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Demographic performance of Brownlip abalone: exploration of wild and cultured harvest potential

FRDC Project No. **2012/016**

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Abbreviations

AIAWA	Abalone Industry Association of Western Australia
AIC	Akaike’s Information Criterion statistic
AMF	Abalone Managed Fishery
CDR	Catch Disposal Record
CJS	Cormack-Jolly-Seber Model
DOF	Department of Fisheries Western Australia
EPR	Eggs Per Recruit
FRDC	Fisheries Research and Development Corporation
GOF	Goodness of Fit
GPS	Global Positioning System
ITQ	Individual Transferable Quota
LML	Legal Minimum Length
NLL	Negative Log-Likelihood
NSW	New South Wales
QAICc	Quasi-likelihood adjusted form of the Akaike’s Information Criterion statistic
SA	South Australia
SCPUE	Standardised Catch Per Unit Effort
SRR	Stock-Recruitment Relationship
SSBA	Surface Supply Breathing Apparatus
SSBR	Spawning Stock Biomass Per Recruit
SPR	Spawning Potential Ratio
TAC	Total Allowable Catch
TACC	Total Allowable Commercial Catch
VIF	Variance Inflation Factor
WA	Western Australia
YPR	Yield Per Recruit

Executive Summary

This research provides the most comprehensive evaluation of Brownlip abalone (*Haliotis conicopora*) biology and fisheries assessment to date, thereby laying a solid foundation for future management of the Brownlip abalone fishery in Western Australia (WA). For wild populations, it has provided the most reliable estimates of natural and fishing mortality, size composition and the first to model growth throughout all stages of life. The development of a per recruit model that was extended to incorporate a stock-recruitment relationship, and a preliminary, length-based integrated model have been able to effectively evaluate the current stock status of the Brownlip abalone fishery. Influential commercial fishing practices have also been identified, such as changes in selectivity and catchability over time and their effect on the Brownlip abalone population in WA. The project has also demonstrated the species ability to be commercially produced in aquaculture.

In the WA Greenlip/Brownlip abalone fishery, catches are dominated by Greenlip abalone with Brownlip abalone deemed only a “by-product” species until 1999, when a fixed, total allowable commercial catch (TACC) was introduced. Brownlip abalone catches have become an increasingly important component of the fishery and in the last few years have been around 34 to 36 t whole weight (~$1.2 million), which comprises a small but valuable component of the total fishery. The limited attention towards Brownlip abalone in the past has meant that until now, research on this species was very limited. Given the growing importance of Brownlip abalone to the fishery, it was recognised that greater research directed towards understanding its biology and stock status in the wild, was essential for the ecological sustainable development of the fishery. The overall aim of this project, therefore, was to address these knowledge gaps and thereby improve the management of the WA Brownlip abalone fishery.

To improve the understanding of Brownlip abalone, several avenues of experimentation and assessment were undertaken. These included a tag-recapture study on wild populations, assessing Brownlip abalone in aquaculture using various system designs, developing models to estimate growth, mortality and spawning biomass, and the development of a preliminary integrated length-based model. Through these assessments the implications of adopting different fishing and management practices were able to be explored. These not only addressed the projects objectives but built an overall picture of Brownlip abalone position in the environment, fishery and aquaculture within WA.

The tag-recapture study conducted on wild Brownlip abalone stocks established 19 sites and tagged 1171 individuals across the WA Abalone Managed Fishery (AMF). The size distribution of Brownlip abalone sampled in the tag-recapture study showed a high frequency of animals captured over 150 mm shell length, indicating that the large, legal size adults formed the dominant component of the tag-recapture survey. Conversely, as small Brownlip abalone are extremely cryptic, very few abalone <100 mm shell length and none below 50 mm were tagged. The lack of small abalone surveyed presents problems when trying to assess growth, let alone use juvenile abundance as a predictive stock analysis. Estimates of survival probability, derived using tag-recapture data (across the 19 sites) and models within the MARK software program, ranged from 0.6-0.9 y^{-1} for the 5 sub-areas. The point estimates of survival resulting from a time constant model ($\phi_{.}p_{.}$), which could be translated into estimates of mortality, produced mortality values ranging from 0.12-0.39 y^{-1} and are the first mortality estimates for this species.

Brownlip abalone were successfully spawned and reared to market size in WA commercial aquaculture systems with only slight alterations to current grow-out practices used for Greenlip abalone. The growth and mortality of Brownlip abalone was assessed in the current systems used in Australian abalone aquaculture. Baseline growth rates indicated the current nursery system was suitable for the production of juveniles, while the concrete slab tanks used in the grow-out system were ineffective. A deeper tank with hides reduced mortality and clustering of animals, and improved growth as it accommodated the highly cryptic nature of Brownlip abalone. Weaning from natural diets in the nursery to artificial diets in the grow-out system, and the effects of various stocking densities in the grow-out system hide tanks, were both shown to dramatically affect growth rates. Tank design can be considered an important factor in the production of Brownlip abalone through the grow-out stage, and at present the hide tanks either with or without higher water flow are the most appropriate design to be used on a commercial abalone farm.

The Brownlip abalone growth data obtained from the wild tag-recapture study, in combination with growth data on hatchery-reared individuals covered the full size range of this species, enabling growth to be modelled throughout life. Two functions, namely a double logistic model and a Gaussian function provided good fits to the growth increment data. Based on a lower value for Akaike's Information Criterion statistic, the Gaussian function was selected as the most appropriate model for these data. The growth analysis indicated that, by 2, 5 and 10 years of age, on average, individuals are expected to attain lengths of 55, 131 and 162 mm respectively.

Estimates of total mortality derived using a length-based catch curve model with the above growth description and assuming logistic size-related selectivity, ranged from 0.18-0.26 y^{-1} with no temporal trends detected. The analysis did, however, show clear evidence of a decline in mean size at which Brownlip abalone become selected into the fishery. Given the large amount of stock protection in the fishery as Brownlip abalone become fully-selected into fishery at sizes >150 mm, well above the typical size at maturity (120 mm), estimates of fishing mortality (F) for full-selected individuals should not simply be related to standard F-based reference points.

The results of traditional per recruit modelling predicted that, if fishers continue to harvest Brownlip abalone above the current minimum harvest size adopted by industry (150 mm), yield per recruit (YPR) would continue to increase even at extremely high levels of F (up to at least 6.0 y^{-1}), which appears unrealistic. Even if spawning potential ratio (SPR) is included into the per recruit model as a measure to consider impacts of fishing on spawning biomass, standard per recruit analysis still assume constant recruitment. The traditional per recruit model was extended to incorporate a stock-recruitment relationship. The latter model (extended model) indicted that yields would decline when F becomes too high, which appears more realistic. The results of the sensitivity analyses highlighted that

estimates of YPR and SPR were sensitive to different changes in minimum harvest size, natural mortality (M), and the steepness parameter (h) of the stock-recruitment parameter. Further research is required to estimate h for commercially fished abalone species. Based on SPR from the extended per recruit model and taking a precautionary approach by including the uncertainty in h (as low as 0.4), current SPR of Brownlip abalone is estimated to be above a limit (0.2) and around a target reference level (0.4). In the per recruit model the estimates of F was shown to be below both $F_{\max}$ and $F_{0.1}$, but when looking at the yield results from the extended model and assuming a h of 0.4, the estimate of F was similar to $F_{\max}$ and above $F_{0.1}$. Given that the catch curve and per recruit models (and extended model) assume that at the time of sampling the population was at equilibrium, a level of caution needs to be applied to these estimates. However, these models did appear to have utility for exploring impacts of alternative fishing strategies and management options for the WA Brownlip abalone fishery.

The development of an integrated length-based model was incorporated as an additional objective in the latter stages of the project. The new model adds substantial value to the project and will be of benefit for the future management of the WA Brownlip abalone fishery. The model uses commercial catch, catch rate and length composition data, with growth being modelled in the same manner as described above. The results suggest that the overall stock status of Brownlip abalone is at an adequate level, with the ratio of current spawning biomass relative to the unfished levels being above a target reference level of 0.4 (0.52-0.56). The integrated length-based model results are broadly consistent with those produced using the per recruit model, after extension to incorporate a stock-recruitment relationship. The assessments undertaken also highlighted recent changes to commercial fishing practices including variations to minimum harvest size and a change in efficiency from the use of two rather than one divers per fishing day.

The biological information gained and assessment methods developed for Brownlip abalone will significantly aid the management of the WA Brownlip abalone fishery. The results presented will have implications for future stock assessment research on WA abalone fisheries. The impact of this research will flow on to the commercial fishing industry through the annual setting of the TACC, and provide industry with information on optimising harvest strategies. The approaches developed in this study are highly relevant to assessments of all abalone species (*H. laevigata*, *H. conicopora* and *H. roei*) in WA and their benefits will be incorporated into the management of the AMF.

Keywords

Brownlip abalone, *Haliotis conicopora*, Tag-recapture, Aquaculture, Growth model, Catch curve analysis, Per recruit analysis, Integrated length-based model.

1 Introduction

1.1 Brownlip Abalone Fishery

Abalone fisheries in Australia are hand capture, dive fisheries generally operating in coastal waters off the south-east, south and south-west coast. In Western Australia (WA) the Greenlip/Brownlip abalone (*Haliotis laevigata* and *H. conicopora*) fishery primarily operates on the south coast. Commercial fisheries use surface supply breathing apparatus (SSBA) from small vessels (generally <9 m length) to dive underwater and prise (chip) the abalone of the substrate (reef/rock) using an abalone "iron".

The Greenlip/Brownlip abalone fishery is part of the Abalone Managed Fishery (AMF) and is separated into 4 management areas spanning from the Western Australian/South Australian (SA) border to the Western Australian/Northern Territory Border (Figure 1.1). However, Areas 2 and 3, located between Point Culver and Busselton Jetty, comprise the majority of the commercial fishery in WA. No catch occurs in Area 4 as it is generally considered outside the species range, and minimal catch is taken in Area 1, which is regarded as an exploratory fishery due to the limited abundance of these species and its remote location near the WA/SA border. The two main management areas (Areas 2 and 3) are divided into 9 sub-areas, 5 in Area 2 and 4 in Area 3, which are utilised for smaller spatial scale management and research purposes (Figure 1.2).

Management of the AMF has evolved from simple effort controls to more complex catch controls and spatial management, and is currently managed predominately through output controls in the form of Total Allowable Commercial Catches (TACCs). The TACCs are set annually for each species in each of the 4 management areas, with the fishing season running from the 1st of April to the 31st March of the following year (Hart et al. 2015). Allocation of TACCs to individual licence holders (limited access fishery – 23 licences) is done through Individual Transferable Quotas (ITQs), i.e. the quotas may be transferred between licence holders. The current determination of the overall annual TACC for each species in each area is undertaken through a formal harvest strategy based on the performance indicator of standardised catch per unit effort (SCPUE), reference levels and harvest control rules, designed to ensure sustainable catch levels across the fishery (Hart et al. 2009; DOF 2017).

The catch and effort statistics, used to inform the management process, are provided by commercial fishers on a daily basis via Catch and Disposal Records (CDR), with data recorded on a spatial scale of 10 x 10 nautical mile grids. Although a Legal Minimum Length (LML) of 140 mm shell length for Greenlip/Brownlip abalone is set to manage the harvest size of abalone, the commercial industry self-impose further constraints on the sizes of abalone they catch, and they generally harvest abalone larger than the LML. In the past, specific regions in the fishery have been closed, such as Flinders Bay near Augusta (Figure 1.2), which was regularly closed for periods up to 2 years between 1975 and 1996 due to the vulnerability of the stock (mainly Greenlip abalone) to both commercial and illegal fishing pressures, but through tighter management and policing in recent times closures have been avoided.

The Greenlip/Brownlip abalone fishery on the south coast of WA began in 1970 with catches dominated by Greenlip abalone and only a small by-product of Brownlip abalone. Greenlip abalone catches reached 275 tonne in the second year and then fluctuated between 140 and 275 t during the 1970s and 1980s (Figure 1.3). In 1990, catches had dropped to around 120 t due to a reduction in the TACC, because the original TACC implemented in the fishery was set too high and deemed unsustainable. Since then, catches have fluctuated between 150 and 190 t until 2015, when the catches reduced to 127 t due to a reduction in TACC (Strain et al. in prep. a). Brownlip abalone catches have only been recorded since 1984 when this species started being caught in reasonable amounts (~25 t), and until 1999, this species was still considered as by-product with no fixed TACC (Figure 1.3). Over the years, Brownlip abalone has become an increasingly important component of the AMF (>20%) and since the late 1990's, annual catches have risen by 25% to a peak of just under 40 t (whole weight) in 2008-2010. However, during the past few years (2011-2014) catches have varied around 34 to 36 t until a drop in 2015 to 25 t (Strain et al. in prep. a). The catch of Brownlip abalone is distributed across Areas 2 and 3, but regions of concentrated catch do occur within these two management areas. For example, the highest proportion of catch is taken from the Windy Harbour sub-area in Area 3 which is between Cape Leeuwin and Albany (Figure 1.4).

Given that Brownlip abalone has only constituted a relatively minor component of the AMF, research on the species to date has been minimal (e.g. Wells and Mulvay 1992), to the extent that fundamental biological parameters such as growth and natural mortality are relatively unknown. In contrast, numerous studies have been conducted on Greenlip abalone in both WA and around Australia, including, biological and habitat characterisation, the determination of fishery size and catch limits, stock enhancement as a management tool, genetic analysis, aquaculture production, etc. (e.g. WA, Daume 2007; Hart et al. 2013a; Hart and Strain 2016). The limitations associated with the lack of information on Brownlip abalone habitat, growth and mortality of wild populations has implications for the effective management of the fishery resource.

The Department of Fisheries Western Australian (DOF) and the Abalone Industry Association of Western Australia (AIAWA) have recognised the growing importance of Brownlip abalone to the fishery and identified research into Brownlip abalone biological parameters and management as essential components in the ecologically sustainable development of the fishery. Through improving the understanding of these key biological parameters and consideration of the likely effectiveness of alternative harvest strategies, greater accuracy in the estimation of appropriate size and harvest limits (TACC) can be achieved. Thus the project addresses the Fisheries Research and Development Corporation (FRDC) strategic challenge 4, ecological sustainable development theme.

The increasing importance of Brownlip abalone in the AMF has also generated interest from the WA abalone aquaculture industry. Driven by factors such as Brownlip abalone being relatively large in size and providing high meat yields (~35% greater meat weight per length than Greenlip abalone), in theory, it is considered an ideal candidate for aquaculture and new sea-ranching aquaculture ventures occurring in WA. However, other factors, such as the animal's growth potential and cryptic nature need greater examination. Development of appropriate culture techniques for Brownlip abalone ensures the project also falls within the scope of the FRDCs strategic challenge 7, production, growth and profitability theme. Overall, Brownlip abalone has marked room for expansion in a variety of production techniques to increase WA's overall abalone production capacity.

1.2 Brownlip Abalone Biology

Brownlip abalone (*Haliotis conicopora*, Peron 1816) is the largest and possibly fastest growing abalone species in Australia. It is a characteristically unique abalone species, reaching considerably larger maximum sizes of nearly 250 mm shell length, compared to Greenlip abalone (230 mm) and Blacklip abalone (220 mm) (Geiger and Owen 2012). Brownlip abalone tend to inhabit hard surfaces (usually granite or limestone) on subtidal, complex rocky reefs between 1 and 40 m depth, displaying very cryptic behaviour within an extremely limited habitat of caves and crevices.

The distribution of Brownlip abalone extends from the south-west of WA to the WA/SA border. Even though Brownlip abalone is considered a distinct species, there is evidence to suggest it is a sub-species of Blacklip abalone (*Haliotis rubra*), whose distribution extends from SA, east across the southern regions of Australia including Tasmania to northern New South Wales (NSW). This sub-species status is separated along an east-west axis, with *H. rubra rubra* in the east and *H. rubra conicopora* in the west (Geiger and Owen 2012). Brown (1991) indicated that Brownlip abalone from one population in WA (Cape Arid, Area 2) did not contribute to population differentiation significantly more than samples of Blacklip abalone from 16 localities in the eastern states. A more detailed genetic study of abalone species from multiple countries showed that Brownlip abalone are genetically similar to Blacklip abalone, particularly from SA, and that *H. conicopora* could be considered conspecific with *H. rubra* (Brown and Murray 1992). This has led to some jurisdictions in Australia considering Blacklip abalone to be distributed from northern NSW to the south-west of WA (e.g. SA Stobart et al. 2015). Given that, taxonomically, Brownlip abalone is still a distinct species, its shell morphology can be easily differentiated and (in WA) is considered more cryptic than Blacklip abalone, *H. conicopora* is managed as a separate species within the AMF in WA (Strain et al. in prep. a).

As there is very limited available research on Brownlip abalone, some biological information for this species has been assumed based on data for either Blacklip abalone in SA, Greenlip abalone in WA or *Haliotis* species in general (e.g. Hart et al. 2013a). Brownlip abalone are considered broadcast spawners with no published information on spawning season, the only evidence for this is visual observations confirming that it corresponds with Greenlip abalone in WA (AIAWA pers. comm.). After spawning and fertilisation, there is a larval stage of 7-8 days and then the larvae metamorphose and settle onto suitable substrate. There is substantial evidence that temperate abalone larvae preferentially settle onto certain habitat based on chemical cues emanating from crustose coralline algae (e.g. McShane 1992; Roberts 2001; Roberts et al. 2010). Early life-stage abalone consume a range of biofilm products (bacteria, mucus, diatoms, coralline algae, turf algae, etc.) as they grow, before their diet becomes dominated by macroalgae at 5-15 mm shell length (e.g. Kawamura et al. 1998; Strain 2012). As adults, abalone feed on drift algae and, in Australia, species show a tendency towards red algae (Rhodophyta) (Shepherd and Cannon 1988; Shepherd and Steinberg 1992). Importantly for Brownlip abalone, however, given their cryptic nature, the habitat needs to have sufficient water movement to provide access to drift algae.

Information on essential biological characteristics such as size composition, size at maturity, weight-length relationship, fecundity, growth and mortality are all required to effectively manage the Brownlip abalone fishery in WA. In an earlier study by Wells and Mulvay (1992), they provided some basic biological information for Brownlip abalone as part of a larger project on Greenlip abalone. Brownlip abalone were shown to mature between around 120-130 mm in Area 3, and ~110-130 mm in Area 2, with all animals below 110 mm being immature. Based on this research, an approximate figure of 120 mm shell length is assumed for the size at maturity of this species. In that study, the sex ratio of Brownlip abalone was recorded as being at parity, the fecundity was shown to range upwards to 6 million eggs, and preliminary size-fecundity relationship established (Wells and Mulvay 1992). Preliminary estimates of the growth and weight-length relationship for this species have been established (Hesp et al. 2008; Hart et al. 2013a), while studies of natural mortality have not been undertaken for Brownlip abalone. The lack of information on Brownlip abalone is addressed in the present study, and the new information obtained used to examine the stock status and management of Brownlip abalone in WA.

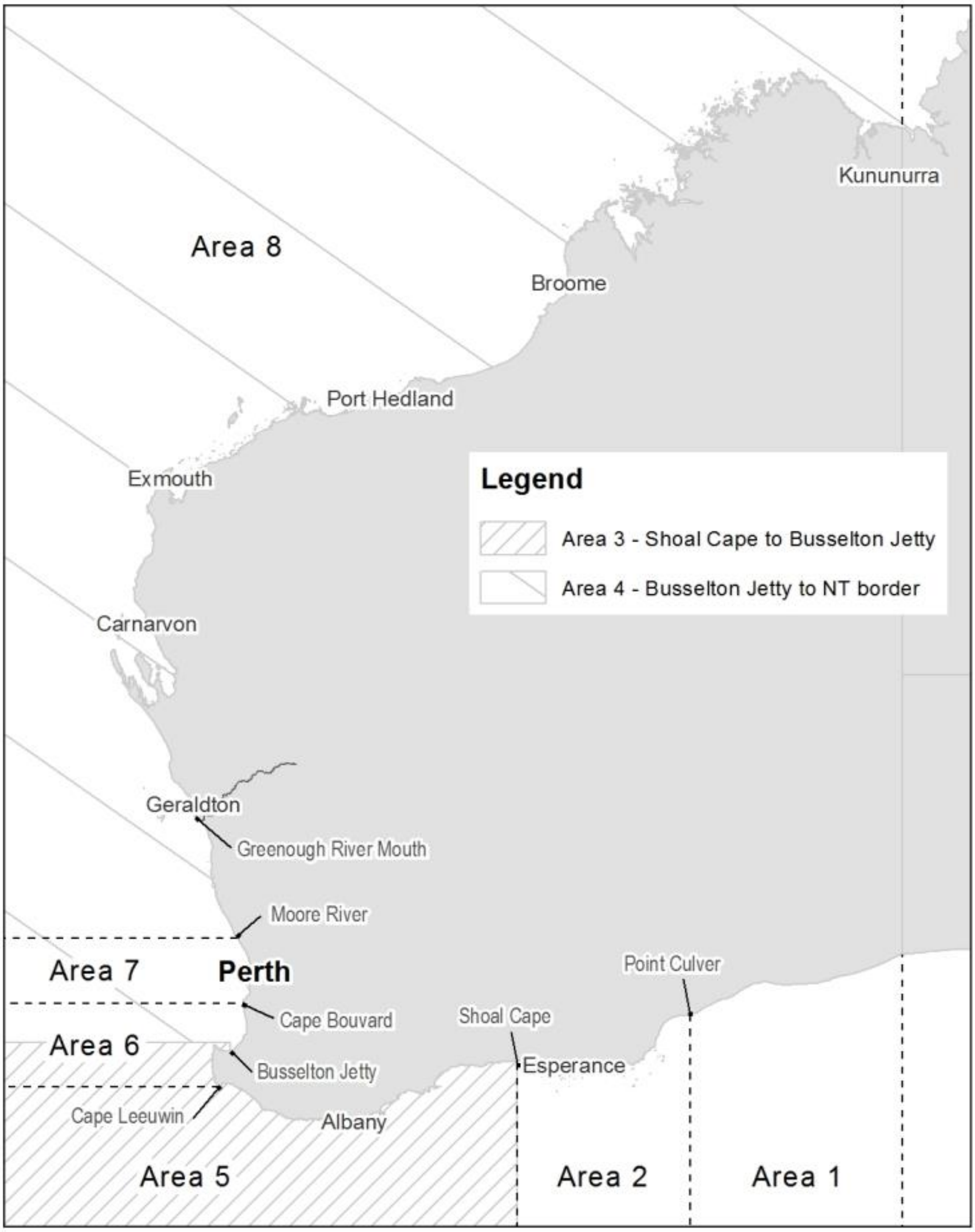


Figure 1.1: Map showing the boundaries of the management areas in the commercial Abalone Managed Fishery in Western Australia. The Greenlip/Brownlip fishery operates in Areas 1, 2, 3 and 4. Other areas are associated with the Roe's abalone fishery in WA.

