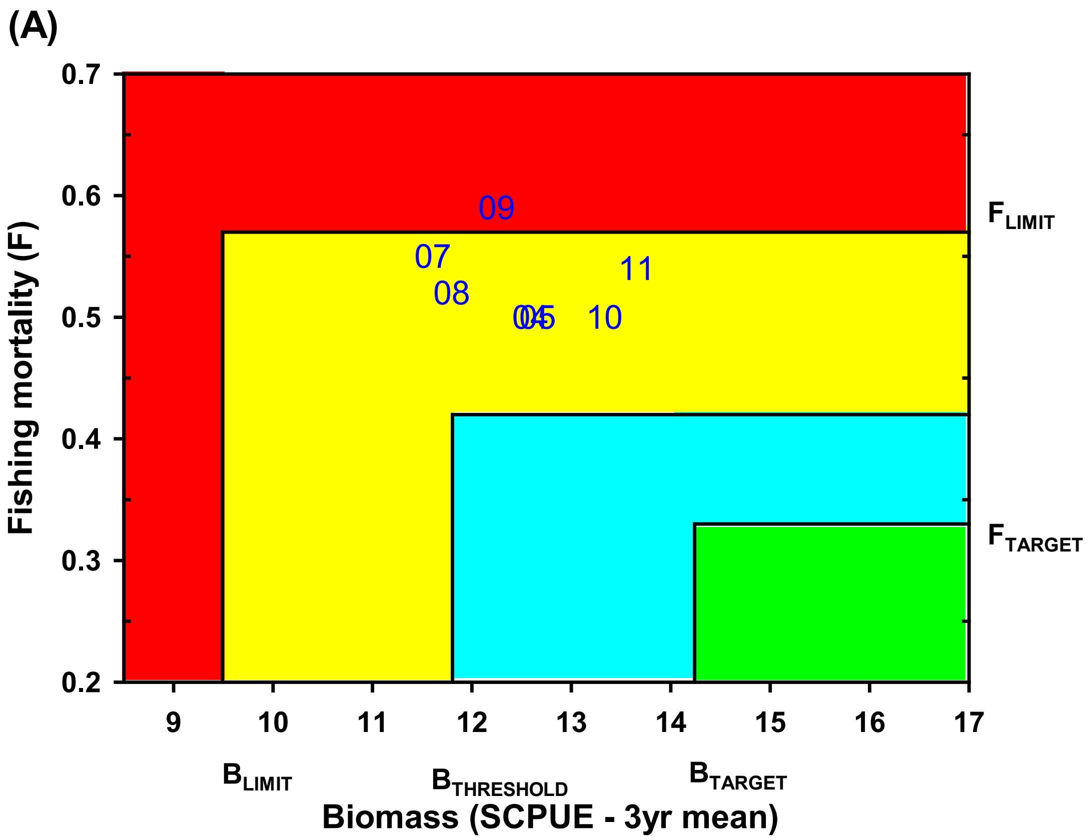
Estimates of F are outputs of the PREP model (see section 4.4.3 for a description).

7.3.2 Harvest Control Rule

A new decision rule for TACC assessment was tested for the 2012/13 TACC year on the Area 2 and Area 3 greenlip fisheries. The decision rule incorporates both biomass (SCPUE) and harvest rate (F) reference points. The SCPUE reference points are given in Table 21, the F reference points are in Table 25, and the decision matrix is summarised in Table 23.

According to the proposed new rule, the current status of the stocks in both the Area 2 and Area 3 fishery is in the yellow zone (Figure 42). While the relative biomass levels are above the threshold levels in both areas, the fishing mortality indicator is below the threshold level in both areas. Therefore the TACC should be set at 10% below the long-term sustainable levels for both Area 2 and Area 3 (Table 24).

This rule is sensitive to three factors. 1) the growth model used to determine total mortality (Z) via catch curve analysis (see section 4.4.2); 2) estimates of natural mortality (M), and 3) choice of egg conservation reference point (e.g. 45% vs 40% Threshold). Further testing is required to ensure robustness of this control rule before full implementation. It is however, a more flexible rule, and may be more suited to situations where alternative harvest strategies are being proposed.