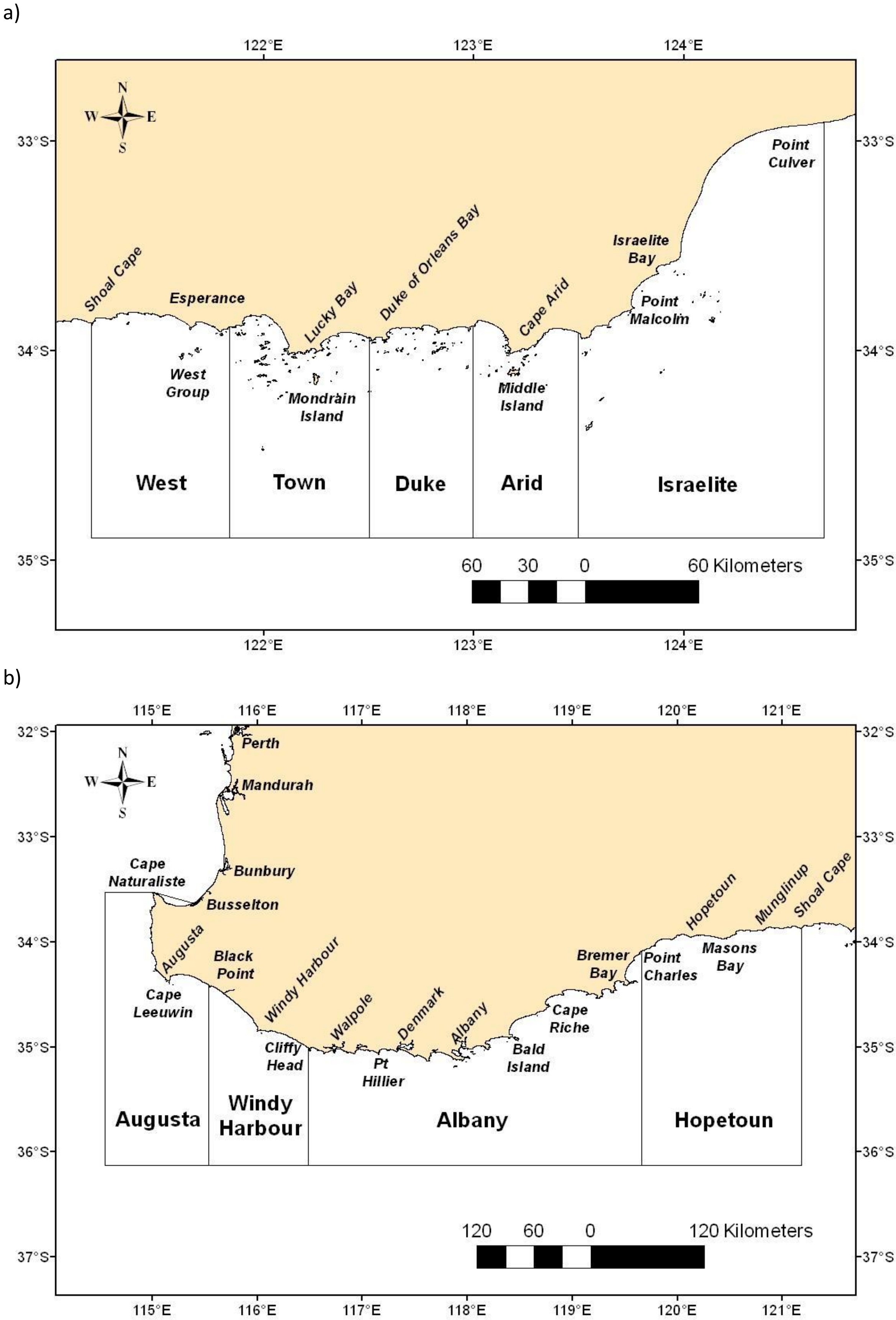


Figure 1.2: Maps showing the nine sub-area boundaries relevant to the two main management areas, Area 2 (a) and Area 3 (b), of the commercial Abalone Managed Fishery in Western Australia. Figure sourced from Hart et al. (2013a).

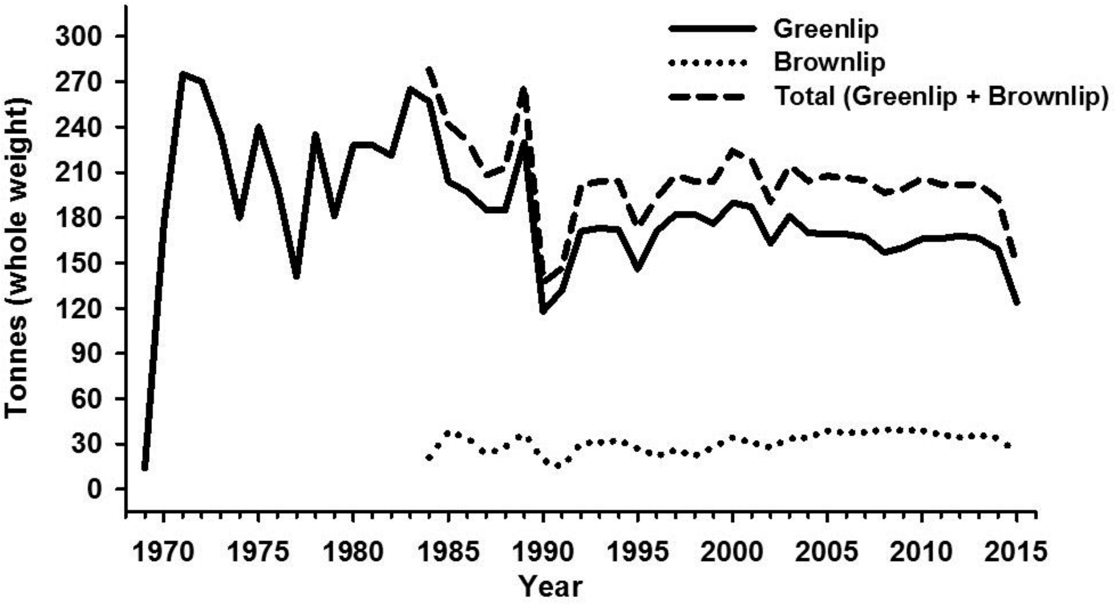


Figure 1.3: Historical commercial catch estimates (tonnes whole weight) from the Greenlip/Brownlip abalone fishery in Western Australia. Historical commercial catches (1969 to 1985) sourced from Prince and Shepherd (1992). Figure updated from Hart et al. (2013a).

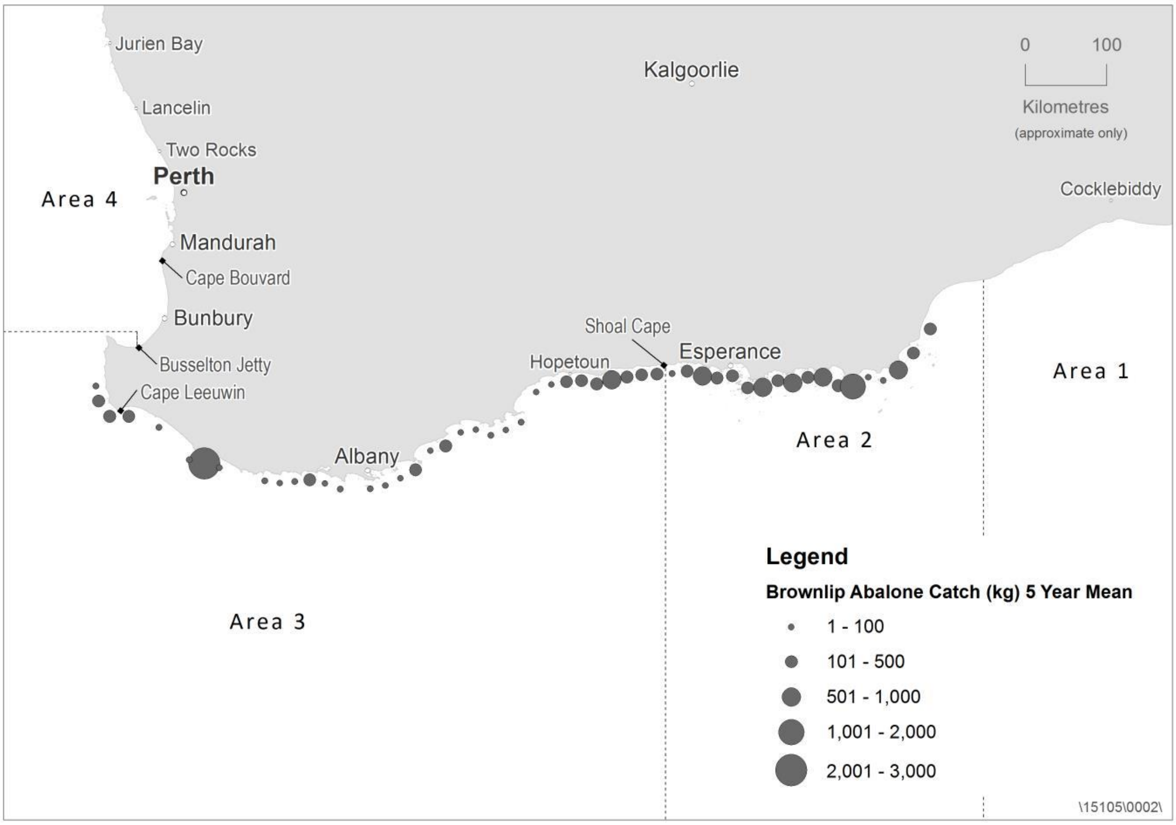


Figure 1.4: Brownlip abalone average annual catch (kg meat weight, 5 year mean) distribution across south-west Western Australia between 2009 and 2014.

2 Objectives

The overarching goal of this project was to address knowledge gaps relating to the biology and population dynamics of Brownlip abalone, while also looking to improve the management of the Western Australian Brownlip abalone fishery. The following objectives were identified to assist in achieving this aim:

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.
5. Preliminary integrated length-based model and harvest/fishing sizes determined.

Note that the third objective was only partially completed. Suitable habitat was identified but given AIAWA support for stock enhancement was withdrawn during the project, no releases of hatchery-reared juveniles into wild populations were conducted. The fifth objective was incorporated during the latter stages of the project. This offset the partial completion of the third objective and added value to the research undertaken earlier in the project, while also helping to inform the management of the Brownlip abalone fishery within WA.

Report structure

To help address the objectives of the study, the report is structured according to a standard format utilised by the FRDC. The method, result and discussion sections of this report are partitioned into the following distinct components (sub-headings) for ease of navigation:

- **Tag-Recapture Study**: a tag-recapture study of wild Brownlip abalone populations to provide data for estimating growth, natural mortality and habitat identification. This section addresses parts of objective 1 and 3 above.
- **Aquaculture Trials**: experimentation on commercial aquaculture systems. This section addresses objective 2 above.
- **Growth and Catch Curve Models**: utilisation of tag-recapture and commercial catch size composition data to estimate growth and mortality of Brownlip abalone. This section addresses parts of objectives 1, 2 and 4 above.
- **Per Recruit Models**: use of biological data in equilibrium-based assessment models, to estimate current stock status and explore the likely impacts of alternative harvest sizes on yield and stock status. This section addresses objective 4 above.
- **Preliminary Integrated Length-based Model**: a length-structured, single area, combined sex model developed to describe general Brownlip abalone population dynamics and estimate current stock status. This section addresses objective 5 above.

3 Methods

3.1 Tag-Recapture Study

This section addresses part of objective 1, which is to determine the growth and natural mortality of wild Brownlip abalone populations. A tag-recapture study was carried out on Brownlip abalone stocks across the WA AMF. To identify individual Brownlip abalone tag-recapture sites to sample for growth and survival of wild populations, catch and catch rate data from across the commercial fishery were examined. The areas identified from commercial data were compared to fishing marks (GPS) provided by several commercial fishers to ensure that appropriate habitat was targeted. These small areas of abalone habitat, identified as potentially suitable sites for Brownlip abalone, were searched by DOF research divers, and if Brownlip abalone were present in sufficient numbers (>15 abalone) within a definable area, it was recorded as a site. A total of 19 tag-recapture sites were established in 5 sub-areas of the fishery between Augusta and Dukes, spanning 800 km of the Western Australian coastline. The sites ranged with respect to several characteristics including location, depth, topography, habitat, food availability and the number of Brownlip abalone present.

At the initial capture events, the sites were searched extensively and any Brownlip abalone found were removed from the habitat by chipping, using an abalone iron. The animals were then tagged *in-situ* with a marine epoxy resin tag. The brand of epoxy resin used was Emerkit 2 part epoxy putty. After tagging the tag number and shell length of each individual was recorded, then all abalone placed carefully back into their position at the site. A series of photographs illustrating the *in-situ* abalone tagging process is shown in Figure 3.1. Recapture surveys for the tagged Brownlip abalone occurred on at least three separate occasions (>3 months apart) post the initial capture event. These recapture events involved locating the permanent sub-surface mooring and as per a site diagram, extracting all Brownlip abalone possible from the site. Any abalone collected with a tag had their tag number and shell length recorded then returned to the site, while any untagged abalone were tagged as per the tagging procedure on the initial capture event. If any animals were injured (foot cut) during the extraction process for tagging or measurement, then these animals were either not tagged or no longer included in the study, noting that there were very few of these.

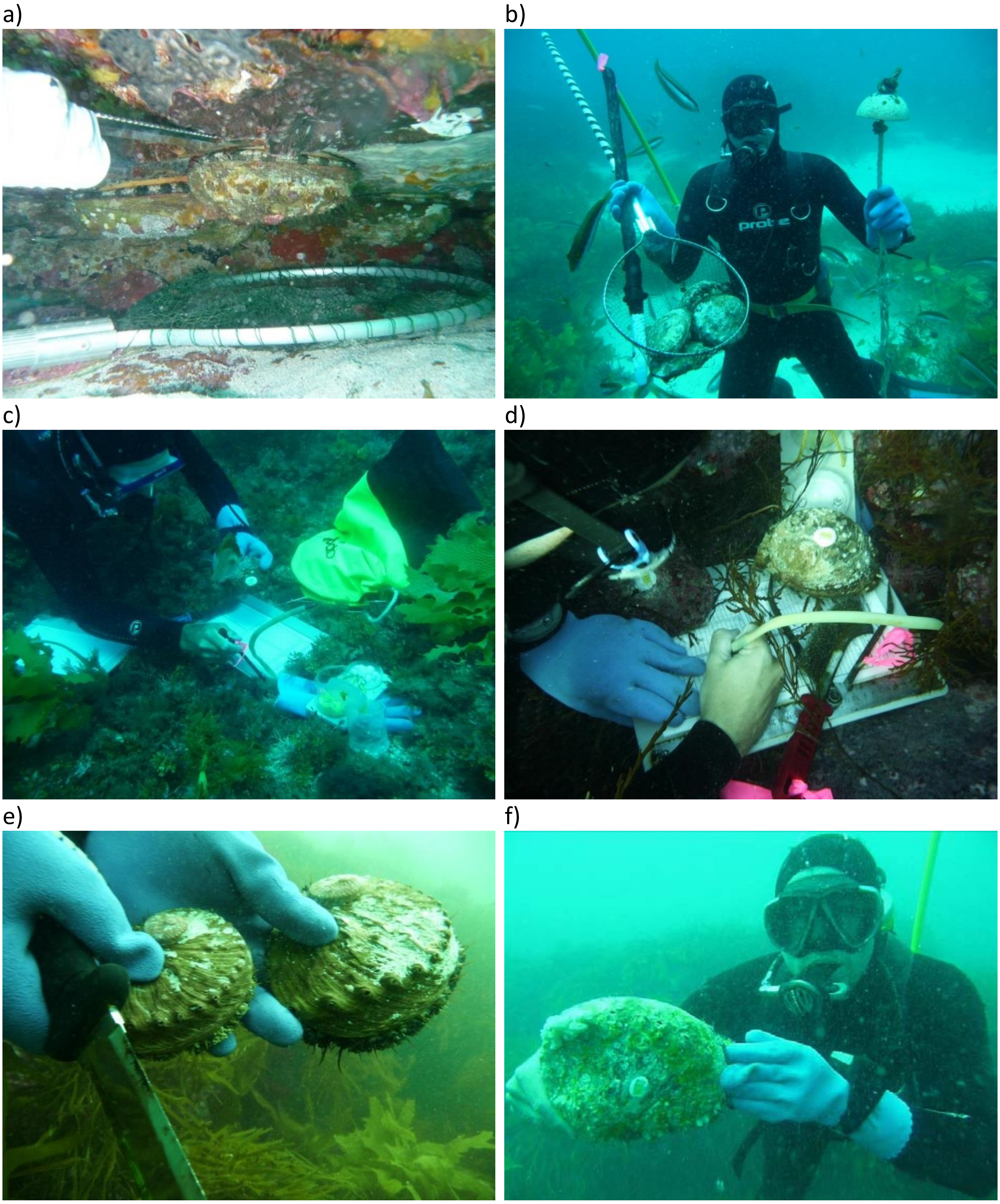


Figure 3.1: A series of photographs showing the *in-situ* Brownlip abalone tagging process; a) chipping abalone in a cave using the extended abalone iron, b) abalone removed from a cave for in-water tagging, c) measuring and tagging abalone, d) recording of tagged abalone data, e) small <100 mm Brownlip abalone, f) large 210 mm tagged Brownlip abalone.

Survival rates for Brownlip abalone in each sub-area surveyed were estimated from the multiple-recapture history of each individually tagged animal. Data from each site within a sub-area were pooled to increase sample size and precision in reporting survival estimates. This was not appropriate for the Augusta sub-area as there were differences in the time between recapture periods for each site (logistical constraints). Therefore, the site survival estimates were averaged *post-hoc* to produce a sub-area estimate. The "MARK" software program, which estimates conditional probabilities of apparent survival (ϕ) and recapture (p) using maximum likelihood techniques, was employed to analyse the tag-recapture study for Brownlip abalone (White and Burnham 1999, http://www.phidot.org/software/mark). To begin, the Goodness of Fit (GOF) testing of the data to the fully parameterised Cormack-Jolly-Seber model (CJS) with time ($\phi_t p_t$) was assessed. If the GOF testing detected over-dispersion of the data, a variance inflation factor ($\hat{c}$) was calculated by bootstrapping methods to adjust the sensitivity of the model selection process (Anderson et al. 1998). Model selection was evaluated by ranking all four models in the candidate set (all variations between fully time dependent and time constant for both ϕ and p) based on the quasi-likelihood adjusted form of the Akaike's Information Criterion statistic (QAICc), with the variance inflation factor incorporated where necessary. Then the models compared by the ΔQAICc, which was calculated as the difference between the various models QAICc and the model with the minimum QAICc. If the ΔQAICc was <2, then those models were considered to have approximately equal weights with respect to their ability to describe the data, and model averaging was used for those models to derive estimates of survival (Burnham and Anderson 2002).

All survival estimates produced by MARK were corrected *post-hoc* for tag loss. A tag loss experiment was conducted at the Windy Harbour sites, where when each animal was initially tagged with the Epoxy resin tag, 2 small dots of the Emerkit 2 part epoxy putty were also put on the Brownlip abalone shell. At each 'recapture period', every animal that was recaptured and measured was assessed for the tag, the epoxy tag putty and the 2 dots of epoxy putty. The tag loss correction factor = 1 + (epoxy putty present but no tag / all animals tagged). The correction factor equated to 1.104 but, as a precautionary measure, the more conservative factor of 1.05 was used due to the tag loss study only being conducted at sites within one sub-area. Information on recovered, dead tagged abalone from personnel conducting the tag-recapture study and commercial fishers were retained but was not used in the survival analyses. The assumption was made that Brownlip abalone did not move outside the study sites as these animals are very cryptic by nature and the sites were generally isolated caves. For comparisons with mortality estimates provided from catch curve analyses (Section 4.3.2), the survival estimates (ϕ or S) for each sub-area provided by MARK were converted to total mortality estimates (Z) by

$$Z = -\ln(S) \tag{3.1}$$

Note that the mortality estimates may not compare directly due to issues associated with differences in the selectivity of sampling of individuals between the two methods.

3.2 Aquaculture Trials

This section addresses objective 2, which is to determine growth rates and mortality of cultured Brownlip abalone. Baseline estimates of Brownlip abalone growth rates in the current culture systems at a commercial abalone farm were established. These growth rates were then examined to assess the current systems suitability for Brownlip abalone culture. Aquaculture trials on multiple size cohorts in the grow-out system were then used to determine the culture conditions required to optimise Brownlip abalone production, by comparing abalone growth rates and mortality in different tank designs.

3.2.1 Current Commercial Brownlip Abalone Growth Estimates

Baseline growth estimates for Brownlip abalone were obtained for the current commercial systems by tracking the sizes of the individuals in a cohort over time. Brownlip abalone were sampled from a particular system by selecting either a plate (nursery system), hide or defined area (grow-out system) within a tank, measuring 5 individuals attached and then repeating until the desired sub-sample of 200 Brownlip abalone per commercial tank per time interval was achieved. Once a cohort had been harvested from one system and stocked into another, this was considered the start and end point for the period over which the growth was estimated for that system. Two Brownlip abalone cohorts were tracked through both the nursery and grow-out systems, with multiple tank designs (hide and slab tank) examined in the grow-out system.

The nursery system, which accommodates abalone from the post larval to juvenile stage, consists of PVC plates arranged vertically in baskets and placed within coffin tanks, while utilising a natural algal diet of *Ulvella lens* and diatoms (Strain 2012). Once the juvenile abalone reached ~15 mm shell length they were harvested from the nursery system, graded and placed in the grow-out system. An alternative grow-out system tank design using concrete hides for habitat (described below) is currently being used as an intermediate stage between the nursery and grow-out (slab tanks) systems. The grow-out system generally consists of concrete slab tanks with no structural habitat and shallow water (<5 cm depth) flowing from one end to the other, where the abalone are fed an artificial diet.

3.2.2 Grow-out System Design Trial

To estimate the conditions required to produce optimal growth of Brownlip abalone in a grow-out system utilising a commercially acceptable stocking density, experimental trials with different hide tank designs were conducted. The Brownlip abalone aquaculture trials were performed at the commercial abalone farm, 888 Abalone Pty Ltd in Bremer Bay, WA. The grow-out system trial tanks were 1500 L polyethylene-lined tanks that replicated the current hide tanks used at the commercial farm for weaning juvenile abalone from the natural algal diet (*Ulvella lens* and diatoms) in the nursery system to artificial diets in the grow-out system. The hide tank design was utilised to examine variations to the habitat structures in order to accommodate the cryptic nature of Brownlip abalone (Figure 3.2). The tanks were on a flow through system with seawater supplied at 20 $L.min^{-1}$ via an inflow above the water surface at one end of the tank and a standpipe at the other, while a single airline attached to the bottom running down the middle of the tank aerated the seawater. The trial consisted of three tank design treatments with four replicate tanks for each design. The control treatment tanks had 2 rows of 6 concrete hides (half Besser blocks upside down) (Figure 3.2a), and were compared with a high water flow treatment (amount and velocity) that had the same configuration of concrete hides but with an increase of 10 L.min^{-1} water flow (Figure 3.2b), and an experimental tank with polyethylene ribs welded on the bottom and polyethylene cross boards for greater abalone habitat and easy of husbandry (Figure 3.2c).

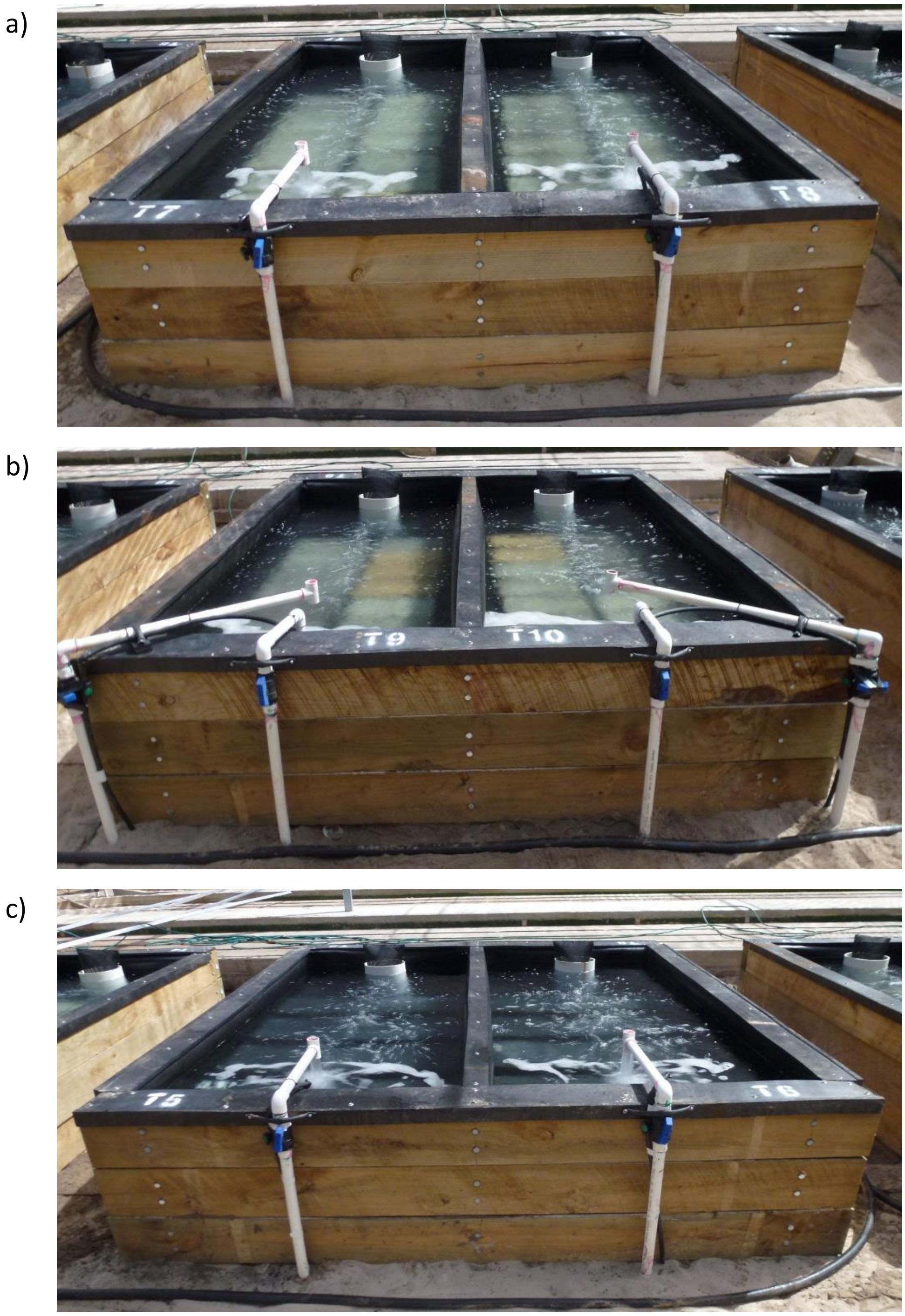


Figure 3.2: The experimental tanks utilised to assess Brownlip abalone growth and survival in aquaculture; a) the control tank with concrete hides, b) the high water flow tank with concrete hides and c) the polyethylene ribbed tanks with cross boards for habitat.

Two separate trials were conducted on 2 different cohorts of Brownlip abalone. The first trial ran for 3 months and utilised a cohort of Brownlip abalone with an average shell length of 45 mm, stocked at 500 animals per tank. The second trial duration was 4 months and incorporated a cohort with an average size of 71 mm shell length, stocked at 120 animals per tank. All Brownlip abalone were harvested from commercial tanks and maintained on the husbandry regime implemented on the farm. Therefore, the Brownlip abalone were fed 3 mm chip (Adam and Amos, Mt. Barker, South Australia) at 2% body weight per day (dry food, live abalone), with the tanks cleaned the following day by flushing any uneaten artificial diet and abalone faeces from the tank. To determine the effect of different tank design treatments on the growth and survival of each Brownlip abalone cohort, the abalone were measured by shell length and weight at the beginning of each trial and then periodically for the duration of the trials. To do this, individual habitat structures (hides or polyethylene cross boards) were randomly selected from a tank and 10 of the abalone attached measured. This procedure was repeated until a sub-sample of 100 abalone per tank in the 3 month trial and 50 abalone per tank in the 4 month trial was attained. The growth, weight gain and survival of abalone in each trial were examined by analysis of variance (one-way ANOVA), to determine if significant differences between treatments were observed ($p<0.05$).

3.3 Growth and Catch Curve Models

This section addresses parts of objectives 1, 2 and 4. These objectives are to determine the growth and mortality of wild and cultured Brownlip abalone, and develop fishing size limits and optimal market sizes based on size distribution and growth, to examine the harvest potential of the total industry.

3.3.1 Growth Models

The tag-recapture study established 19 sites throughout the WA AMF where substantial fishing effort occurs. At these sites, Brownlip abalone were captured, tagged and these individuals were subsequently re-measured on up to 3 possible occasions (see Section 4.1). For each animal tagged, a single recapture period was randomly selected from up to 3 recapture periods for that individual, thereby avoiding the issue of repeated measures. In the wild, juveniles are highly cryptic and were unable to be sampled, data on the growth of Brownlip abalone in aquaculture (see Section 4.2) was used to provide information on the growth of early juveniles, i.e. in their first year of life. This enabled estimation of growth increments for various durations between the time of hatching and 1 year of age. The combination of the two data sets provided information on the growth of individuals of Brownlip abalone over the full size range of this species. Across all individuals, the periods between initial capture, marking and measurement, and re-measurement, varied considerably, i.e. between ~6 months and 2.5 years and thus, for modelling, it was important to account for differences in time at liberty.

To estimate the growth parameters for Brownlip abalone from tag increment data, several models were compared including the von Bertalanffy growth model (which assumes there is a linear pattern of change in growth rate with respect to initial length), the Gompertz growth model (which allows for initially increasing and then decreasing growth rates as the initial lengths of animals increase), the Gaussian function (which allows for low growth rates over a range of both small and large initial lengths) and the double-logistic curve (which incorporates the "inverse logistic" curve described by Haddon et al. (2008) but also contains an ascending logistic curve for describing the growth of the very small individuals).

Applying the von Bertalanffy growth model, dL_t / dt, the instantaneous rate of change in length of an individual, given its shell length at age t years, L_t, is

$$dL_t / dt = (L_\infty - L_t)(1 - e^{-k\Delta t}) \qquad 3.2$$

where L_∞ is the average maximum length of individuals in the population, k is the growth coefficient, and Δt is specified as a minute number between capture and recapture (e.g. Haddon, 2011). Fitting the Gompertz growth model, dL_t / dt is estimated as

$$dL_t / dt = L_\infty \left(\frac{L_t}{L_\infty} \right)^{e^{(-g\Delta t)}} \qquad 3.3$$

where g is a growth constant (Heliodoniotis et al. 2011). Using the Gaussian function, dL_t / dt is estimated as

$$dL_t / dt = Ae^{-(L_t - u)^2 / 2\sigma_{GF}^2} \qquad 3.4$$

where A is the maximum growth (mm, y^{-1}), u is the size at maximum growth (mm) and σ_{GF} is the standard deviation of the distribution of maximum growth *vs* size (Rogers-Bennett et al. 2007). Finally, employing the double-logistic curve, dL_t / dt was described as

$$dL_t / dt = a \left\{ 1 / \left[1 + e^{-\ln(19)\left(L_t - L_{50_1}\right)/\left(L_{95_1} - L_{50_1}\right)} \right] \right\} \left\{ 1 / \left[1 + e^{\ln(19)\left(L_t - L_{50_2}\right)/\left(L_{95_2} - L_{50_2}\right)} \right] \right\} \qquad 3.5$$

where a is the estimated maximum length increment attained by individuals at any initial length, L_{50_1} is the initial length midway between the smallest and maximum growth increment on the ascending limb of the curve, L_{95_1} is the initial length at which 95% of the difference between the smallest growth increment and maximum growth increment on the ascending limb of the curve is reached, L_{50_2} is the initial length midway between the largest and smallest growth increment on the descending limb of the curve, and L_{95_2} is the initial length at which 95% of the difference between the largest and smallest growth increment on the descending limb of the curve is reached. This growth curve incorporates the (non-seasonal) "inverse logistic" curve described by Haddon et al. (2008), but also contains an ascending logistic curve for describing the growth of the very small individuals.

Applying the Gaussian function, for example, if the length of an abalone at time $t = t_0$ is $L_{t=t_0}$, then its expected length $\hat{L}_{t=t_0+T}$ at time $t = t_0 + T$ is

$$\hat{L}_{t=t_0+T} = L_{t=t_0} + \Delta\hat{L}_{t_0,t_0+T} = L_{t=t_0} + \int_{t=t_0}^{t=t_0+T} Ae^{-(L_t - u)^2 / 2\sigma_{GF}^2} dt, \qquad 3.6$$

where $\Delta\hat{L}_{t_0,t_0+T}$ is the expected length increment between $t = t_0$ and $t = t_0 + T$. For each tagged Brownlip abalone, this "initial value problem" was solved using a 4th order Runge-Kutta algorithm to calculate an estimate of its expected length at its time of re-measurement given the values of the growth parameters A, u and σ_{GF}. The parameters of the growth model (as described by the above Gaussian function) were estimated by minimising the negative log-likelihood where it was assumed that, for abalone j, the observed length increment X_j

represented a random variable drawn from the normal distribution about the estimated increment $\hat{X}_j$ given its initial length and the time between its tagging and re-measurement.

All of the growth models were fitted in AD Model builder by maximising the negative of the log-likelihood associated with the predicted length increments of individuals at the end of their times at liberty. The overall log-likelihood for the growth curve, λ_{gc} , was calculated as

$$\lambda_{gc} = -\frac{n}{2}\left\{\ln(2\pi) + 2\ln(\hat{\sigma}) + 1\right\} \qquad 3.7$$

where n is the number of animals for which measurements were taken of their initial and final length lengths, $\ln$ is the natural logarithm and $\hat{\sigma}$ is the standard deviation associated with the deviations between the observed and predicted final lengths (Haddon 2011).

The statistical fits of the various growth models was assessed by comparing the values of Akaike's Information Criterion, *AIC*. The model with the lowest *AIC* value, i.e. $AIC_{\min}$, was the one considered to provide the best statistical fit to the data. *AIC* was calculated as

$$AIC = 2LL + 2K \qquad 3.8$$

where K is the total number of growth parameters in the respective growth model (including the variance) (Burnham and Anderson 2002).

3.3.2 Length-based Catch Curve Models

Total mortality of abalone has generally been estimated by either tracking the abundance of tagged animals at intervals over time, or by using catch length-frequency data combined with growth data for catch curve analysis (Hart et al. 2013a). In this analysis, commercial catch samples (individual animal shells) were collected from across the fishery and operators (5 randomly-selected Brownlip abalone shell per fishing day per operator). Sample sizes in the different management areas were weighted according to the commercial catches taken in those areas and were pooled for 3 year blocks. The growth data and model selected in Section 4.3.1 was combined with the catch length-frequency data to perform the catch curve analysis.

This approach involved estimating the time taken for abalone to grow from one length class to the next (denoted below as Δt), and estimating the relative frequencies of abalone in successive length classes, based on a value of total mortality and a specified selectivity pattern. Given that the rate of change of length with respect to time is estimated by the growth curve, an estimate of the expected duration between the mid-point of length class l and that of $l+1$ may be obtained by determining the value of Δt that would result in this change of length. For a given initial length L and time interval, the expected length at the end of that time interval, t, may be estimated using numerical integration (as outlined above in the growth description). The value of t at which the expected length at that time $\hat{L}_t$ was equal to a specified length may be determined using an iterative approach, e.g. using Newton's algorithm. Considering, for the j^{th} fish, the value of length at time t as a function, i.e.

$$L_{t,j} = f(t, L_{t_0,j}) \qquad 3.9$$

where the value of t at which $L_{t,j} = L_{F,j}$ may be estimated as the root of the equation, i.e.

$$L_F - f(t, L_{t_0,j}) = 0 \qquad 3.10$$

In this study, two catch curve methods were applied for obtaining an estimate of total mortality for Brownlip abalone across the fishery. The first was a length-converted catch curve based on the Baranov catch equation to estimate the catches in different length categories, combined with a logistic selectivity function, which enabled the model to be fitted to both partially and fully-selected individuals. In fitting this catch curve, S_l, the length-based selectivity of abalone to fishing in length class l, was calculated as

$$S_l = 1/1 + \exp\left\{-\ln(19)\left[\left(L - L_{50}\right)/(L_{95} - L_{50})\right]\right\} \qquad 3.11$$

F_l, the fishing mortality in length class l, is calculated as

$$F_l = S_l F \qquad 3.12$$

N_l, the expected number of survivors per recruit in length class l was calculated from the survival equation, i.e.

$$N_l = N_{l-1}\exp(-Z_l \Delta t) \qquad 3.13$$

where Δt represents the time taken for animals to grow from the mid-point of length class $l-1$ to that of l, and where Z_l is the sum of F_l and natural mortality, M.

Applying the Baranov catch equation, the expected catch per recruit in length class l may be calculated as

$$C_l = \frac{F}{Z}(1 - \exp(-Z\Delta t)N_l \qquad 3.14$$

The negative multinomial log-likelihood associated with the catch curve, λ_{cc}, is

$$\lambda_{cc} = n\sum_l p_l \ln \hat{p}_l \qquad 3.15$$

where n is the sample size of the commercial length composition, and p_l and $\hat{p}_l$ are the observed and expected proportions, respectively, of abalone in length class l. To account for uncertainty in estimating growth when fitting catch curves, the growth and catch curve models were fitted simultaneously. The overall log-likelihood, λ, was thus calculated as

$$\lambda = \lambda_{gc} + \lambda_{cc} \qquad 3.16$$

The log-likelihoods associated with the growth curves and catch curves, which were within the same order of magnitude, were given equal weighting within the overall objective function. Preliminary sensitivity analyses, applying alternative weightings for the two components of the overall objective function (e.g. reducing the weighting of the likelihood associated with length composition data, λ_{cc}, by a factor of up to 10), showed that mortality estimates were similar across a range of alternative weightings.

The catch curve analyses for Brownlip abalone also involved comparisons between the results obtained by the model described above with those obtained from the length-converted catch curve described by Pauly (1984). This second catch curve, which is fitted to the descending limb of length frequency distributions calculated from annual catch samples taken by commercial fishers, is

$$\ln\left[N_l\left(dl_l / dt_l\right)\right] = -Zt + b \qquad 3.17$$

where Z is total mortality, b is the intercept of the line, N_l is the number of abalone in length class l and dl_l / dt_l is the growth rate (cm.y^{-1}) in that length class at age t, estimated from the growth model.

3.4 Per Recruit and Related Equilibrium-based Models

This section addresses objective 4, which is to develop fishing size limits and optimal market sizes based on size distribution and growth to examine the harvest potential of the total industry.

3.4.1 Per Recruit Model

The yield per recruit (YPR), spawning stock biomass per recruit ($SSBR$) and egg per recruit (EPR) for Brownlip abalone were calculated from age zero assuming constant natural mortality (across all ages) and constant fishing mortality for fully-recruited animals, employing a monthly time step (Table 3.1).

S_t, the selectivity of Brownlip abalone at age t is calculated as

$$S_t = 1/\{1 + \exp[-\ln(19)(L_t - L_{50})(L_{95} - L_{50})]\} \qquad 3.18$$

where L_t is the mean length at age t, determined from the growth curve (Section 4.3.1), and L_{50} and L_{95} are the lengths at which 50 and 95% of individuals become selected into the fishery (Table 3.1). The fishing mortality at age t, F_t, is calculated as $S_t F$, where F is the instantaneous rate of fishing mortality (y^{-1}) for fully-selected individuals. Z_t, is the instantaneous rate of total mortality (y^{-1}) at age t for such individuals, calculated as $F_t + M$, where M is instantaneous rate of natural mortality (y^{-1}).

N_t, the numbers of Brownlip abalone, per recruit, that survive to age t, and at age zero it is set to 1, whereas for all subsequent ages it is calculated as

$$N_t = N_{t-1}\exp(-Z_{t-1}(1/12)) \qquad 3.19$$

where T is the maximum age assumed in the analysis for Brownlip abalone, the value of which (50 y) is considered well above the likely maximum age for this species.