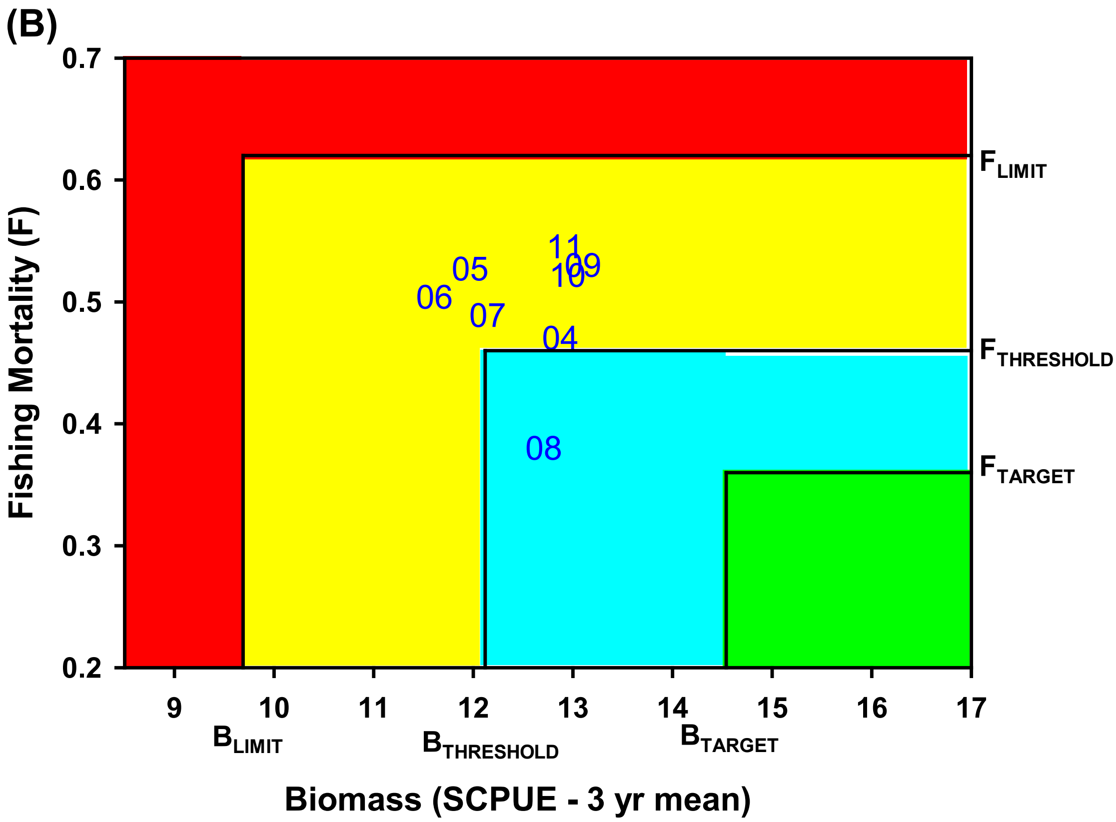


Figure 42. Draft harvest control rules for the (A) Area 2, and (B) Area 3 greenlip fisheries based on the relationship between biomass (SCPUE) and fishing mortality (F) reference points (BRPs). The current status of the fishery is shown by the blue symbols (05 = 2005, 08 = 2008 etc.). TACC decision pertaining to the colour codes are summarised in Table 23.

8.0 General Discussion

This report presents the first comprehensive summary of Western Australian abalone fisheries. Many of the biological parameters have not previously been published and represent a significant body of work over a number of years. Similarly, the trend data from fishery independent surveys in both the greenlip and roe's abalone fisheries have not previously been available and some valuable findings have come to light. For example, surveys of the Perth metropolitan roe's abalone stock have resulted in a predictive model for stock abundance. In the case of greenlip abalone, fishery independent surveys suggest that stock levels have been stable over the past 3 – 5 years.

The research into stunted greenlip stocks has clearly established the presence of 'stunting' in this species, both from an individual and a stock perspective. The correlation of growth and population survey data has enabled a practical definition of 'stunting' to be applied in field surveys, and this has assisted the development of management strategies for these stocks. However, the research has also shown that growth and productivity of all greenlip stocks will lie somewhere in a large continuum from the very stunted, where maximum size reached is less than 120 mm, to the fast growing areas, where maximum size reached is greater than 180 mm. Size-at-maturity is similarly variable, ranging from 70 to 100 mm shell length.

Yield-per-recruit and egg-per-recruit analyses demonstrated that the Area 2 fisheries were optimally exploited with respect to egg conservation targets, however the Area 3 fisheries would benefit from minor reductions in minimum size of fishing. Further work is needed on these models, looking at effects of changes in growth, natural mortality, and fecundity parameters and also examining the value of different size abalone.

Environmental influences on abalone fisheries abundance continue to be important. In the most severe case, the Area 8 roe's abalone fishery has been wiped out by a single event of elevated water temperatures and associated deoxygenation of shallow waters. Further to this there may have been sub-lethal effects in the Area 7 (Perth metro) roe's abalone fisheries, with predicted stock levels of large animals (≥71 mm) not been achieved. Investigations are continuing and early signs suggest that the TACC and recreational catch quota for Area 7 may not be achieved in the 2012/13 season. Despite this strong recruitment is predicted in the Area 7 fishery within the next year or two, and a full recovery expected.

Development of performance indicators and TACC decision rules for Western Australian abalone fisheries is a major objective achieved with this assessment. These rules have established the appropriate biological reference points for both stock biomass, and fishing mortality. The reference points rely on fishery-independent and fishery-dependent survey information to ensure stock levels are high enough for sustainable fishing. Use of decision rules facilitates a responsive and flexible management regime capable of accommodating events such as altering size-at-harvest, or increasing recruitment with a stock enhancement program.

Overall, the assessments show that stock levels are currently stable and fishing is sustainable. The economic performance of any changes in fishing or management regime should also be considered. The advantage of taking this adaptive management approach is that adequate performance indicators and TACC decision rules are now in place. These will monitor the response of the fishery to any changes in fishing or management regime and adjust catch quotas accordingly.

9.0 Recommendations for future research

- Investigation of the basic biology of brownlip abalone, such as studies of growth and natural mortality.
- Further analysis on yield and egg-per recruit models to optimise growth, natural mortality, and fecundity parameters
- Examine catch variability in the Perth recreational roe's ablone fishery as a function of individual 'weather condition' factors such as swell, tide, wind, rainfall, and cloud cover.
- Development of a population dynamics models for Western Australian abalone fisheries that enable formal evaluations of appropriate harvest levels.
- Bioeconomic evaluations of fishing policy, including economic yield-per-recruit, and assessment of increases in NPV (Net Present Value) under different harvest scenarios.
- Develop catch predictions
- Consider environmental factors affecting recruitment and evaluate the effects of climate change.