W_a, the weight of Brownlip abalone at age t (expressed as a meat weight), was calculated as

$$W_t = a_{\text{lnwt}} {L_t}^{b_{\text{lnwt}}} \qquad 3.20$$

where a_{lnwt} and b_{lnwt} are the parameters of this power relationship (Table 3.1).

The yield per recruit (YPR) for combined sexes, was calculated as

$$YPR = \sum_{t=0}^{T} \left(\frac{F_t}{Z_t}\right) \{1 - \exp[-(Z_t(1/12))]\} N_t W_t \qquad 3.21$$

Assuming a sex ratio of 0.5, and equal growth and mortality of females and males, N_t^f, the number of females per recruit surviving to age t, is $0.5N_t$. The proportion of females at age t that are mature, ψ_t^f, was specified as zero for female abalone with shell lengths <120 mm, and as one, for those with shell lengths ≥120 mm (Table 3.1).

Female spawning stock biomass per recruit, $SSBR$, was estimated as

$$SSBR = \sum_{t=0}^{T} N_t^f \psi_t W_t \qquad 3.22$$

Fec_t, the fecundity of females (millions of eggs) at age t, is determined from a power relationship, i.e.

$$Fec_t = a_{\text{egg}} {L_t}^{b_{\text{egg}}} \qquad 3.23$$

where a_{egg} and b_{egg} are the parameters. Eggs per recruit (EPR) was calculated as

$$EPR = \sum_{t=0}^{T} N_t^f \psi_t^f Fec_t \qquad 3.24$$

The spawning potential ratio (SPR), for females, was calculated in terms of both spawning biomass per recruit and egg per recruit. Denoting the catch curve estimate for F as F_{current}, SPR in terms of $SSBR$ was estimated as

$$SPR = SSBR_{F=F_{\text{current}}} / SSBR_{F=0} \qquad 3.25$$

Similarly, SPR in terms of EPR was calculated as

$$SPR = EPR_{F=F_{\text{current}}} / EPR_{F=0} \qquad 3.26$$

Sensitivity analyses

The levels of YPR and SPR were calculated assuming three alternative selectivity patterns. The first of these was a base case scenario corresponding to the selectivity pattern estimated by catch curve analysis (Section 4.3.2), using data for the most recent three year period for which length composition data were available (2013-2015). For the second scenario, the values of the selectivity parameters (i.e. L_{50} and L_{95}) were increased by 10 mm to approximately reflect the extent of the differences, among the selectivity curves, estimated by catch curve analysis for first time period (2004-2006) verse the most recent time period (2013-2015). That is, in the earlier time period, the values for L_{50} and L_{95} were 8 and 9.8 mm higher, respectively, compared with those estimated for the current time period. For the third scenario, the values of the selectivity parameters were 10 mm less than those specified for the base case scenario, thereby enabling assessment of the likely impact of any further substantial decrease in the size at which abalone are fished, beyond the decrease already observed in recent years. Note that, when specifying a scenario, all but one of the parameters values were kept the same as those of the base case scenario, so that the effects of a single parameter on the results was not confounded with changes made to any other parameter.

The sensitivity of the results of the per recruit analyses to alternative values of natural mortality (M) was also assessed. The first value for M of 0.15 y^{-1} used for the base case scenario was an estimate for M derived from a tag-recapture study (Section 4.1.2). The second value for M of 0.12 y^{-1} corresponded to an estimate of total mortality (Z) for Brownlip abalone in a lightly fished area, again derived from analysis of tag-recapture data (Section 4.1.2). The third value for M of 0.18 y^{-1} corresponded to the lowest value of Z estimated by catch curve analysis for Brownlip abalone across the fishery in the various time periods, and thus considered to represent an upper limit for feasible values of M for Brownlip abalone (Section 4.3.2).

3.4.2 Extension to the Per Recruit Model to Incorporate a Stock-recruitment Relationship

The per recruit analysis described above was extended to include a Beverton and Holt stock-recruitment relationship. The relationships between yield and spawning biomass were then explored with differing specified levels of the steepness parameter of this relationship between recruitment and stock size. Specifying an arbitrary value for the level of initial recruitment, R^*, of 1 million abalone (Table 3.1) and noting that the change in yield and spawning biomass curves relative to fishing mortality are unaffected by the value of this parameter, then the unfished level of female spawning biomass, S^*, is

$$S^* = R^* X \tag{3.27}$$

where X is taken to be equivalent to the unfished level of female spawning stock biomass per recruit, i.e. $SSBR_{F=0}$.

Specifying a value for the Beverton and Holt stock-recruitment steepness parameter, h (Table 3.1), the two parameters of this relationship, a_{SRR} and b_{SRR} may be calculated as

$$a_{\text{SRR}} = \frac{S^*}{R^*}\left(\frac{1-h}{4h}\right) \tag{3.28}$$

and,

$$b_{\text{SRR}} = \frac{h-0.2}{0.8hR^*} \tag{3.29}$$

Having determined the parameters of the stock-recruitment relationship, the equilibrium recruitment for a fished stock at a given level of fishing mortality may be calculated as

$$R_{\text{eq}} = \frac{X - a_{\text{SRR}}}{b_{\text{SRR}} X} \tag{3.30}$$

The expected yield, given the level of R_{eq} is thus

$$Yield = R_{\text{eq}} YPR_{F=F_{\text{current}}} \tag{3.31}$$

and the expected level of spawning biomass, given that level of recruitment, is

$$SpBiom = R_{\text{eq}} SSBR_{F=F_{\text{current}}} \tag{3.32}$$

Sensitivity analyses

The sensitivity analyses described above for the per recruit analyses, to explore the effects of different selectivity patterns and values of M, were repeated using the extended model. In addition, a sensitivity analysis was undertaken to explore the influence of alternative values for h, using values of 0.4, 0.6 (base case) and 0.8.

Table 3.1: Parameters for per recruit analysis and the extended analysis incorporating a stock-recruitment relationship for the Brownlip abalone fishery in Western Australia (management Areas 2 and 3 were combined due to limited information for some biological parameters between areas).

Parameters	**Value**	**Source of Information**	**Additional Information**
Growth parameters (Gaussian function)		This study	Growth model (Section 4.3.1)
A	0.094		Combined for management Areas 2 and 3
U (mm)	55.33		
σ (mm)	53.17		
Weight-Length		Hart et al. (2013a)	Length to meat weight
a_{lnwt}	0.00008		
b_{lnwt}	2.93		
Mean size at maturity (mm)	120	Wells and Mulvay (1992)	Used Area 2 parameter for combined analysis (Area 3=125 mm)
Sex Ratio	0.5		
Fecundity		Wells and Mulvay (1992)	Used Area 2 parameters for combined analysis
a_{egg}	0.00169		
b_{egg}	4.15		
Selectivity-at-size		This study	Catch Curve Analysis (Section 4.3.2)
L_{50} (mm)	150.2		Time period 2013-2015 parameters used
L_{95} (mm)	160.9		Time period 2004-2006 L_{50}=158.2 and L_{95}=170.7
Natural mortality (M, y^{-1})	0.15	This study	Tag-Recapture Study (Section 4.1.2)
Fishing mortality (F, y^{-1})	0.11	This study	F=Z (Catch Curve Analysis Section 4.3.2) – M (Tag-Recapture Study Section 4.1.2)
Recruitment	1		
Legal minimum length (mm)	140		
Stock-recruitment parameters			
Initial Recruitment (R^{*})	1		R^{*} is an arbitrary value for the level of initial recruitment (million)
Steepness parameter (h)	0.6		Beverton and Holt stock-recruitment steepness parameter

3.5 Preliminary Integrated Length-based Model

This section addresses objective 5, which is a preliminary integrated length-based model to determine harvest/fishing sizes.

3.5.1 Overview of Model

The preliminary length-structured, single sex model for Brownlip abalone described below, has been implemented in AD Model Builder, and is fitted to commercial catch and catch rate data, as well as length composition data. The description of growth of Brownlip abalone in the integrated model is very similar to the growth model that was used for catch curve analysis (i.e. a Gaussian function is fitted to growth increment data from the tag-recapture study, Section 3.3.1). The growth models differ in an assumption relating to error structure, i.e. the one used to inform the integrated model assumes that the observed length increments represent a random variable drawn from a gamma distribution (rather than a normal distribution) about the estimated increment. The change was made to allow the length transition matrix to be modelled employing a gamma distribution (i.e. assuming that abalone cannot reduce in shell length). For completeness, some of the equations used to describe how growth of Brownlip abalone was estimated have been repeated in this section to provide a complete description of the integrated model. The parameters of this 'growth model', which include an estimate of the variance associated with the observed growth increments about the expected increments, are used to derive a length transition matrix for describing the probabilities of individuals, at each model (annual) time step, growing from a given length class into any other possible length class. The integrated model, which is conditioned on catch, tracks the abundances of abalone belonging to each length classes over the history of the fishery to provide annual estimates of total biomass, spawning biomass, vulnerable (i.e. exploitable) biomass and fishing mortality. The model also estimates average annual levels of recruitment based on a Beverton and Holt stock-recruitment relationship, and logistic selectivity parameters describing the vulnerability of abalone to being caught at different lengths. The "base" model, for which results are reported here, assumes a value of 0.15 y^{-1} for M (Section 4.1.2), and a value of 0.6 for the steepness parameter (h) of the stock-recruitment relationship.

3.5.2 Model Description

Population dynamics

The state of the Brownlip abalone population is described by the numbers within each of a set of length classes that encompass the range of lengths of abalone from age 1 to some large maximum age. The midpoint of length class j $(1 \le j \le n)$ is denoted by L_j and the lower and upper bounds of this class are denoted by L_j^- and L_j^+, respectively. Broadly, the dynamics of the population are represented by the equation describing the numbers of individuals in the exploited abalone population surviving to year y, i.e. $\mathbf{N}_y$. That is,

$$\mathbf{N}_y = \mathbf{G}\mathbf{S}_{y-1}\mathbf{N}_{y-1} + \mathbf{R}_y \qquad 3.33$$

where $\mathbf{G}$ is a size transition matrix, $\mathbf{S}_y$ is the survival matrix for year y and $\mathbf{R}_y$ is a vector for the numbers of abalone recruiting to the different size classes in year y (Haddon 2011; see also Fisher et al. 2011).

$\mathbf{N}_y$ is a vector, containing the number of abalone $N_{j,y}$ within length class j of the n different length classes comprising the length composition in year y, i.e.

$$\mathbf{N}_y = \begin{bmatrix} N_{1,y} \\ N_{2,y} \\ \cdot \\ N_{n,y} \end{bmatrix} \tag{3.34}$$

Mortality and Selectivity

The survival matrix $\mathbf{S}$ describes the proportions of abalone in each length class j that survive the combined effects of fishing and natural mortality in year y, i.e.

$$\mathbf{S}_y = \begin{bmatrix} S_{1,y} & 0 & 0 \\ & S_{2,y} & \\ & & .\ 0 \\ 0 & & 0\,S_{n,y} \end{bmatrix} \tag{3.35}$$

The proportion of individuals surviving from the start to the end of the annual time step is calculated as

$$S_{j,y} = \exp(-Z_{j,y}) \tag{3.36}$$

where $Z_{j,y}$ is the instantaneous rate of total mortality (y^{-1}) in length class j and year y, and is calculated as

$$Z_{j,y} = M + (V_{j,y} F_y) \tag{3.37}$$

In the above equation, M is the instantaneous rate of natural mortality (0.15 y^{-1}) specified in the model as a constant (Section 4.1.2), $V_{j,y}$ is the selectivity of abalone in length class j and year y, and F_y is the fishing mortality estimated for that year. In the absence of fishing mortality, $S_{j,y}$ is calculated as

$$S_{j,y} = \exp(-M) \tag{3.38}$$

$V_{j,y}$ is described by the following logistic relationship

$$V_{j,y} = 1/\left\{1 + \exp\left[-\alpha\left(L_j - L_{50,y}\right)\right]\right\} \tag{3.39}$$

where α denotes the slope of the curve (assumed to remain constant in all years), and $L_{50,y}$ corresponds to the length at which 50% of animals are selected into the fishery in year y. $L_{50,y}$ and α are estimated as model parameters. As the results of the catch curve analyses for Brownlip abalone presented in this report (Section 4.3.2) provided evidence that the mean size at which this species becomes selected into the fishery has changed in recent years, it was considered appropriate to allow for temporal changes in selectivity in the model. Note that the values of $V_{j,y}$ in years prior to the first annual length composition sample data were set to the values estimated for the year in which that first sample was collected. For other periods of missing length composition data, the values of $L_{50,y}$ were estimated using linear interpolation between the values estimated for the years on either side of the missing years of data. F_y is estimated by applying Newton's algorithm (e.g. Haddon, 2011) to match the expected catch to the observed catch in that year.

Stock-recruitment

The recruitment R_y that results from spawning in year $y-1$ is assumed to be distributed over the n length classes as $\mathbf{R}_y$, where

$$\mathbf{R}_y = \begin{bmatrix} R_{1,y} \\ R_{2,y} \\ . \\ R_{n,y} \end{bmatrix}, \tag{3.40}$$

The proportion of 1 year old abalone recruiting into length class k, i.e. θ_k, is calculated as

$$\theta_k = \begin{cases} \int_{-\infty}^{L_k^+} f_{a=1}(L)dL & \text{if } k=1 \\ \int_{L_k^-}^{L_k^+} f_{a=1}(L)dL & \text{if } 1<k<n \\ \int_{L_k^-}^{\infty} f_{a=1}(L)dL & \text{if } k=n \end{cases} \tag{3.41}$$

where L is the length, L_k^- and L_k^+ are the lower and upper limits, respectively, of length class k and $f_{a=1}(L)$ is the value of the normal probability density function for abalone at age 1 with length l, calculated using a constant standard deviation over all ages, i.e. $l \sim N(\mu, \sigma_{\mathrm{Rec}}^2)$. That is,

$$f_{a=1}(L) = \frac{1}{\sigma_{\mathrm{Rec}}\sqrt{2\pi}} \exp\left[\frac{(L-\mu)^2}{2\sigma_{\mathrm{Rec}}^2}\right] \tag{3.42}$$

The mean and standard deviation associated with the normal size distribution for 1+ recruits was estimated using empirical data for ~1 year old individuals raised in a hatchery (Section 4.2).

The relationship between annual recruitment and female spawning stock size is considered to follow a Beverton and Holt curve. The expected level of recruitment of 1 year old abalone in year y is calculated as

$$R_y = B_{y-1}^S / \left(a_{SRR} + b_{SRR} B_{y-1}^S\right) \tag{3.43}$$

where a_{SRR} and b_{SRR} are parameters of the Beverton and Holt stock-recruitment curve and B_{y-1}^S is the female spawning biomass in year $y-1$. As described above, these recruiting abalone are distributed over a number of length classes.

a_{SRR} is calculated as

$$a_{SRR} = \left(B^{S_0} / R^*\right)\left[(1-h)/(4h)\right] \tag{3.44}$$

where B^{S_0} is the unfished spawning biomass, R^* is the unfished recruitment (which is estimated as a model parameter) and h is the steepness parameter, specified as a fixed value in the model (currently set to 0.6).

b_{SRR} is calculated as

$$b_{SRR} = \left(h - 0.2\right) / \left(0.8hR^*\right) \tag{3.45}$$

B^{S_0} is calculated as

$$B^{S_0} = R^* SBR^0 \tag{3.46}$$

where SBR^0 is the unfished level of female spawning biomass per recruit, calculated as

$$SBR^0 = \sum_{T=1}^{50} \sum_{j=1}^{n} N_{j,T}^R W_j \tag{3.47}$$

where $N_{j,T}^R$ is the number of Brownlip abalone, per female recruit, at time step T in length class j, and W_j is the mean weight of individuals in length class j, based on a weight-length relationship (see below). At time step $T = 1$, the values of $N_{j,y}^R = \theta_k$. At each subsequent time step, the values of $N_{j,T}^R$ are calculated as

$$N_{j,T}^R = N_{j,T-1}^R \exp(-M) \tag{3.48}$$

A size-transition matrix (see below) is then applied to estimate the size composition of individuals at the current time step, given their sizes at the previous time step. Note that the value of 50 years, for the maximum time step, was considered well beyond the likely maximum age for this species.

The initial recruitment, at the specified initial equilibrium level of fishing mortality, R_{init}, is

$$R_{init} = \left(SBR^{F_{init}} - a_{SRR}\right) / \left(a_{SRR} SBR^{F_{init}}\right) \tag{3.49}$$

where $SBR^{F_{init}}$ is the estimated level of spawning biomass per recruit at the initial level of fishing mortality. $SBR^{F_{init}}$ is calculated in the same manner as SBR^0, but where the annual survival rate is determined based on the summed values of M and the initial equilibrium fishing mortality, F_{init}. The latter value is estimated as a parameter in the model assuming that the selectivity pattern associated with this initial equilibrium recruitment was the same as that determined for the first year of the model.

Note that, because the length composition data are derived from commercial fishers who target only relatively large (slower-growing) individuals, there was insufficient information in the data to allow for recruitment deviations.

Growth

The instantaneous rate of change in length of Brownlip abalone is assumed to be a Gaussian function of the length L_t of an abalone of age t years, i.e.

$$dL_t / dt = Ae^{-(L_t - u)^2 / 2\sigma_{\mathrm{GF}}^2} \tag{3.50}$$

where A is the maximum instantaneous growth rate (mm y^{-1}), u is the shell length (mm) at which the instantaneous growth rate is a maximum and σ_{GF} (mm) is a parameter that determines the shape of the Gaussian function (Rogers-Bennett et al. 2007). This form of growth function was selected from several alternative models by comparing the values of Akaike's Information Criterion for the fitted curves (Section 4.3.1). If the length of an abalone at time $t = t_0$ is $L_{t=t_0}$, then its expected length $\hat{L}_{t=t_0+T}$ at time $t = t_0 + T$ is

$$\hat{L}_{t=t_0+T} = L_{t=t_0} + \Delta\hat{L}_{t_0,t_0+T} = L_{t=t_0} + \int_{t=t_0}^{t=t_0+T} Ae^{-(L_t-u)^2/2\sigma_{\mathrm{GF}}^2} dt, \qquad 3.51$$

where $\Delta\hat{L}_{t_0,t_0+T}$ is the expected length increment between $t = t_0$ and $t = t_0 + T$. For each tagged Brownlip abalone, this "initial value problem" was solved using a 4th order Runge-Kutta algorithm to calculate an estimate of its expected length at the time of re-measurement given the values of the growth parameters A, u and σ_{GF}. The durations "at liberty" of the individuals of Brownlip abalone ranged between ~6 months to ~2 years. The parameters of the growth model (as described by the above Gaussian function) were estimated by minimising the negative log-likelihood where it was assumed that, for abalone j, the observed length increment X_j represented a random variable drawn from the gamma distribution about the estimated increment $\hat{X}_j$ given its initial length and the time between its tagging and re-measurement.

The shape and scale parameters of this distribution, i.e. α_j and β_j, were calculated as

$$\beta_j = \left(\frac{\hat{X}_j}{\hat{\sigma}_\Gamma^2} \right) \qquad 3.52$$

and

$$\alpha_j = \left(\frac{\hat{X}_j}{\hat{\sigma}_\Gamma^2} \right) \hat{X}_j \qquad 3.53$$

where $\hat{\sigma}_\Gamma^2$, the variance associated with the gamma distribution, was estimated as a parameter of the model. The log-likelihood, λ_1, associated with the observed length increments was calculated as

$$\lambda_1 = \sum_j \log_e \left\{ \frac{\beta_j^{\alpha_j}}{\Gamma(\alpha_j)} X_j^{\alpha_j - 1} e^{-\beta_j X_j} \right\}. \qquad 3.54$$

Length-transition matrix

Growth is modelled using a size transition matrix, $G = \{g_{k,j}\}$, which represents the probability that an abalone in length class *j* grows into length class *k* during an annual time step. That is,

$$G = \begin{bmatrix} g_{1,1} & & \cdot & & \\ g_{2,1} & g_{2,2} & \cdot & & \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ g_{n-1,1} & g_{n-1,2} & \cdot & g_{n-1,n-1} & \\ g_{n,1} & g_{n,2} & \cdot & g_{n,n-1} & g_{n,n} \end{bmatrix} \qquad 3.55$$

where n is the largest of the (2 mm) length classes considered in the model, and each column sums to 1 (e.g. Haddon 2011). Growth is treated as a discrete event occurring at the end of each biological year. The model was updated at annual time steps.

As described by Punt et al. (1997; see also Hall et al. 2000; Haddon 2011), the general form of a size-transition matrix is

$$g_{k,j} = \begin{cases} \int\limits_{-\infty}^{L_k^+} f\left[\underline{\phi}\left(T, L_j\right)\right] dL & \text{if } k = 1 \\ \int\limits_{L_k^-}^{L_k^+} f\left[\underline{\phi}\left(T, L_j\right)\right] dL & \text{if } 1 < k < n \\ \int\limits_{L_k^-}^{\infty} f\left[\underline{\phi}\left(T, L_j\right)\right] dL & \text{if } k = n \end{cases} \qquad 3.56$$

where L is the length, f is the specified distribution function, L_j^- and L_j^+ are the lower and upper limits, respectively, of length class j, and $\underline{\phi}$ is a vector of parameters dependent on the time period *T*, i.e. $T = 1$ year, and the midpoint of size class *j*, L_j.