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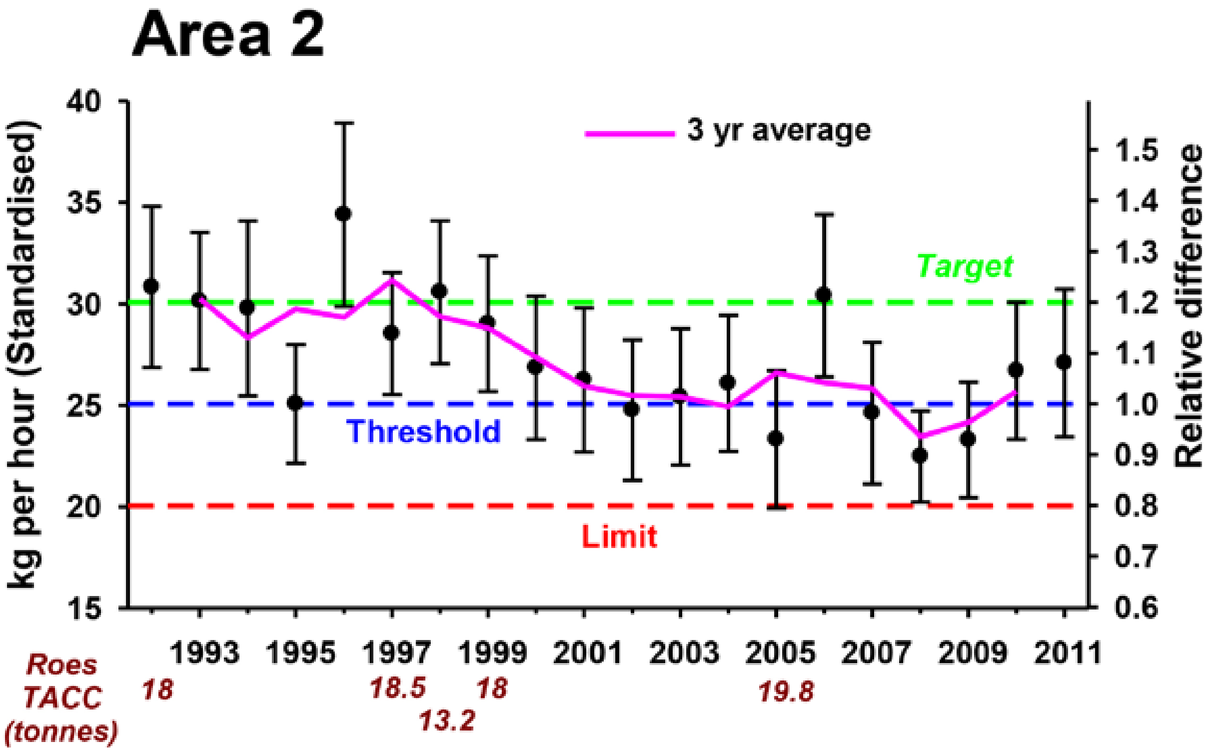
11.0 Appendices

11.1 Performance indicators and biological reference points for each management area and species

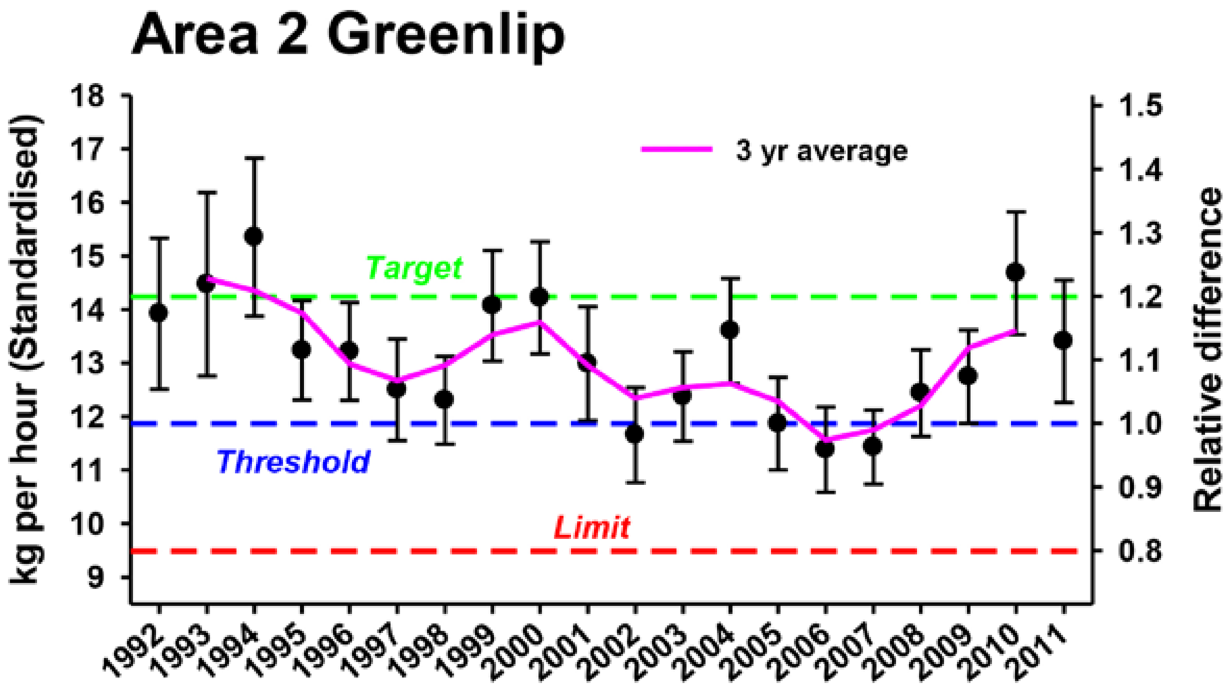
11.1.1 Area 1 Greenlip and Roe's abalone fishery

Area 1 is remote and inaccessible, being principally stationed below the Nullabor Cliffs (see Figs. 2 & 3) and fishing is generally of an exploratory nature. Consequently, the historical time series of catch per unit effort for both Greenlip and Roe's abalone was too variable to be used to develop PI's. TAC assessment and management in this region will continue to be based largely on raw data trends and feedback from industry divers as to their own harvest plans.

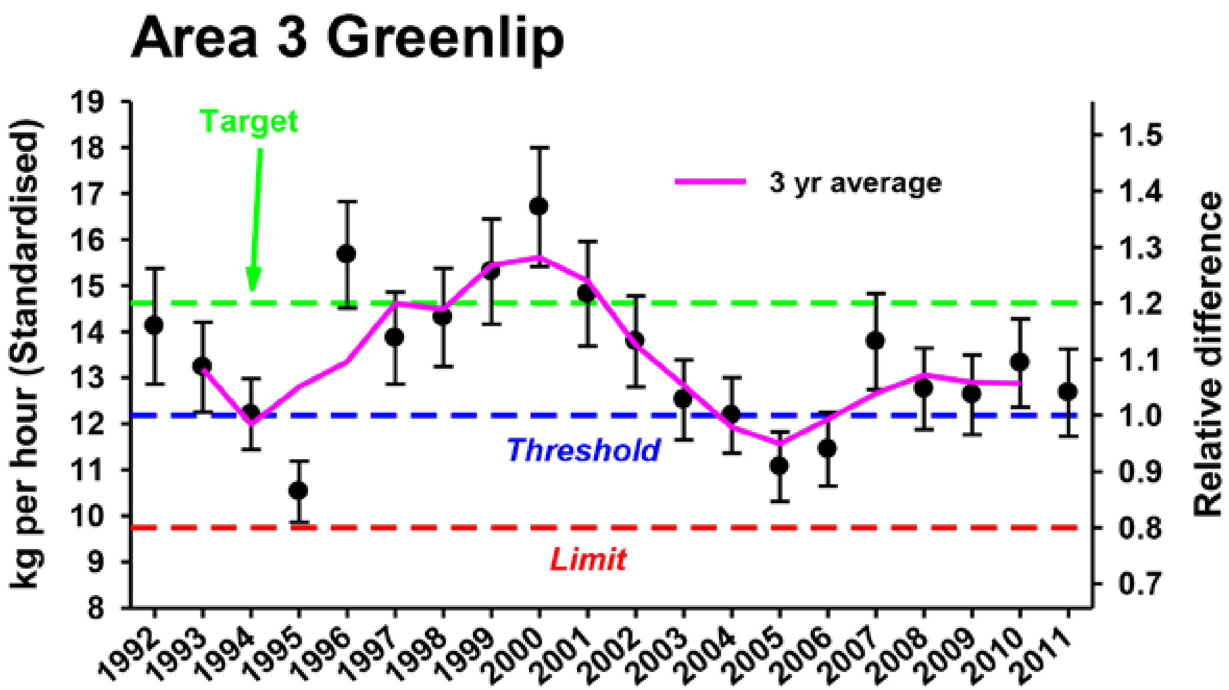
11.1.2 Area 2 Roe's abalone fishery



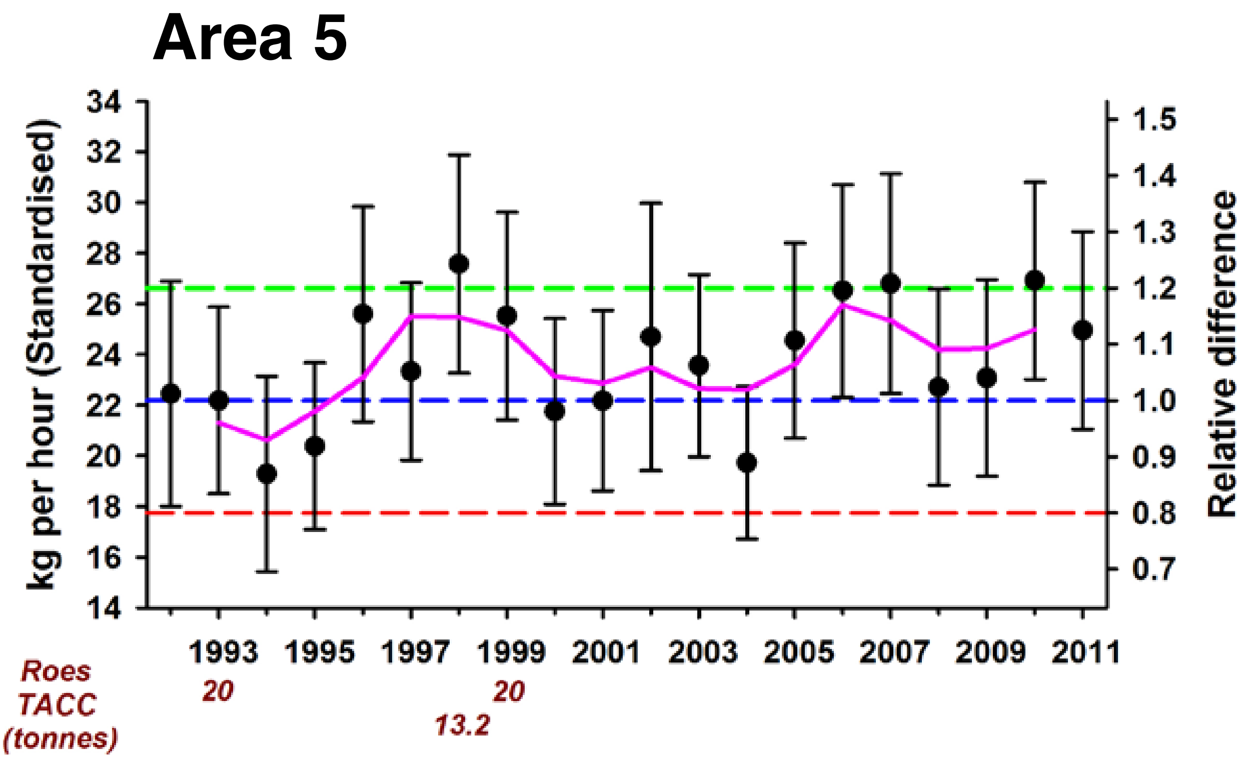
11.1.3 Area 2 Greenlip abalone fishery



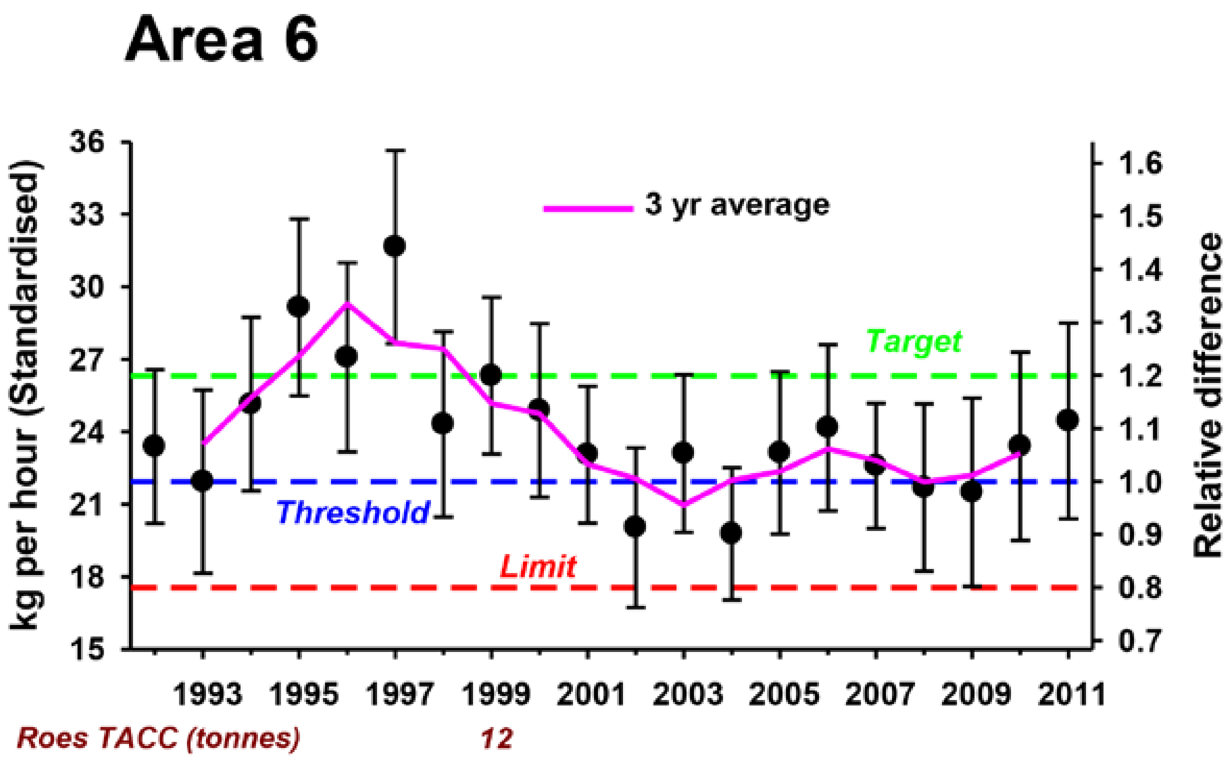
11.1.4 Area 3 Greenlip abalone fishery



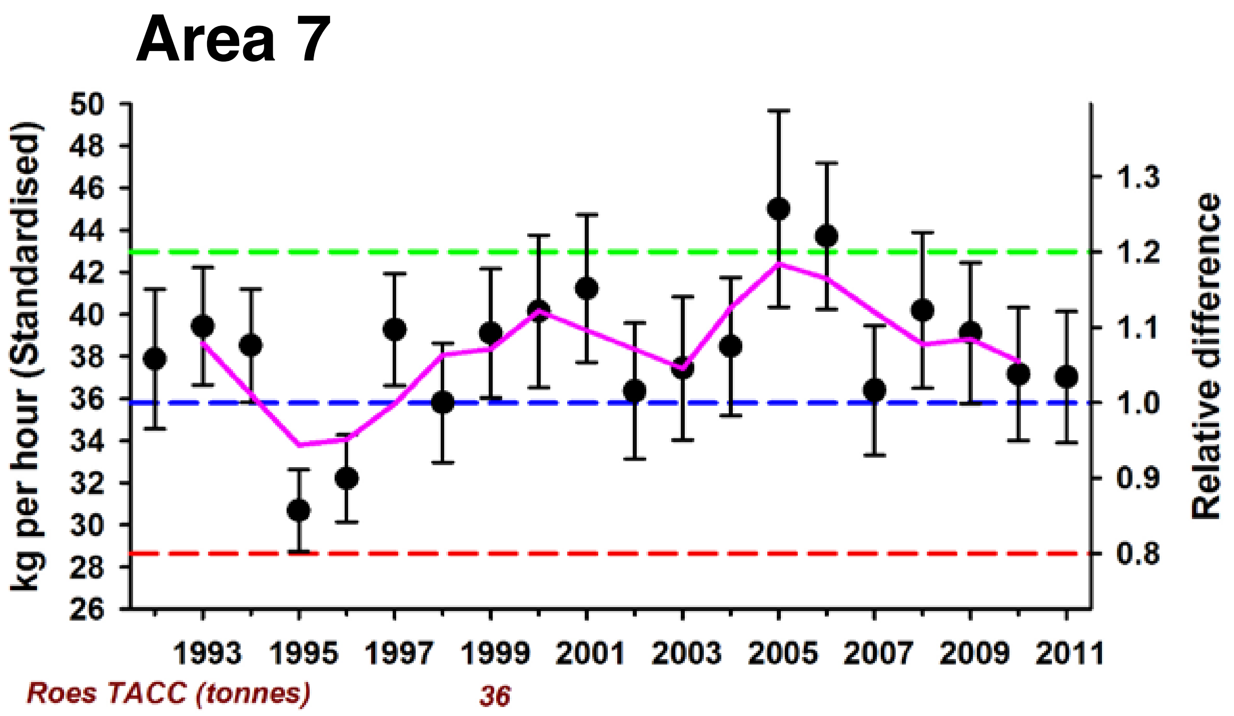
11.1.5 Area 5 Roe's abalone fishery



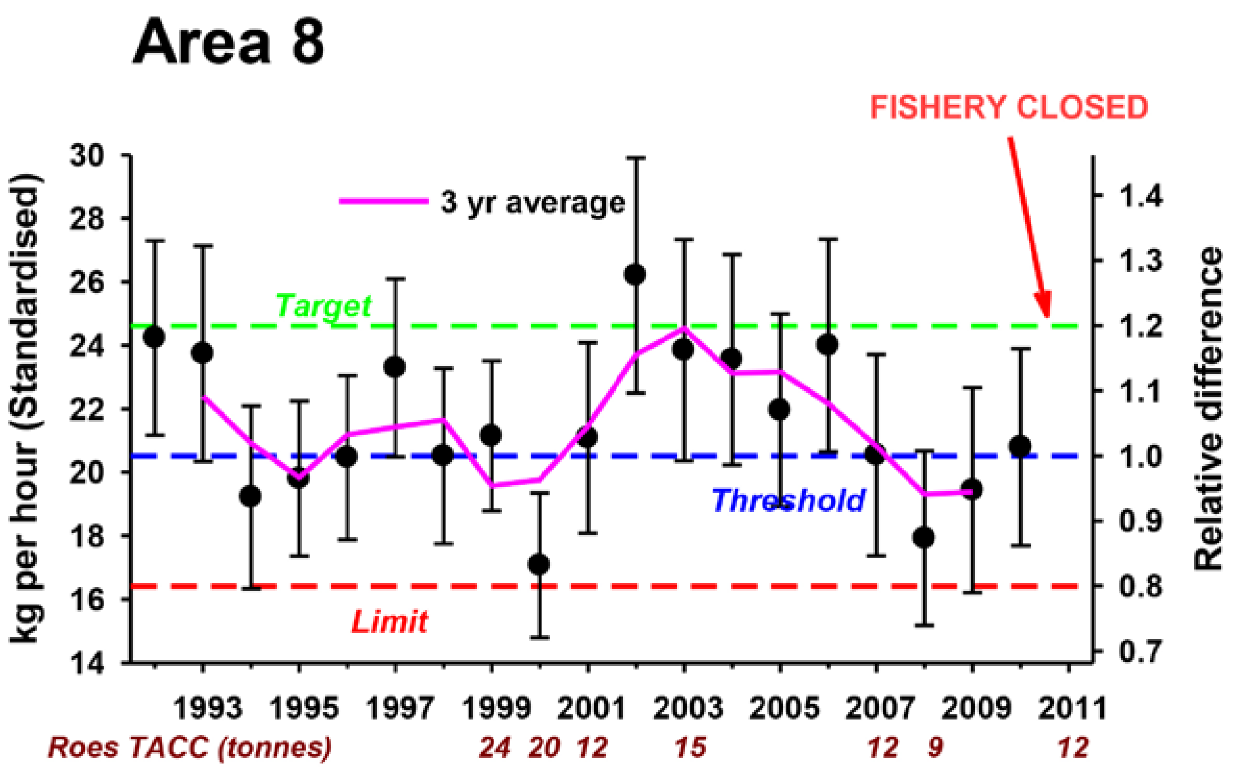