In this model, f is a gamma distribution (to allow for potential skewness and prevent negative growth) for which

$$f\left[\underline{\phi}\left(T, L_j\right)\right] = \left(\frac{\beta_j^{\alpha_j}}{\Gamma\left(\alpha_j\right)}\right)\left[L - L_j\right]^{\alpha_j - 1} e^{-\beta_j\left[L - L_j\right]} \qquad 3.57$$

and where α_j and β_j are the parameters of the distribution for an initial length of L_j and time step $T = 1$ year, and $\Gamma(.)$ is the gamma function.

The mean and variance of the gamma distribution in the above equation is α_j / β_j and α_j / β_j^2, respectively, where it was assumed that the variance of annual increments about their mean is constant for all L_j and equal to $\hat{\sigma}_\Gamma^2$. If the mean growth increment from length class j for the period $T = 1$ year is denoted ΔL_j, then $\beta_j = \Delta L_j / \hat{\sigma}_\Gamma^2$ and $\alpha_j = \beta_j \Delta L_j$. The mean growth increment for a 1 year time interval was calculated using the maximum likelihood estimates of the parameters of the growth function and the associated statistical distribution of length increments for tagging data, as outlined above.

Weight-length relationship

W_j, the meat weight (kg) of an individual in length class *j*, is calculated as

$$W_j = \left\{\exp\left[a + b \log_e L_j\right]\right\} \exp\left(0.5\sigma_{\text{wtlen}}^2\right) / 1000 \qquad 3.58$$

where a and b are the weight-length parameters common to both sexes. The weight-length relationship includes a bias correction associated with back transformation from the logarithm of expected weight (Beauchamp and Olson 1973), where σ_{wtlen}^2 is the variance estimated from the fitted linear log-transformed weight-length relationship.

Maturity

ψ_j^{mat}, the proportion mature in length class j, is calculated as

$$\psi_j^{mat} = \begin{Bmatrix} 0 & \text{if } L_j < 120 \\ 1 & if\, L_j \geq 120 \end{Bmatrix} \tag{3.59}$$

where L_j is the midpoint of length class j.

Catches

The estimated catch biomass (kg) of abalone of length class j taken in year y is calculated from the Baranov catch equation, i.e.

$$C_{j,y} = \left(F_{j,y} / Z_{j,y}\right)\left\{1 - \exp\left(-Z_{j,y}\right)\right\} N_{j,y} W_j \tag{3.60}$$

Calculation of the objective function

Length compositions

The size compositions were assumed to conform to a Dirichlet distribution (Schnute and Haigh 2007). This distribution was used in preference to the multinomial distribution (most often used in stock assessments for compositional data) because, when applying the Dirichlet distribution, the parameters required to appropriately weight the likelihood associated with the compositional data are estimated inside the model. This thereby avoided any need to apply an iterative weighting procedure for compositional data outside the model (Francis 2011; Francis 2014). Denoting the observed and estimated proportions in length class j for year y as $P_{j,y}$ and $\hat{P}_{j,y}$, respectively, and where $\hat{P}_{j,y}$ is calculated as

$$\hat{P}_{j,y} = \frac{\hat{C}_{j,y}}{\sum_j \hat{C}_{j,y}} \tag{3.61}$$

The log-likelihood associated with the catch curve data is

$$\lambda_2 = \sum_y \sum_j \left[\log_e \Gamma\left(\varsigma_y \hat{P}_{j,y}\right) - \varsigma_y \hat{P}_{j,y} \log_e\left(\hat{P}_{j,y}\right)\right] - \log_e \Gamma\left(\varsigma_y\right) \tag{3.62}$$

where the estimated effective sample size for year y, ς_y, depending on Stirling's approximation for the gamma function, is calculated as

$$\varsigma_y \approx \frac{n-1}{2}\left[\sum_{j=1}^{n} \log_e\left(\frac{\hat{P}_{j,y}}{P_{j,y}}\right)\right]^{-1} \tag{3.63}$$

The Dirichlet likelihood function was 'robustified' by 1) left-truncating the length frequency distributions in all years to minimise the number of length classes for which zero frequencies were recorded. For the few remaining length classes in each year for which a zero frequency was recorded, the zero value was replaced by a small number of similar magnitude to the lowest observed proportion within the dataset (i.e. 0.0001) (Francis 2014).

Catch Rates

$\hat{U}_y$, the estimated catch rate in year y is estimated as

$$\hat{U}_y = q_p B_y^E \tag{3.64}$$

where q_p is the catchability coefficient in catch rate period, p, estimated as a model parameter. The catch rate data were separated into two periods, namely 1999-2011 and 2012-2015. Because, during the first period, a single diver fished during each fishing day per vessel, whereas, in the second period, generally two divers fished on each of those days, so it was considered likely that this would have influenced catchability. B_y^E is the estimated exploitable biomass in year and is calculated as

$$B_y^E = \sum_j N_{j,y} W_j V_{j,y} \tag{3.65}$$

The observed catch rates were assumed to be log-normally distributed about the expected values. The negative log-likelihood for the catch rate data, λ_3, was calculated as

$$\lambda_3 = 0.5n \log_e 2\pi + 0.5 \sum_y \log_e \left(\sigma_{1,y}^2 + \sigma_2^2\right) + 0.5 \sum_y \log_e \left[\left(\log_e \left(U_y\right) - \log_e \left(\hat{U}_y\right) \right)^2 / \left(\sigma_{1,y}^2 + \sigma_2^2\right) \right] \tag{3.66}$$

where $\sigma_{1,y}^2$ is the variance associated with the observed mean catch rate in year y and σ_2^2 is the additional "model" variance, estimated as a parameter.

The overall negative log-likelihood, λ, was calculated as $\lambda = \lambda_2 + \lambda_3$.

If growth were to be estimated inside the assessment model (not in this study), then the overall negative log-likelihood would be calculated as $\lambda = \lambda_1 + \lambda_2 + \lambda_3$, where λ_1 represents the value associated with the growth curve.

4 Results

4.1 Tag-Recapture Study

This section addresses part of objective 1, which is to determine the growth and natural mortality of wild Brownlip abalone populations.

4.1.1 Size Frequency and Growth

At the 19 tag-recapture sites established, 1171 Brownlip abalone were captured and tagged over all surveys (Table 4.1). The number of Brownlip abalone tagged varied within each site and subsequently sub-area, with the Windy Harbour sub-area having nearly twice the number of sites and abalone tagged than any other sub-area. Across all the sub-areas surveyed and recapture occasions, 52.3% of the abalone tagged were recaptured. Only the Augusta sub-area had a recapture rate lower than 50%, and of all animals tagged in the study only 2.8% were reported as dead (Table 4.1). An example of a tag-recapture site with Brownlip abalone in their natural habitat, and the epoxy resin tag adhered to the shell which individually identifies the animal is shown in Figure 4.1.

The length frequency data for all Brownlip abalone tagged, highlights that very few (<6%) of the animals captured had a size less than 100 mm shell length, whilst the length range with the highest frequency of Brownlip captures was 150-170 mm shell length (Figure 4.2). The tag-recapture sites within Area 3 had a slightly higher proportion of Brownlip abalone at lengths <160 mm, whereas Area 2 had a greater proportion of abalone with lengths >160 mm (Figure 4.2). The mean length of Brownlip abalone tagged in Area 2 was 151.1 ± 1.2 mm while those in Area 3 had a mean length of 144.4 ± 0.9 mm. When the tagged Brownlip abalone length frequencies were separated by sub-area, the variation between Areas 2 and 3 becomes apparent (Figure 4.3). The Hopetoun sub-area had tagged Brownlip abalone with a relatively even spread over a 100 mm size range (90-190 mm), but a bimodal distribution with animals at both the 160 and 190 mm size categories having the highest proportion. Very few (<10%) Brownlip abalone tagged in the Town sub-area were below the LML of 140 mm and a relatively large proportion (39%) of animals were 170-180 mm in length. The tagged Brownlip abalone from the remaining three sub-areas tended to follow a unimodal distribution with a mode of 150 mm shell length (Figure 4.3).

The high frequency of Brownlip abalone captured over 150 mm shell length (Area 2=71% and Area 3=62%) indicated that the large, legal size adults formed the dominant component of the tag-recapture survey. At this size, a considerable number of Brownlip abalone exhibit very little (<5 mm) to no growth based on shell length (Figure 4.4). Tagged Brownlip abalone >160 mm rarely had growth increments between recapture periods (standardised to a year time at liberty) of >10 mm, while abalone below 120 mm produced growth increments ranging from 0 to 55 mm shell length. Brownlip abalone in Area 2 appeared to grow slightly faster than Brownlip abalone in Area 3 (Figure 4.4). These growth increments presented in Figure 4.4 have been standardised to a year time at liberty to give a visual impression of the growth variability present in Brownlip abalone. For any statistical modelling in this study that estimates growth utilising these growth increments, the varying time at liberty has been accounted for as described in Section 3.3.1.

Table 4.1: The total number of Brownlip abalone tagged, recaptured and recovered dead at the tag-recapture sites in each sub-area across the Western Australian Brownlip abalone fishery.

Sub-area	No. Sites	Total Tagged	Recaptured	Recovered Dead
Augusta	3	186	77	7
Windy Harbour	7	419	235	6
Hopetoun	4	155	84	11
Town (Esperance)	3	224	116	3
Duke	2	187	100	6
Total	19	1171	612	33

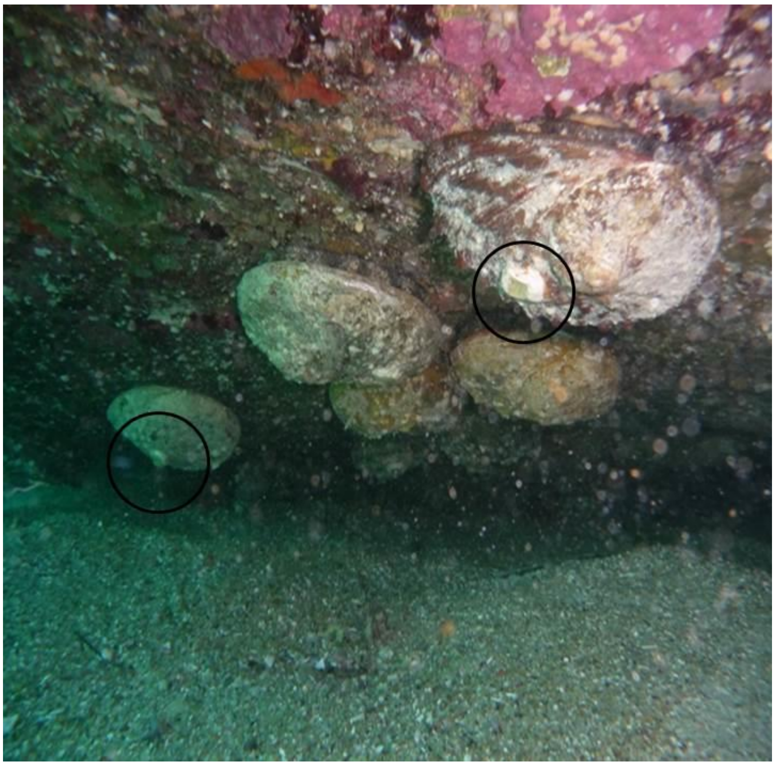


Figure 4.1: A Brownlip abalone tag-recapture site with several Brownlip abalone showing the epoxy resin tags (highlighted by the circles).

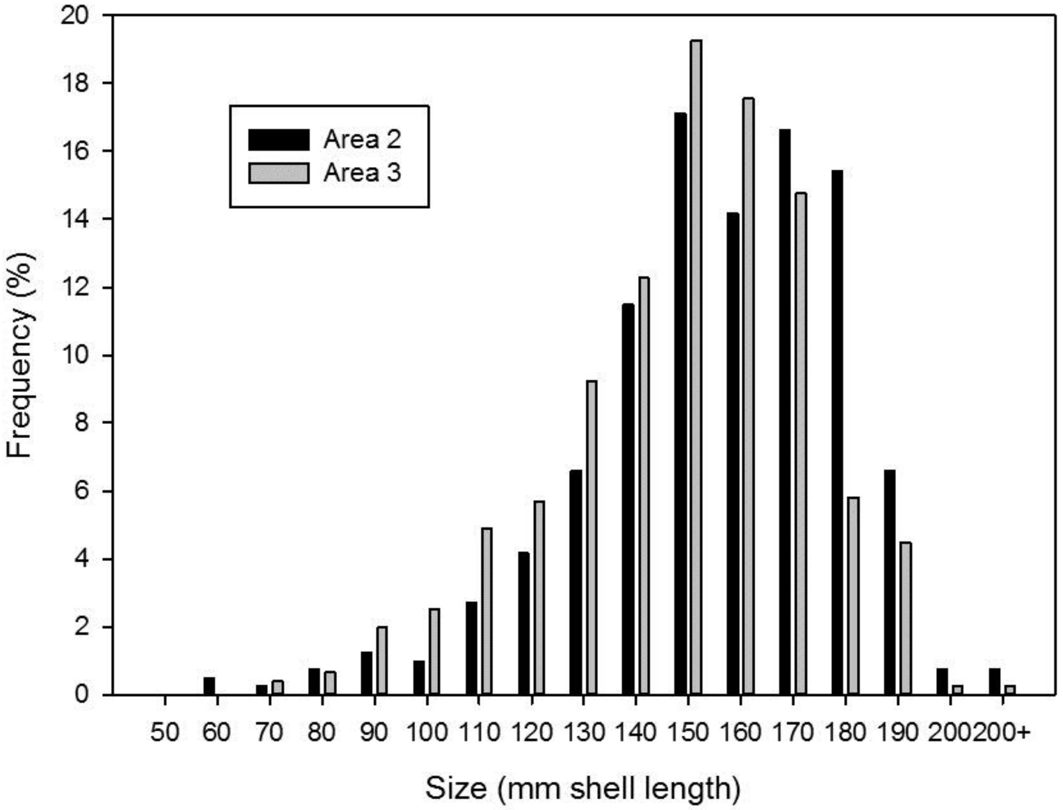


Figure 4.2: Length frequency of tagged Brownlip abalone for all 19 tag-recapture sites, plotted by management area. The frequencies of different size categories in each area represent the percentages of those size categories over all sizes in that area (Area 2 *n*=411 and Area 3 *n*=760).

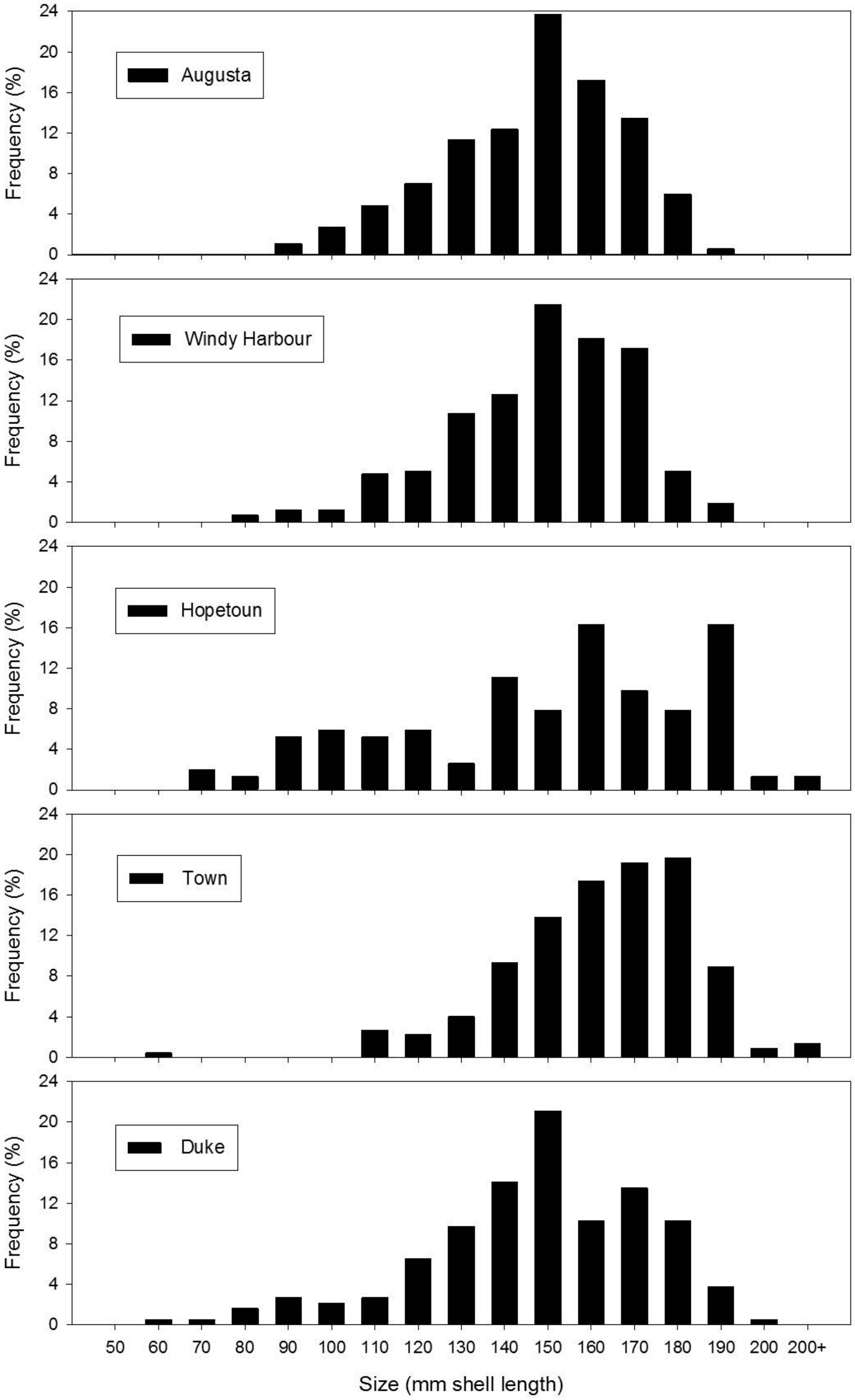
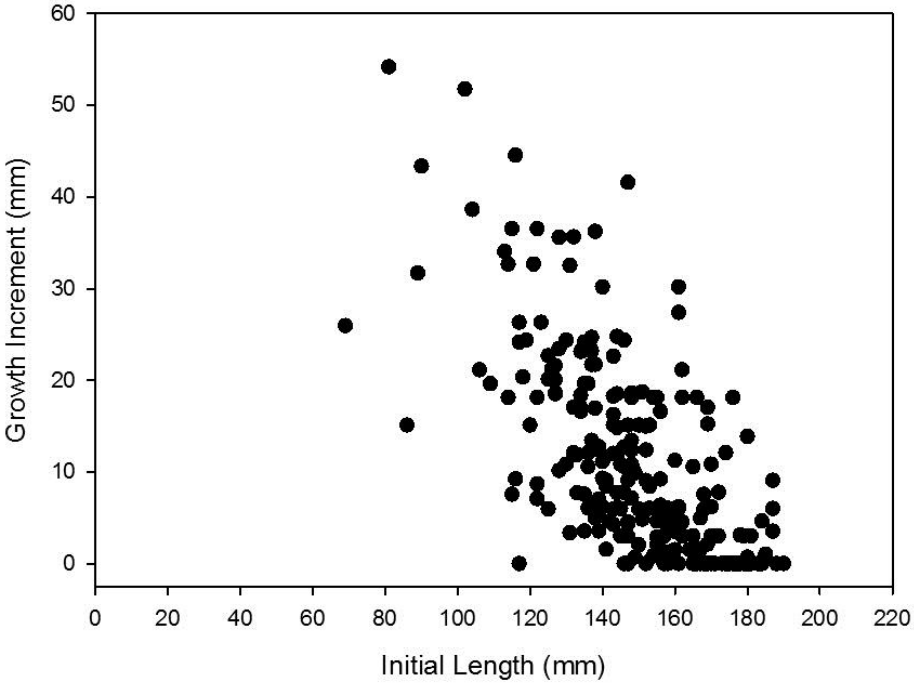


Figure 4.3: Length frequency of tagged Brownlip abalone for all 19 tag-recapture sites, plotted by management sub-area (for sample size see Table 4.1).

a)



b)

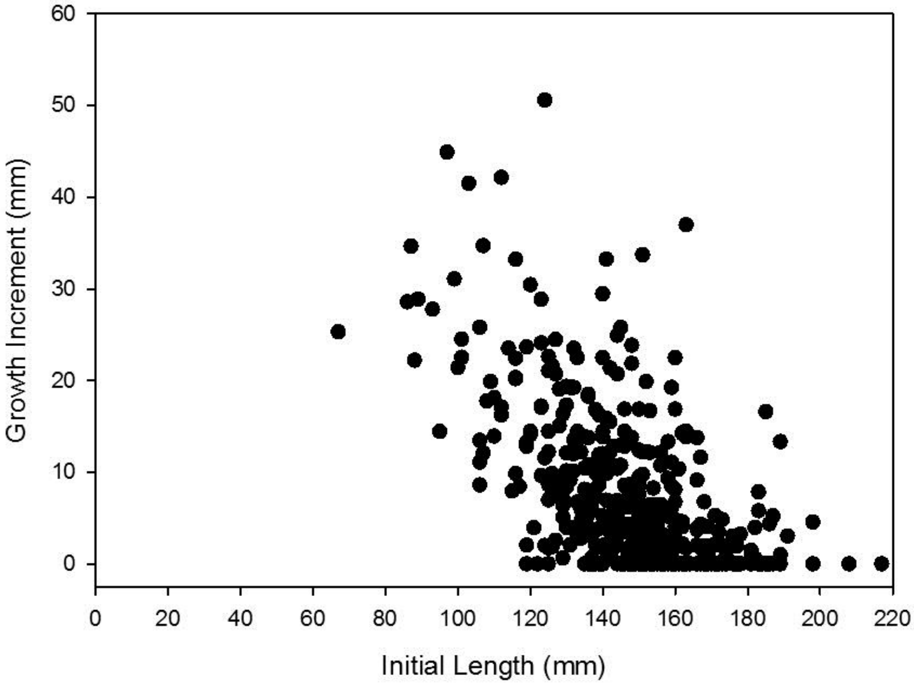


Figure 4.4: Brownlip abalone growth increments (mm) standardised to a year time at liberty plotted against their initial tagged length (mm), for animals captured at sites within management Area 2 (a) and Area 3 (b) of the Brownlip abalone fishery.

4.1.2 MARK Survival Estimates

The results of the GOF tests revealed minor over-dispersion for the saturated model for all sub-areas, as the variance inflation factor ($\hat{c}$) was estimated and ranged from 1.17 to 2.75 (Table 4.2). The model fit to the data indicated violations of the CJS assumption of equal probability of capture and survival of tagged animals. This was more likely the case for the probability of capture, as Brownlip abalone are very cryptic and it could be difficult to capture all animals at a site when considering the safety of divers. Given the minor over-dispersion of the data, the $\hat{c}$ estimates were incorporated to calculate the QAICc values and adjust the sensitivity of the model selection process. The ΔQAICc was <2 in the candidate set of models for the Windy Harbour, Duke and Town sub-areas, and so the models were considered to have approximately equal weight of describing the data, therefore estimates of survival were derived by model averaging. The candidate set of models (see Section 3.1) for the Hopetoun sub-area had a ΔQAICc of 4.2, but only the fully time dependent model ($\phi_t p_t$) had a ΔQAICc >2. This particular model's weighting was only 0.068, so its effect on the estimates produced by model averaging was low, while the survival estimates were within the range of the survival estimates of the other 3 models in the candidate set.

Survival probability estimates derived from model averaging for the 5 sub-areas across the 3 recapture periods ranged from 0.6 to 0.9 y^{-1} (Figure 4.5). For all sub-areas but Town, there is a similar trend in the point estimates for survival between recapture periods, where those for the first and third recapture periods are higher than the second recapture period. Given the 95% confidence levels of survival estimates overlap to some degree between recapture periods for each individual sub-area it is unlikely there will be significant differences in the estimates. The Augusta sub-area sites were unable to be pooled as there were differences in time at liberty between each site's recapture periods, subsequently the site survival estimates were averaged *post-hoc*. Overall, the Town sub-area had the highest estimates for survival (0.79-0.88 y^{-1}), while the Windy Harbour sub-area had the lowest (0.61-0.70 y^{-1}) (Figure 4.5).

The recapture (p) estimates for all sub-areas ranged from 0.61 to 0.8 y^{-1} (Table 4.2). However, given that the 95% confidence levels for the various estimates all overlapped, and as the methods for deriving those estimates were the same, the recapture estimates were unlikely to have differed significantly across the sub-areas.

As a result of the time constant model ($\phi_{.} p_{.}$) having a ΔQAICc <2 for all sub-areas, this model was used for point estimates of survival that could then be transformed into total mortality (Z) estimates. The Z estimates ranged from 0.12 to 0.39 y^{-1} with the Town sub-area having the lowest estimate and the Windy Harbour sub-area the highest (Table 4.2).

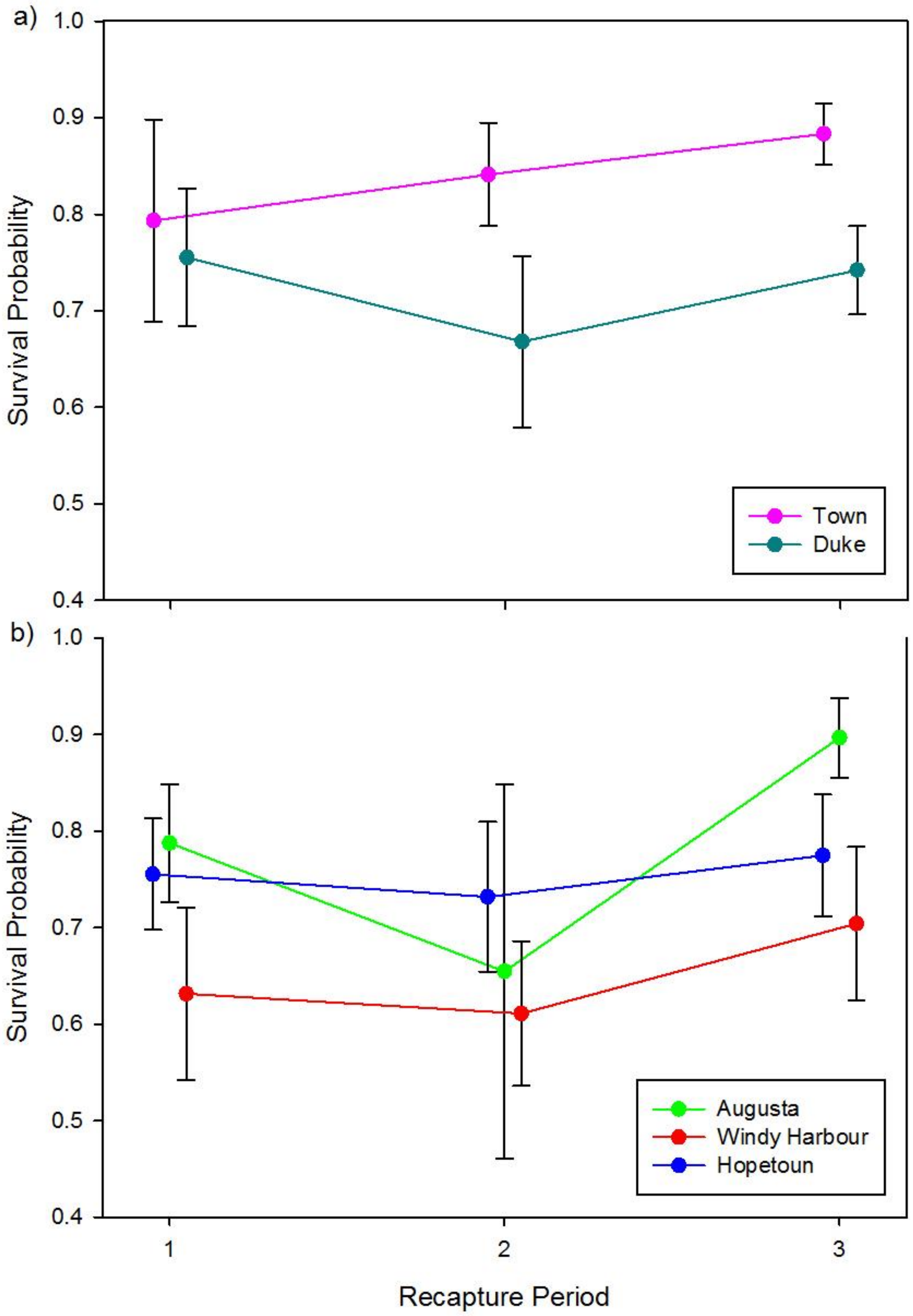


Figure 4.5: Apparent survival estimates (± se) for Brownlip abalone in the 5 sub-areas across the 3 recapture periods surveyed in the tag-recapture study, a) sub-areas in Area 2 and b) sub-areas in Area 3. Survival estimates were produced by the MARK software program with model averaging results based on the candidate set of models for each site.

Table 4.2: Total Mortality ($\boldsymbol{Z}$; y^{-1}) and probability of recapture ($\boldsymbol{p}$) estimates for Brownlip abalone from each of the 5 sub-areas in the tag-recapture study. Survival and recapture estimates were produced by the MARK software program using the time dependent model ($\dot{\phi}\boldsymbol{p}_{.}$). The variance inflation factor (VIF, ĉ) for the fully parameterised model and the ∆QAICc for the time constant model were used in the model selection process. Survival estimates were then converted *post-hoc* to mortality estimates.

Sub-area	**Mortality**		**Recapture**		**VIF**	**∆QAICc**
	Z	±2 se	p	±2 se	ĉ	
Augusta	0.26	0.18	0.75	0.10	na	na
Windy Harbour	0.39	0.10	0.63	0.14	2.75	1.85
Hopetoun	0.27	0.09	0.80	0.17	2.33	0
Town	0.12	0.07	0.61	0.16	1.91	1.04
Duke	0.31	0.07	0.77	0.13	1.17	0.69

4.2 Aquaculture Trials

This section addresses objective 2, which is to determine growth rates and mortality of cultured Brownlip abalone.

4.2.1 Current Commercial Brownlip Abalone Growth Estimates

Baseline growth estimates of Brownlip abalone in the current systems at a commercial abalone farm have been established. Juvenile Brownlip abalone exhibited growth rates averaging 62.2 ± 0.5 $\mu m.d^{-1}$ in the nursery system from settlement to harvest (6-8 months). The grow-out systems shallow, exposed concrete slab tanks were relatively ineffective at housing juvenile Brownlip abalone, as they resulted in a high rate of walk out (abalone crawled out of the tank) or clumping into high density patches, which both cause mortality and stunted growth. To try and overcome this, a change in tank design to an intermediate tank, which was deeper and had concrete hides for habitat was considered (e.g. Figure 3.2a). These hide tanks facilitated growth rates of 36.2 $\mu m.d^{-1}$ for 25 to 35 mm animals and 41.8 $\mu m.d^{-1}$ for 35 to 45 mm Brownlip abalone. Grading in the hide tanks to select the larger sizes of Brownlip abalone and remove the animals with slower growth, consequently reduced stocking density and led to an increase in growth rates to 67.8 $\mu m.d^{-1}$ for 30 to 45 mm and 69.9 $\mu m.d^{-1}$ for 40 to 55 mm animals. After being in the hide tanks the Brownlip abalone were moved into slab tanks to assess this grow-out systems tank design suitability for larger sized animals. Brownlip abalone of 60 to 75 mm shell length were able to produce a growth rate of 44.0 $\mu m.d^{-1}$ in the slab tanks but did still exhibit walk out and clustering due to the shallow exposed nature of the tank.

4.2.2 Grow-out System Design Trial

The Brownlip abalone (45 mm shell length) in all tank design treatments grew during the first 3 month trial, with the two treatments using concrete hides producing abalone of 49.5 mm shell length and the Poly Ribs tank design recording abalone of 46.5 mm shell length (Figure

4.6). The control treatment (hide tank design) produced Brownlip abalone with a growth rate of 49.48 µm.d^{-1} and weight gain of 60.99 µg.d^{-1}, which was followed closely by the increased water flow treatment (Table 4.3).

The Poly Ribs tank design housed Brownlip abalone that recorded a significantly slower growth rate and weight gain than the abalone stocked in the other two tank designs. The survival of Brownlip abalone over the 3 month trial ranged from 88.9 to 94.7% with no significant difference between the treatments (Table 4.3).

In the 4 month trial stocked with 71 mm Brownlip abalone, the growth rate and weight gain per individual abalone was greatest in the hide tanks with high water flow, at 58.63 µm.d^{-1} and 200.3 µg.d^{-1} respectively, followed by the abalone in the control hide tanks and then the Poly Rib tanks (Table 4.4). Although there was no significant difference between abalone growth rates (in terms of length) in the three tank design treatments, the weight gain per individual was significantly less for the abalone in the Poly Ribs tank design than the other two treatments (Table 4.4). The survival of Brownlip abalone over the 4 month trial ranged from 88.7 to 92.5% with no significant difference between the treatments (Table 4.4).

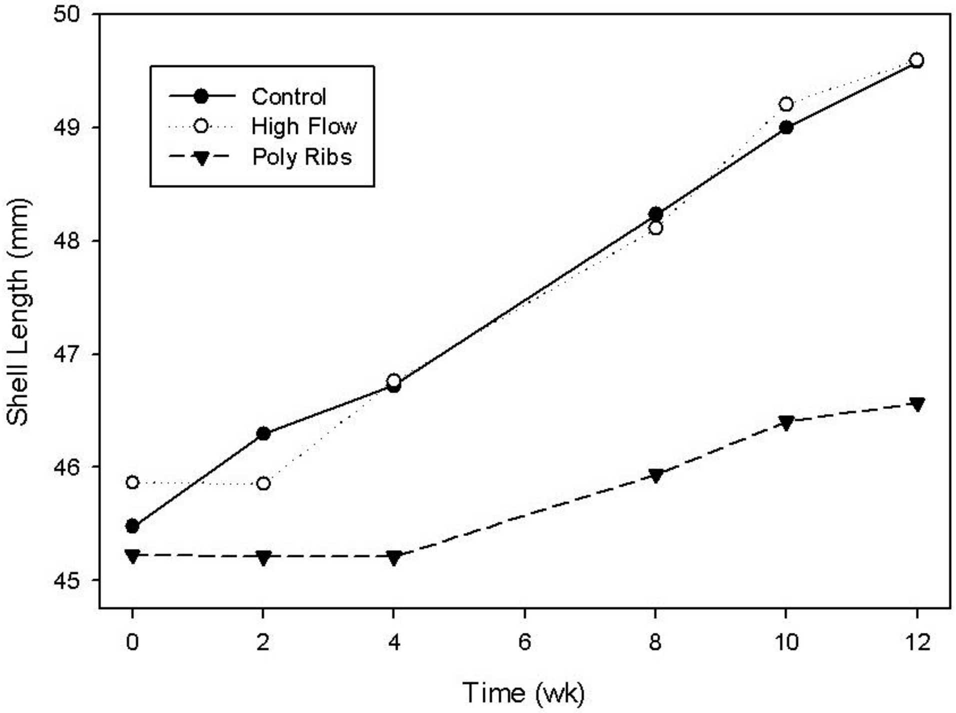


Figure 4.6: The growth in shell length (mm) of Brownlip abalone (45 mm cohort) in the 3 month trial for the three experimental tank designs, Control, High Flow and Poly Ribs. Mean (*n*=4).

Table 4.3: Growth rate (μm.d^{-1}), weight gain per individual (μg.d^{-1}) and survival (%) of 45 mm shell length Brownlip abalone in the three experimental tank designs over a 3 month trial. One-way ANOVA indicated significant differences (p<0.05) between tank design means for each abalone measurement as illustrated by different superscripts (columns). Mean ± std error (n=4).

Tank Design	**Growth Rate** μm.d^{-1} ± se	**Weight Gain** μg.d^{-1} ± se	**Survival** % ± se
Control	49.48 ± 3.41^{a}	60.99 ± 1.92^{a}	94.7 ± 2.7
High Flow	44.95 ± 5.99^{a}	53.52 ± 5.09^{a}	88.9 ± 2.9
Poly Ribs	16.16 ± 4.29^{b}	28.82 ± 3.12^{b}	92.9 ± 2.9
df	2, 9	2, 9	2, 9
F	24.41	44.17	1.08
p value	<0.05	<0.05	0.38

Table 4.4: Growth rate (μm.d^{-1}), weight gain per individual (μg.d^{-1}) and survival (%) of 71 mm shell length Brownlip abalone in the three experimental tank designs over a 4 month trial. One-way ANOVA indicated significant differences (p<0.05) between tank design means for each abalone measurement as illustrated by different superscripts (columns). Mean ± std error (n=4).

Tank Design	**Growth Rate** μm.d^{-1} ± se	**Weight Gain** μg.d^{-1} ± se	**Survival** % ± se
Control	55.15 ± 4.43	192.6 ± 5.9^{a}	89.4 ± 3.8
High Flow	58.63 ± 3.20	200.3 ± 14.5^{a}	88.7 ± 3.3
Poly Ribs	50.72 ± 1.85	151.5 ± 10.8^{b}	92.5 ± 2.4
df	2, 9	2, 9	2, 9
F	1.42	5.72	0.39
p value	0.29	<0.05	0.68

4.3 Growth and Catch Curve Models

This section addresses parts of objectives 1, 2 and 4. These objectives are to determine the growth and mortality of wild and cultured Brownlip abalone, develop fishing size limits and optimal market sizes based on size distribution and growth, and examine the harvest potential of the total industry.

4.3.1 Growth Models

When fitted to data from the Brownlip abalone tag-recapture study sites (Areas 2 and 3 combined) as well as the growth from aquaculture trials, the double logistic model and Gaussian function both provided substantially better fits to the Brownlip abalone data than the Gompertz (unable to be fitted) and von Bertalanffy models (Table 4.5).

Although the quality of the fits provided by the former two models were very similar, the negative log-likelihood for the double logistic model was the lower of the two, while the AIC for the Gaussian function was slightly lower than for the double logistic curve (Table 4.5). On the basis of the AIC statistic, the Gaussian function would be considered the most parsimonious model (i.e. the most justifiable level of model complexity given the available data).

Plots showing the fit of the Gaussian function to the available growth increment data for Brownlip abalone from the entire WA fishery (Area 2 and 3 combined) and associated diagnostic plots are provided in Figure 4.7. The times at liberty of Brownlip abalone were variable and thus the relationship between the growth increments, and also final lengths with respect to initial length was not “smooth” (Figure 4.7 a, b), For example, the observed growth increments of Brownlip abalone in the aquaculture trials initially measured at 45 and 70 mm were few and generally much less than for individuals below and above this range. This, to a major extent, reflected the relatively short times at liberty of animals of 45 and 70 mm used from the aquaculture trials (~100 days) compared with those for most other individuals. The Gaussian function provided a relatively good fit to the length increment data, as indicated by the lack of obvious structural deviations of the residuals between the observed and estimated final shell lengths with respect to initial length, or time at liberty (Figure 4.7 c, d).

On the basis of the fitted growth model, on average, Brownlip abalone of initial lengths of 50, 100 and 150 mm, respectively, are estimated to grow by 32, 19 and 6 mm within a year. By 2, 5 and 10 years of age, on average, individuals are expected to have attained lengths of about 55, 131 and 162 mm. The same plots produced when fitting the double logistic model to the data for Brownlip abalone are almost identical (figure not included).

Table 4.5: Values of estimated parameters derived by fitting the Double logistic model, Gaussian function, Gompertz model and von Bertalanffy growth model to tag-recapture data for Brownlip abalone in Western Australia. Stdev refers to standard deviation, $\boldsymbol{NLL}$ refers to negative log-likelihood, and $\boldsymbol{AIC}$ refers to Akaike's Information Criterion statistic. The growth curves were fitted to 628 observations.