11.1.6 Area 6 Roe's abalone fishery



11.1.7 Area 7 Roe's abalone fishery

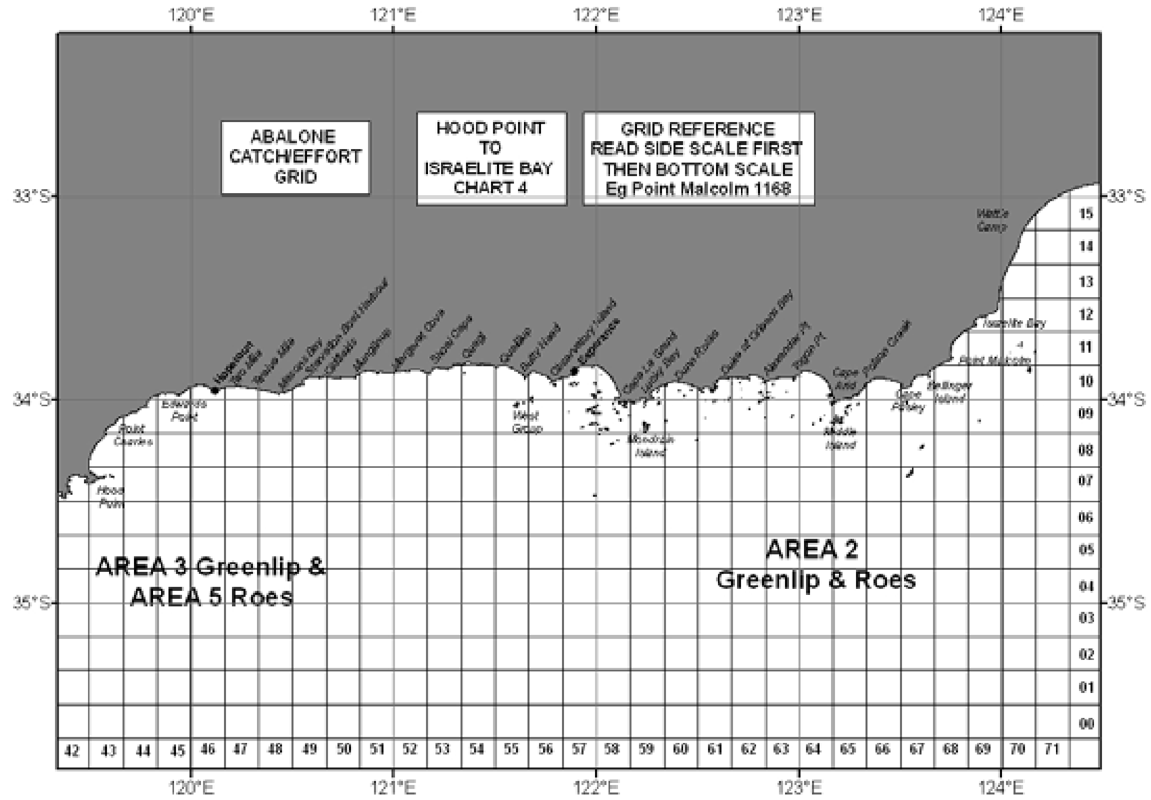


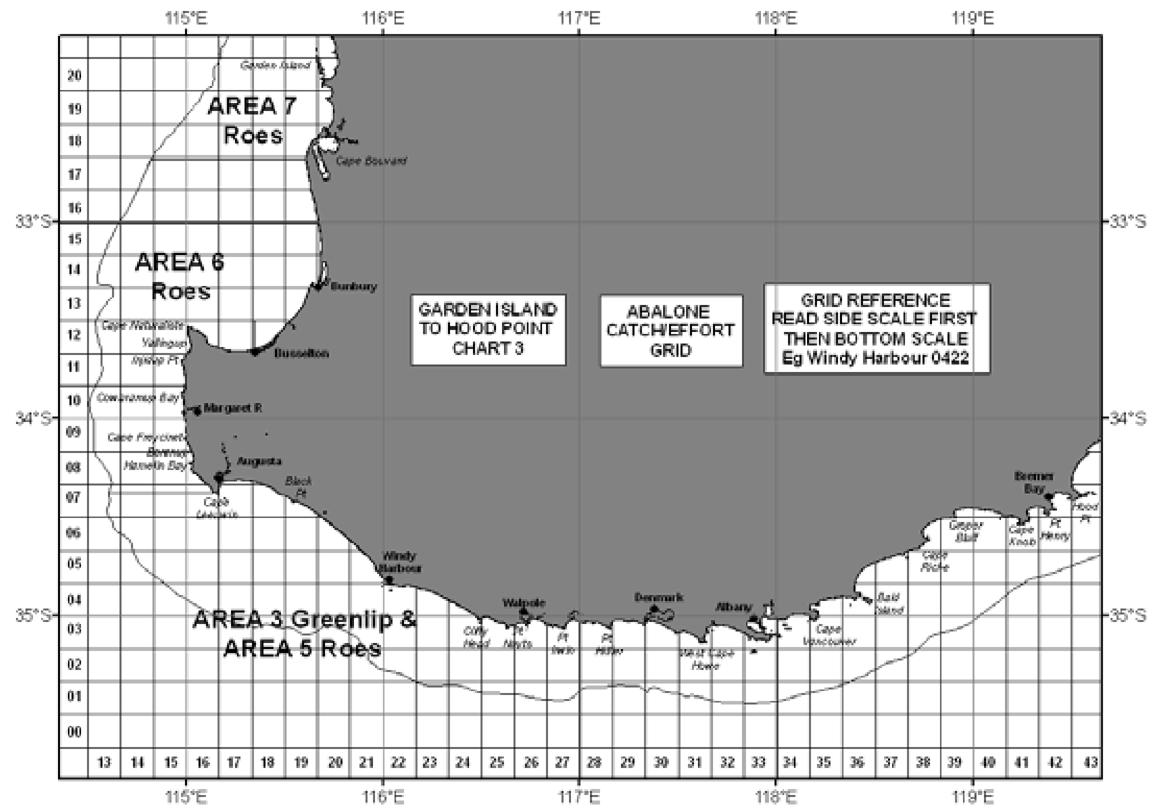
11.1.8 Area 8 Roe's abalone fishery

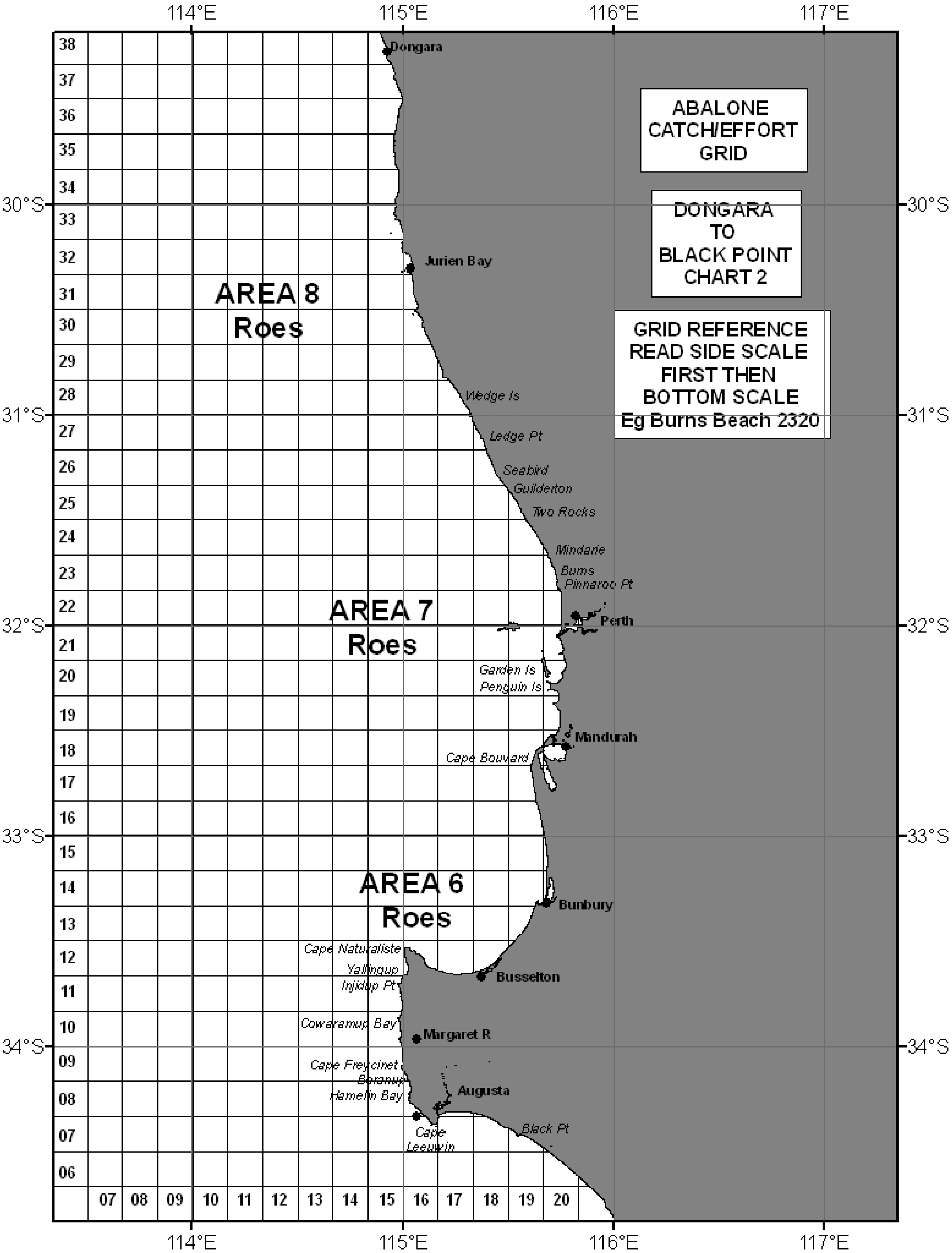


11.2 Catch and Effort maps

These maps show spatial scale (10 x 10 nautical mile grids) at which catch and effort information is recorded for the commercial abalone fishery.