Double logistic model			**Gaussian function**			**Gompertz model**			**von Bertalanffy model**		
Parameters	Estimates	Stdev	Parameters	Estimates	Stdev	Parameters	Estimates	Stdev	Parameters	Estimates	Stdev
a	0.113	0.009	A	0.094	0.013	L_∞ (mm)	NA	NA	L_∞ (mm)	198.05	10.23
$L_{50,1}$ (mm)	46.48	25.15	U (mm)	55.33	5.38	g	NA	NA	k (y^{-1})	0.15	0.09
$L_{95,1}$ (mm)	121.31	92.20	σ (mm)	53.17	5.54						
$L_{50,2}$ (mm)	121.91	12.09									
$L_{95,2}$ (mm)	171.84	7.00									
NLL	743.93			745.46						749.85	
AIC	1497.86			1496.93						1503.7	

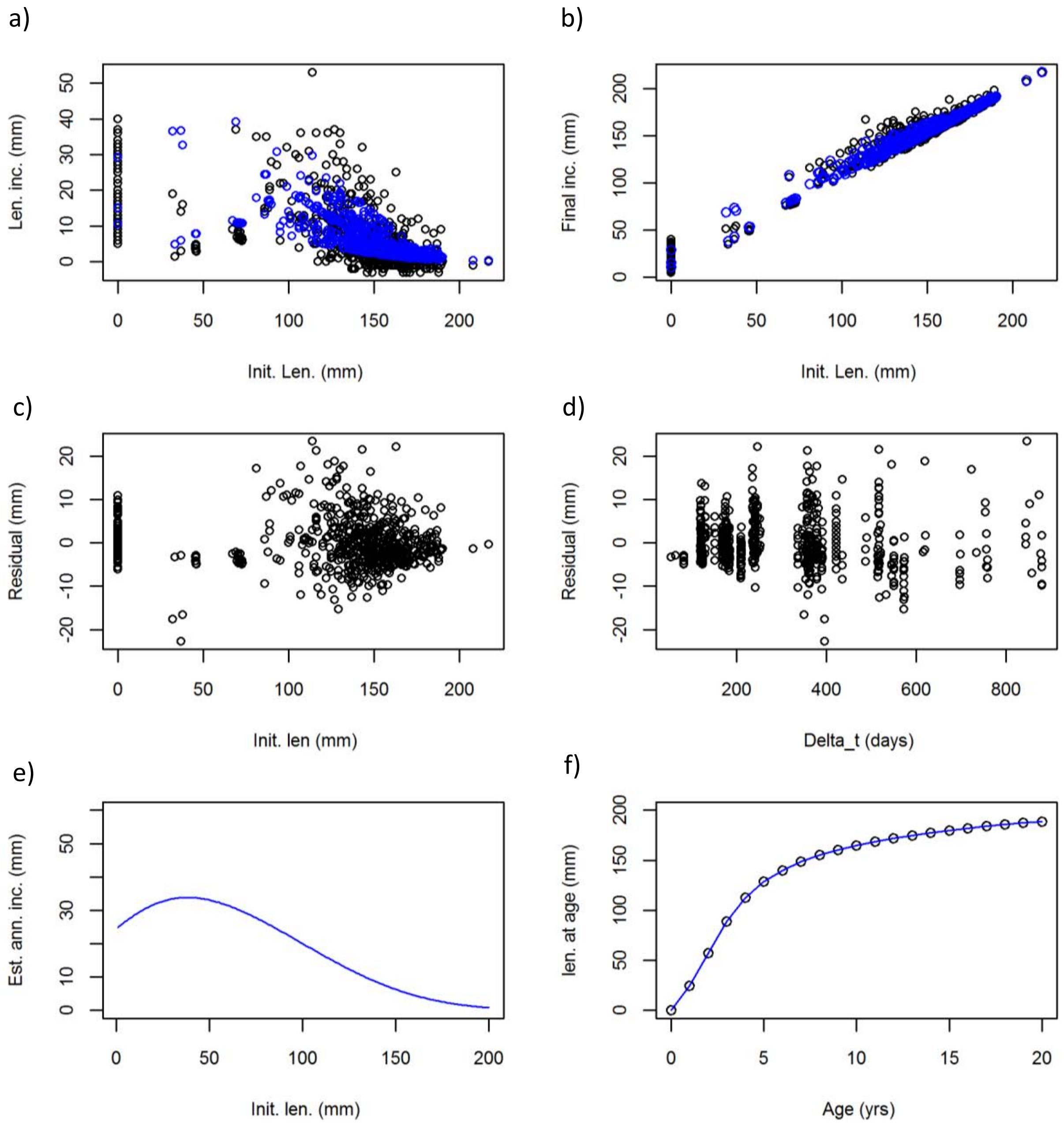


Figure 4.7: Plots associated with the fitting of a Gaussian function to tag increment data for Brownlip abalone in Western Australia. a) observed (black circles) and expected (blue circles) growth increments; b) final lengths after one year, for abalone with respect to their initial sizes and taking into account their varying times at liberty; c) residuals between the observed and expected annual growth increments with respect to initial length and d) time at liberty (days); e) estimated average annual growth increment as a function of initial length; and f) expected lengths at each integer age, based on the relationship described in e).

4.3.2 Length-based Catch Curve Models

The catch curve model, based on the Baranov catch equation and employing a logistic function to describe the length-based selectivity pattern, tended to provide good visual fits to the Brownlip abalone commercial catch length-frequency data in pooled 3 year blocks between 2004 and 2015 (Figure 4.8). The estimates of total mortality for Brownlip abalone across the fishery ranged from 0.18 to 0.26 y^{-1} (Table 4.6). The estimated lengths at which 50% and 95% of Brownlip abalone become selected into the fishery were relatively similar in the pooled years, i.e. 150-158 mm and 160-170 mm, respectively. However, there was a gradual decreasing trend present in both the L_{50} and L_{95} over time (Table 4.6), indicating that, on average, the sizes of Brownlip abalone caught have declined. This is evident by the lower proportions of larger animals and higher proportions of smaller animals caught during 2013-2015 compared with the earlier time periods (Figure 4.8). Although the point estimates for Z derived from the two catch curve models were relatively similar, the precision of those derived from the Pauly (1984) method were very poor (Table 4.7), and thus the method of Pauly (1984) was considered less useful for Brownlip abalone.

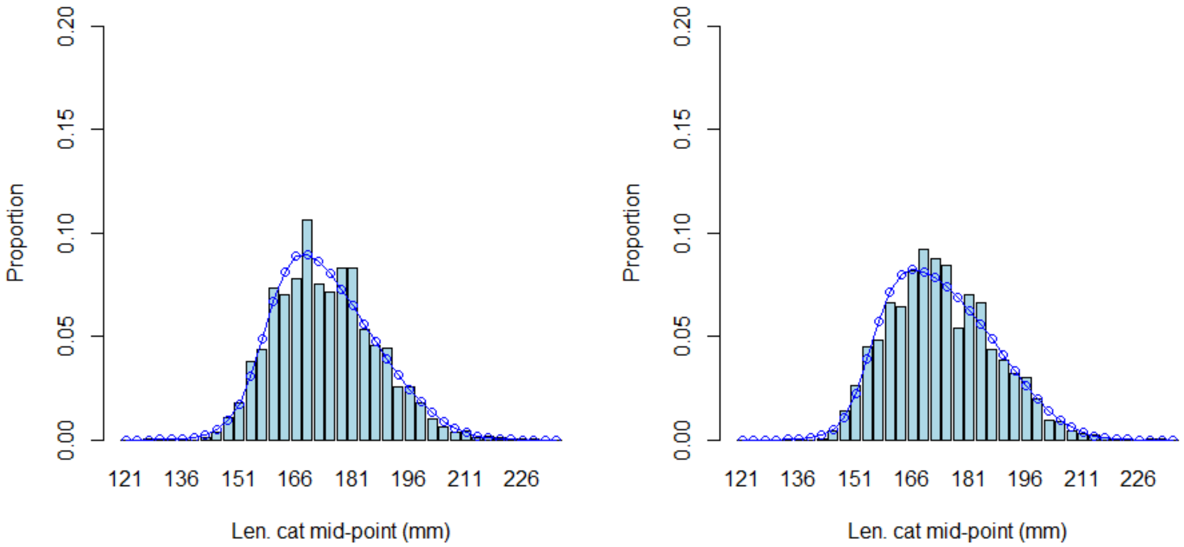
Table 4.6: Estimates of total mortality ($\boldsymbol{Z}$; y^{-1}) and selectivity parameters ($\boldsymbol{L_{50}}$ and $\boldsymbol{L_{95}}$; mm) derived by fitting a catch curve assuming a multinomial likelihood to commercial length-frequency data for Brownlip abalone. Growth curves were fitted simultaneously to tag-recapture data whilst fitting each catch curve to pooled 3 year blocks of annual commercial catch length-frequency data. Standard error denoted by se.

Year	Z, y^{-1} (± se)	L_{50}, mm (± se)	L_{95}, mm (± se)	NLL	*n*
2004 – 2006	0.26 (0.04)	158.2 (1.0)	170.7 (1.9)	5777.42	1733
2007 – 2009	0.20 (0.03)	154.9 (0.9)	165.6 (1.9)	7089.14	2166
2010 – 2012	0.18 (0.03)	153.3 (1.6)	164.2 (3.2)	3096.92	814
2013 – 2015	0.26 (0.04)	150.2 (0.7)	160.9 (1.5)	8856.48	2781

Table 4.7: Estimates of total mortality ($\boldsymbol{Z}$; y^{-1}) derived by fitting the Pauly (1984) length-based catch curve to commercial length-frequency data for Brownlip abalone. Growth curves were fitted simultaneously to tag-recapture data whilst fitting each catch curve to pooled 3 year blocks of annual commercial catch length-frequency data. Standard error denoted by se.

Year	Z, y^{-1} (± se)	y intercept (± se)	NLL	*n*
2004 – 2006	0.15 (3.25)	6.33 (57.03)	765.51	1733
2007 – 2009	0.14 (2.58)	6.46 (52.31)	766.81	2166
2010 – 2012	0.18 (7.79)	5.83 (76.83)	761.59	814
2013 – 2015	0.19 (4.01)	7.14 (53.2)	766.81	2781

2004-2006 2007-2009



2010-2012 2013-2015

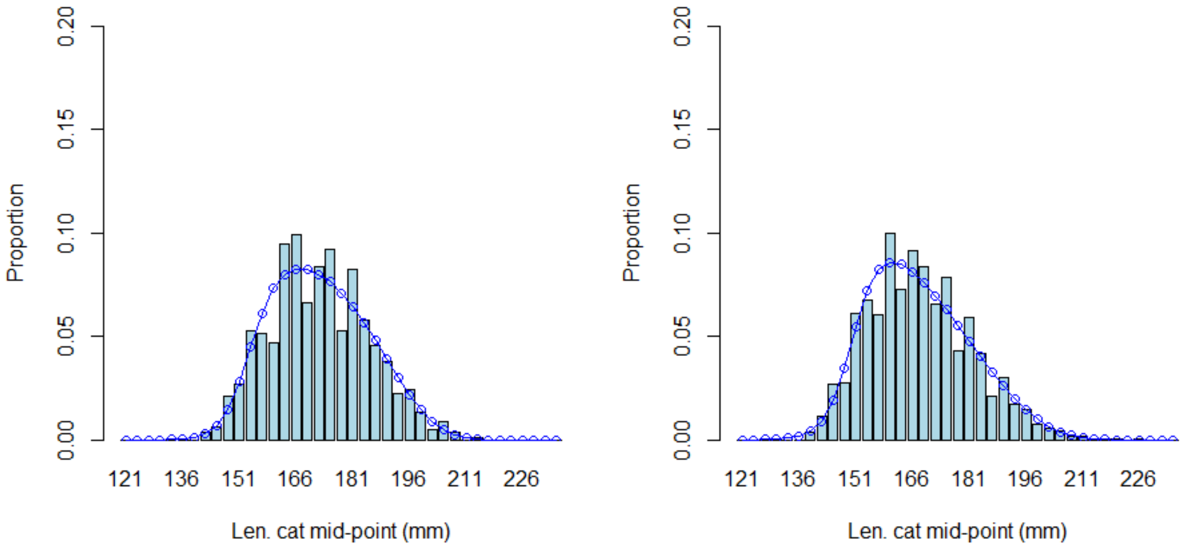


Figure 4.8: Catch curve model assuming a multinomial likelihood (blue lines) fitted to Brownlip abalone commercial catch length-frequency data pooled in 3 year blocks collected between 2004 and 2015. Growth curves were fitted simultaneously to tag-recapture data (*n*=628) whilst fitting each catch curve to commercial length-frequency data. Each bar represents a length category of 3 mm with the bar positioned at the mid-point of the length category (Len. cat mid-point).

4.4 Per Recruit and Related Equilibrium-based Models

This section addresses objective 4, which is to develop fishing size limits and optimal market sizes based on size distribution and growth to examine the harvest potential of the total industry.

4.4.1 Per Recruit Model

Assuming a current legal minimum length (LML) of 140 mm, a fishing mortality (F) for individuals fully-selected into the fishery of 0.11 y^{-1} and a logistic selectivity pattern with an L_{50} of 150.2 mm and an L_{95} of 160.9 mm (Table 3.1), i.e. the base case scenario, the estimated yield per recruit (YPR) is 0.036 kg and the spawning potential ratio (SPR) is 0.62 (Figure 4.9 and Figure 4.10, base case). Applying this per recruit model, F would need to be increased to 0.34 y^{-1} before SPR would be expected to decline to below 0.4 (represents a level that could potentially be used as a target reference point). An examination of the per recruit analysis results for abalone over a large range in F values highlighted that the expected YPR curve for Brownlip abalone does not decline, even at very large F values (up to 6.0 y^{-1}). Furthermore, SPR is not expected to decline below 0.25 at extreme values of F. Thus, the model results for YPR suggest that the stock of Brownlip abalone stock is highly resilient to fishing pressure, and also suggests that any target for fishing mortality should not be set based on the level of F corresponding to maximum yield per recruit (i.e. F_{max}).

Increasing the size at which individuals become selected into the fishery, at any given value of F, yielded lower estimates of YPR but higher estimates of SPR. Thus, when the selectivity pattern was modified (from the base scenario) by increasing the L_{50} and L_{95} by 10 mm, i.e. to a similar selectivity pattern experienced historically in this fishery, the YPR at the current estimated level of F (0.11 y^{-1}) declined by ~14% and SPR increased by ~11% (Figure 4.9). Conversely, if the L_{50} and L_{95} were reduced from the base case scenario by 10 mm, i.e. representing a scenario of a further decline in the sizes over which Brownlip abalone become selected into the fishery, then the YPR at F=0.11 y^{-1} would be expected to increase by ~9% and SPR to decrease by about the same amount relative to the base case scenario. However, even with such a reduction in the size at which individuals become selected into the fishery, according to the per recruit model at the current estimated level of F (0.11 y^{-1}), SPR would still be expected to remain above 0.4, noting that this would also require a reduction in the LML to allow capture and retention of individuals at such small shell lengths. Thus, potentially, these results highlight that the per recruit model provides overly optimistic results.

For a given value of F, reducing M yielded higher values of YPR and lower values of SPR. For example, a decrease in M from 0.15 to 0.12 y^{-1} resulted in a 44% increase in YPR and a 12% decrease in SPR (Figure 4.10). The values of YPR, in particular, varied substantially over the specified range of M values. Highlighting that the accuracy of estimates of M is an important factor influencing the reliability of results for Brownlip abalone produced by per recruit modelling.

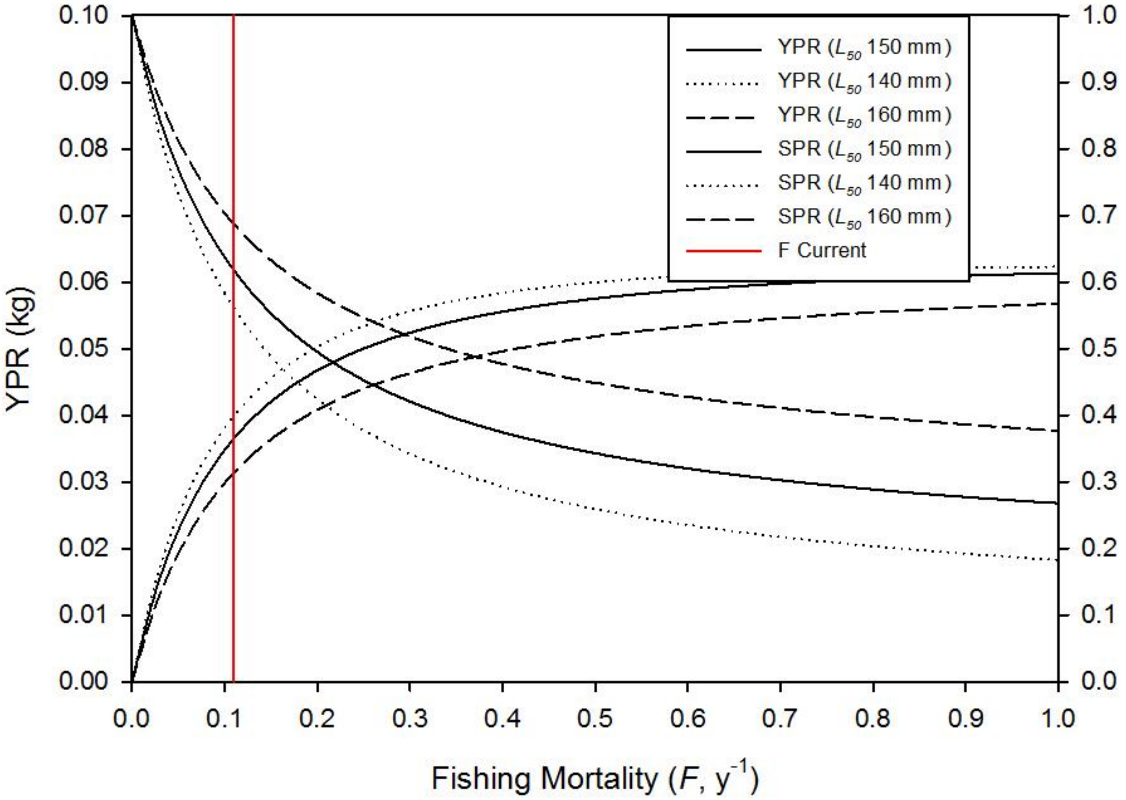


Figure 4.9: Relationships between yield per recruit (YPR, kg) and spawning potential ratio (SPR) with fishing mortality (F, y^{-1}) for Brownlip abalone in Western Australia. Calculated for three alternative scenarios relating to the sizes at which individuals become selected into the fishery, including; 1) the current estimated selectivity pattern (L_{50} of 150 mm and L_{95} of 161 mm), 2) increase in size by 10 mm (historical pattern) and 3) decreased in size by 10 mm (future pattern if current trends continue). The red line represents the current estimate for F.

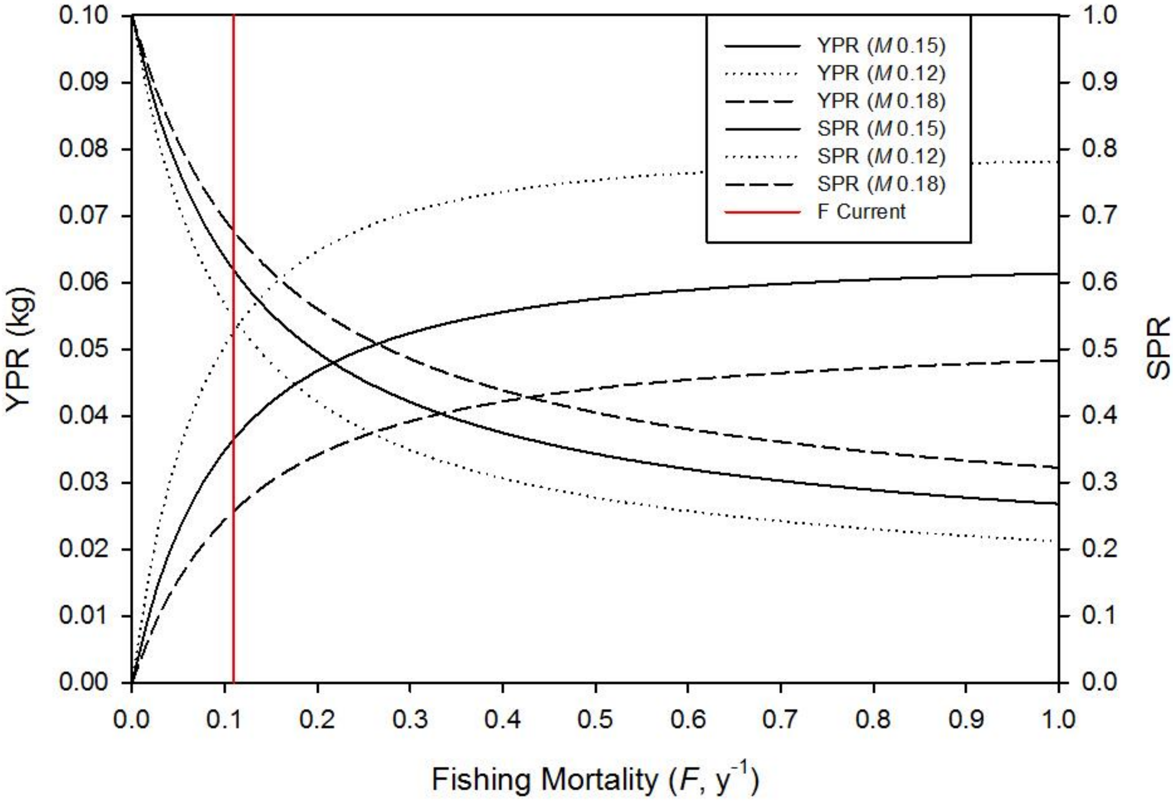


Figure 4.10: Relationships between yield per recruit ($\boldsymbol{YPR}$, kg) and spawning potential ratio ($\boldsymbol{SPR}$) with fishing mortality ($\boldsymbol{F}$, y^{-1}) for Brownlip abalone in Western Australia. Calculated for three alternative scenarios relating to values of natural mortality ($\boldsymbol{M}$, y^{-1}), i.e. 0.12, 0.15 (base case) and 0.18 y^{-1}. The red line represents the current estimate for $\boldsymbol{F}$.

4.4.2 Extension to the Per Recruit Model to Incorporate a Stock-recruitment Relationship

For the extended model base case scenario, which assumed a value of 0.6 for the steepness of the stock-recruitment relationship, the value of SPR at the level of F of 0.11 y^{-1} is 0.54 (Figure 4.11, Figure 4.12 and Figure 4.13). The value of fishing mortality at which YPR is estimated to be at its maximum ($F_{\max}$) is 0.28 y^{-1}. The increase in yield at $F_{\max}$ relative to that which would be obtained at the current estimated level of F is ~19%. Applying the extended model, for this base case scenario, SPR is only expected to fall below 0.4 (represents a potential threshold or target reference level) when F increases to 0.2 y^{-1}.