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ABALONE CATCH/EFFORT GRID
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AREA 7 Roes
AREA 6 Roes
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Jurien Bay
Wedge Is
Ledge Pt
Seabird
Guilderton
Two Rocks
Mindarie
Burns
Pinnaroo Pt
Perth
Garden Is
Penguin Is
Mandurah
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Bunbury
Cape Naturaliste
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Injidup Pt
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Margaret R
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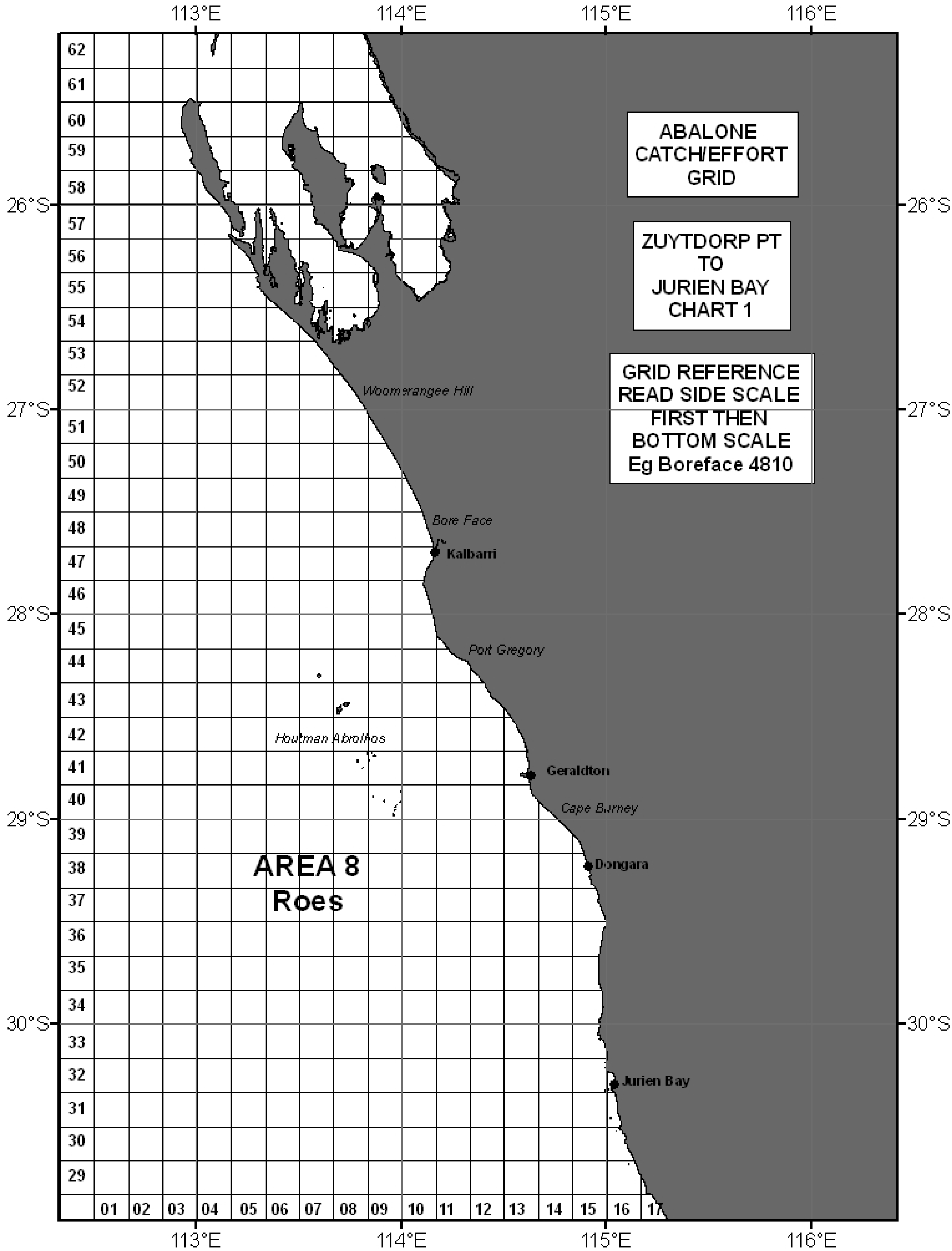
07 08 09 10 11 12 13 14 15 16 17 18 19 20


ABALONE CATCH/EFFORT GRID
ZUYTDORP PT TO JURIEN BAY CHART 1
GRID REFERENCE READ SIDE SCALE FIRST THEN BOTTOM SCALE Eg Boreface 4810
AREA 8 Roes
113°E
114°E
115°E
116°E
26°S
27°S
28°S
29°S
30°S
Woomerangee Hill
Bore Face
Kalbarri
Port Gregory
Houtman Abrolhos
Geraldton
Cape Burney
Dongara
Jurien Bay
62
61
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01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17