Once the per recruit model was extended to incorporate a stock-recruitment relationship, the trends in YPR and SPR with F became inconsistent with those obtained from the traditional per recruit model when F became large. When F was relatively low and using the extended model, increasing the sizes at which individuals become selected into the fishery resulted in lower YPR estimates and higher SPR estimates, as was also the case with the traditional per recruit model. However, the opposite was true when F became relatively large, which thus differed from the results obtained by the traditional per recruit model. Also in contrast to the results from the traditional per recruit model, when the extended model is used, YPR declines when fishing pressure becomes relatively large. Applying the extended model, the expected yield at the current level of F (relative to the arbitrary level of recruitment) varied by 18% over the range of alternative selectivity patterns. Regardless of selectivity pattern, SPR remained above 0.47 at this level of F (Figure 4.11). However, at values of F higher than 0.2 y^{-1}, the expected yield varied markedly, with the values declining to very low levels for the scenario for which the L_{50} and L_{95} was reduced by 10 mm from the current estimates. For the base case scenario, SPR would be expected to decline to about 0.12 at an F of 1.0 y^{-1}, and for the scenario with lowered L_{50} and L_{95} values, the stock would be expected to become virtually extinct at this very high level of F.

Depending on the value of M, at the current fishing mortality, the yields estimated by the extended model varied considerably as did the results obtained using the traditional per recruit model (Figure 4.12). Thus, at the current estimated level of F, the expected yield (relative to the specified recruitment level) at M=0.12 y^{-1} was 37% greater than at M=0.15 y^{-1} (base case), and was as much as 89% greater than the expected yield at M=0.18 y^{-1} (Figure 4.12). As with the traditional model, for any value of F below ~0.5 y^{-1}, lowering M resulted in higher yields but lower estimates of SPR. In contrast to the results obtained using the traditional model, however, when F increased beyond ~0.5 y^{-1}, estimates yields were lower for lower values of M.

A parameter to which the extended model was also very sensitive was changes in the assumed steepness parameter for the Beverton and Holt stock-recruitment relationship (Figure 4.13). Although, at F=0.11 y^{-1}, increasing the value of the steepness parameter from 0.6 to 0.8 resulted in only a slight increase in yield and spawning biomass (~9%), lowering the value to 0.4 resulted in a 28% decrease in yield (despite this estimate for F now equating to $F_{\max}$), and a marked lowering of SPR from 0.54 to 0.39.

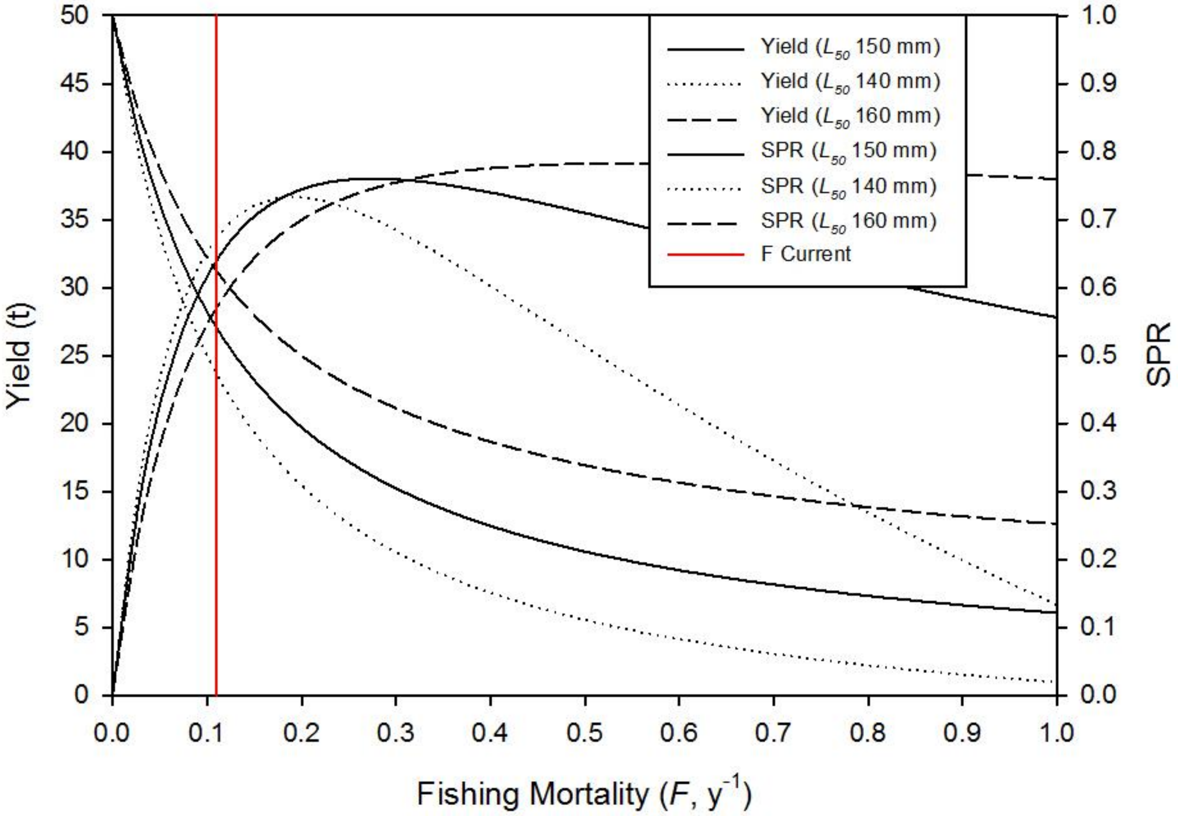


Figure 4.11: Relationships between relative yield (t) (for an arbitrary, specified level of recruitment) and spawning potential ratio ($\boldsymbol{SPR}$) with fishing mortality ($\boldsymbol{F}$, y^{-1}) for Brownlip abalone in Western Australia. Calculated for three alternative scenarios relating to the sizes at which individuals become selected into the fishery, including; 1) the current estimated selectivity pattern ($\boldsymbol{L_{50}}$ of 150 mm and $\boldsymbol{L_{95}}$ of 161 mm), 2) increase in size by 10 mm (historical pattern) and 3) decreased in size by 10 mm (future pattern if current trends continue). The red line represents the current estimate for $\boldsymbol{F}$. *Note that as the estimates of relative yield relate to an arbitrary recruitment level, it is not meaningful to relate these to actual values of commercial catch.

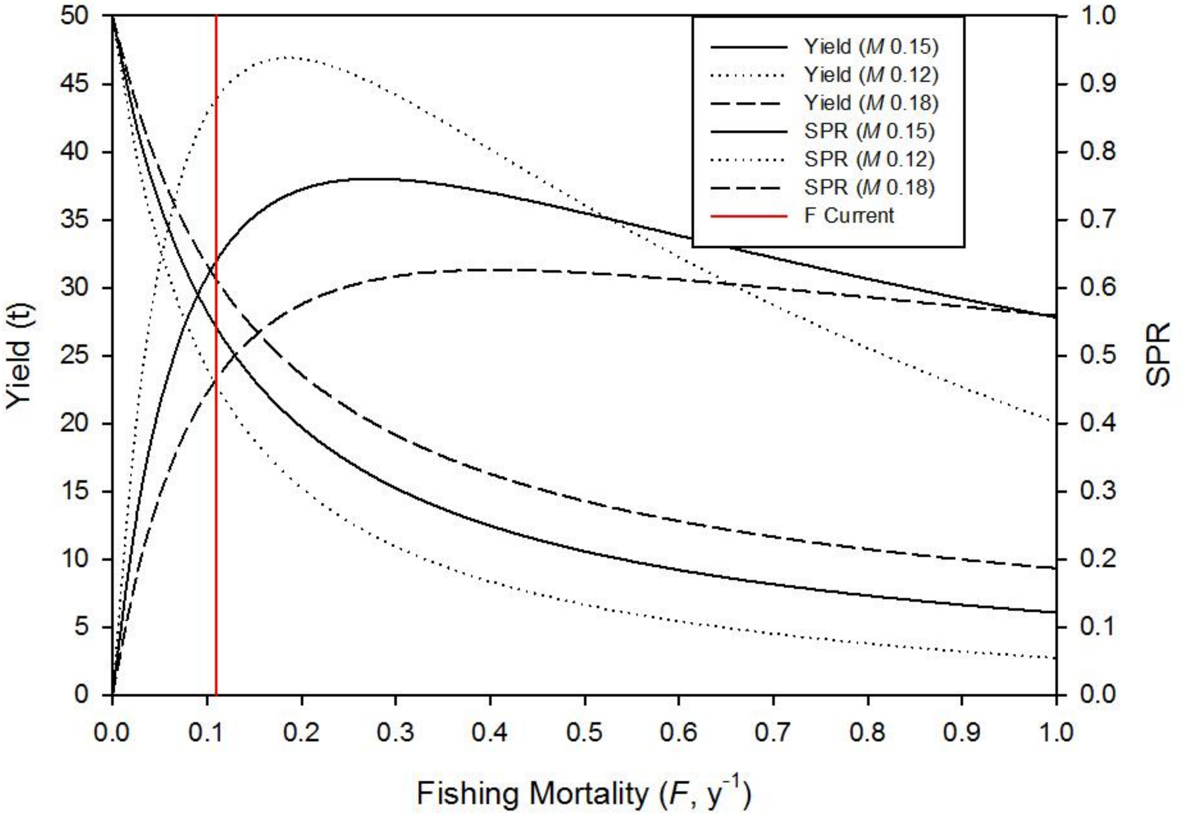


Figure 4.12: Relationships between relative yield (t) (for an arbitrary, specified level of recruitment) and spawning potential ratio ($\boldsymbol{SPR}$) with fishing mortality ($\boldsymbol{F}$, y^{-1}) for Brownlip abalone in Western Australia. Calculated for three alternative scenarios relating to values for $\boldsymbol{M}$, i.e. 0.12, 0.15 (base case) and 0.18 y^{-1}. The red line represents the current estimate for $\boldsymbol{F}$. *Note that as the estimates of relative yield relate to an arbitrary recruitment level, it is not meaningful to relate these to actual values of commercial catch.

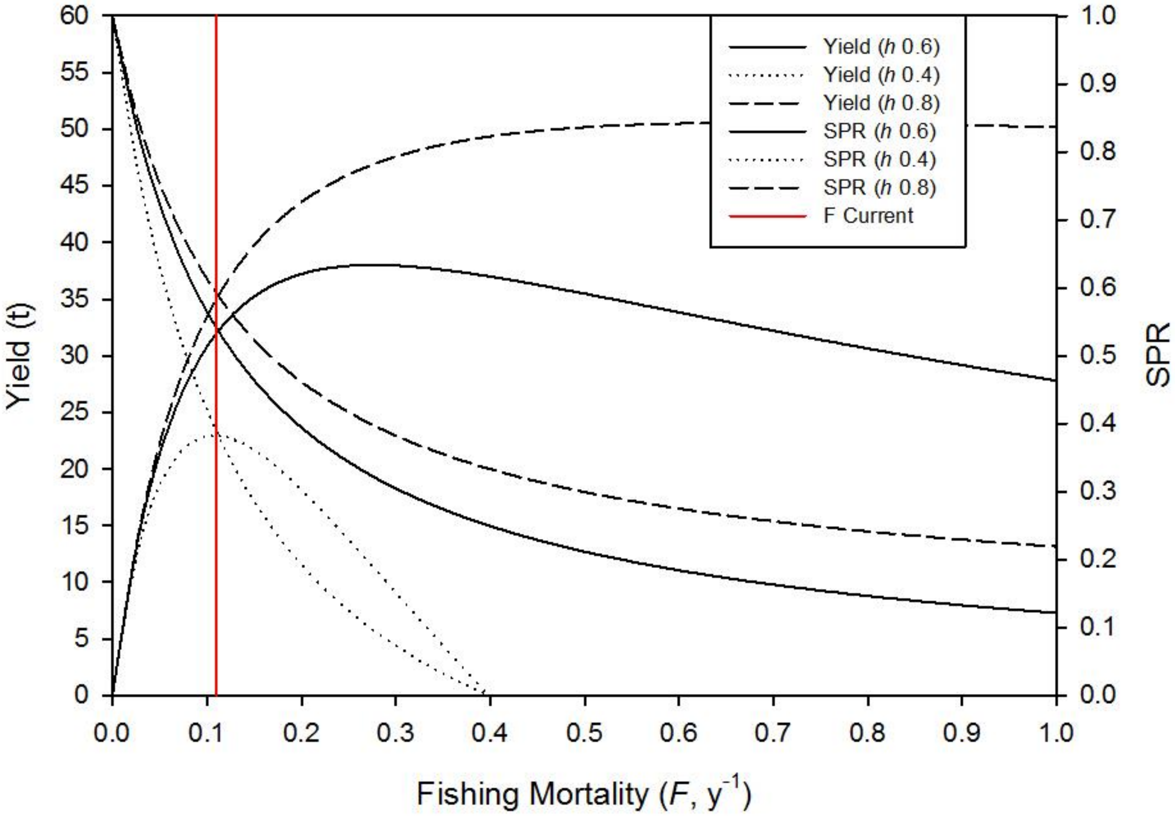


Figure 4.13: Relationships between relative yield (t) (for an arbitrary, specified level of recruitment) and spawning potential ratio ($\boldsymbol{SPR}$) with fishing mortality ($\boldsymbol{F}$, y^{-1}) for Brownlip abalone in Western Australia. Calculated for three alternative scenarios relating to assumed values of the steepness parameter ($\boldsymbol{h}$) in the Beverton and Holt stock-recruitment relationship, i.e. 0.4, 0.6 (base case) and 0.8. The red line represents the current estimate for $\boldsymbol{F}$. *Note that as the estimates of relative yield relate to an arbitrary recruitment level, it is not meaningful to relate these to actual values of commercial catch.

4.5 Preliminary Integrated Length-based Model

This section addresses objective 5, which is a preliminary integrated length-based model to determine harvest/fishing sizes. A mathematical description of the model was given in Section 3.5.1, and the key outputs of the model are described below.

Length transition Matrix

The length transition matrix was developed using the Gaussian growth model based on the increment data from the Brownlip abalone tag-recapture study (Section 4.1 and 4.3.1). To illustrate the results of the length transition matrix employed in the integrated model, the probabilities of an individual of one of several specified initial lengths (i.e. 21, 41, 61, 81, 101, 121, 141, 161, 181 or 201 mm) growing to any length (between 1 and 230 mm), after an annual time step, was plotted (Figure 4.14). The plot demonstrates that, with increasing initial length, the amount of growth (at the end of the time step) tends to decline, and the variation in possible lengths to which the individual will grow reduces. The trend also demonstrates that the length transition matrix does not allow for the possibility of negative growth, which would appear a reasonable assumption given that in the case of abalone they are measured according to shell length (Figure 4.14).

Observed and expected annual catch and catch rates

The observed commercial catch of Brownlip abalone between 1998 and 2015 has fluctuated between ~5 and 15 t (meat weight), while in the past three years the commercial catch has declined from ~14 t to 9 t (Figure 4.15). In the model, Newton's algorithm is employed to find the value of F for which the expected and observed catches match. Thus, in Figure 4.15, the estimated annual catches completely overlay the observed catches.

The (standardised) commercial annual catch rates remained steady between 1999 and 2010, fluctuating around 20 kg meat wt. fishing day^{-1} (Figure 4.15). In 2011, the observed catch rate fell to ~12 kg meat wt. fishing day^{-1} after which it remained relatively steady at around 9-11 kg meat wt. fishing day^{-1} until 2015. Therefore, the observed commercial catch rates differ between two main periods, i.e. 1999-2010 and 2011-2015. Note that, at the beginning of the second period fishing practices changed, with commercial operators starting to employ 2 divers per day rather than a single diver each day. Fishing using 2 divers is considered to lower catch rates as the second diver is generally less experienced and there can be an overlap of effort in fishing the bottom. It is hypothesised that the change in catch rate between the two periods reflects a change in catchability, not necessarily abundance. The expected catch rates, as estimated by the integrated model, match closely with the observed catch rates in almost all years throughout both periods. Thus, the estimated 95% confidence limits for the observed and estimated catch rates overlapped in all years apart from 2003 and 2009, but even in those years, the degree of separation between the confidence bounds was marginal (Figure 4.15).

Length composition data and selectivity

In each sampling year, the observed length compositions were unimodal and are almost symmetrical. The model provided good visual fits to the length composition data derived from random sampling of commercial catches (Figure 4.16a). Examination of the residuals associated with the observed and expected proportions of Brownlip abalone at length for each year show a degree of correlation in residual pattern between successive length classes (Figure 4.16b). However, the extent of that correlation does not appear that marked in most years. The selectivity curves estimated by the model varied considerably between the first catch rate period of 2004-2010 and the second catch rate period of 2011-2014 (Figure 4.17a). Although the curves differed between these two periods, the slopes were the same, which in part, reflected an assumption in the model (aimed at minimising the number of model parameters) that although the L_{50} may vary, the slope was constant across all years. Prior to 2011 the estimates of L_{50} (length at which abalone are 50% selected by the fishery) fluctuated around 165 mm whereas in 2011-2015, the estimates of L_{50} fluctuated around 155 mm (Figure 4.17b).

Fishing mortality, spawning biomass, exploitable biomass and recruitment

Estimated annual fishing mortality between 1988 and 2015 ranged from ~0.06 to ~0.18 y^{-1} (Figure 4.18a). Following the first 10 years when F was relatively volatile, a trend which mirrored that for the annual catches in those years (see Figure 4.15), F steadily increased until 2010 when it peaked at ~0.18 y^{-1}. Following that period, F progressively declined to about 0.08 y^{-1} in 2015 (Figure 4.18a). The 95% confidence limits associated with the annual estimates of F are fairly broad, with for example, in 2015 the estimate ranged between 0.11 and 0.25 y^{-1}. In interpreting estimates of fishing mortality, it must be recognised that the estimates of F represent the fishing mortality experienced by individuals that have become fully-selected into the fishery. As the sizes at which commercial fishers harvest Brownlip abalone are typically substantially greater than the size at which this species matures (~120 mm), the fishing mortality experienced, on average, by mature-sized individuals will be lower.

In general, the estimated female spawning biomass of Brownlip abalone remained relatively stable over the full modelling period, i.e. 1988-2015 (Figure 4.18b). The point estimates for annual female spawning biomass fluctuated around 128-131 t between 1988 and 2002, but then declined very gradually to a minimum of 121 t in 2015. It may be noteworthy that the average catch in 1988-2002 (11.1 t) was 28% lower than the average catch in 2003-2015 (14.2 t), and that in the last of these years, the catch had reduced to 9 t due to TACC reductions (see Figure 4.15). However, it should be recognised that the confidence intervals for female spawning biomass are very broad, e.g. in 2015, the estimated female spawning biomass ranged from 82 t to 150 t (Figure 4.18b). The estimated ratio of spawning biomass in 2015 relative to the unfished level was 0.63 (95% CLs, 0.61-0.65).

In the model, the calculation of exploitable (or vulnerable) biomass in each year accounts for changes in size-based selectivity patterns among years. Thus, in interpreting the annual trends in exploitable biomass, a change in such biomass may potentially occur due to a change in abundance and/or a change in fishing pattern, i.e. fishers may have elected to harvest a different component of the stock. Over the period when the selectivity pattern (is assumed to have) remained relatively stable (1988-2010), the exploitable biomass remained steady at around 100-112 t (Figure 4.19a). During subsequent years when selectivity changed markedly, the estimated exploitable biomass increased substantially to range between 123 t (in 2011) and 139 t (in 2014). This contrasts with the estimated trend for female spawning biomass and also for the amount of estimated biomass above 165 mm (i.e. the approximate L_{50} at which, during 1988-2010, 50% of individuals were selected into the fishery). Thus, the biomass of Brownlip abalone >165 mm remained steady at ~110 t between 1988-2003, before declining slowly, but progressively, to 92 t in 2011 and remaining at about this level until 2015 (Figure 4.19a).

The model estimated level of annual recruitment remained very steady at ~320,000-330,000 individuals between 1988 and 2015 (Figure 4.19b).

Sensitivity to steepness values

When the model was re-run assuming a more conservative value for steepness (h) of 0.4, the annual trends in spawning biomass were similar to those recorded when h was set to 0.6. Thus, female spawning biomass remained relatively stable, but with the lower steepness value, the degree of decline was slightly greater, i.e. ~131 to 116 t verse ~131 to 121 t (*cf* Figure 4.20a and Figure 4.18b). The decline in biomass above 165 mm was slightly greater when assuming a steepness of 0.4 compared with 0.6 (*cf* Figure 4.20b and Figure 4.19a). Specifying the lower steepness value led to a more conservative estimate of the ratio of spawning biomass in 2015 relative to the unfished level, i.e. 0.54 (95% CLs, 0.52-0.56) for a h of 0.4 verse 0.63 (95% CLs, 0.61-0.65) for a h of 0.6.

Estimated effective sample size

Applying the base model, the annual effective sample sizes (estimated internally by the model when fitting to the composition data, assuming that those data conform to a Dirichlet distribution) were, as expected, substantially less than the number of individual samples used for modelling. For example, the effective sample size in 2015 (373) was markedly less than the 2131 individual samples used for modelling. As another example, the respective values were 192 and 619 in 2014. Note, that the numbers of individuals included in the overall size composition from the two management areas in each year had been weighted according to the catches taken from those areas in that year.

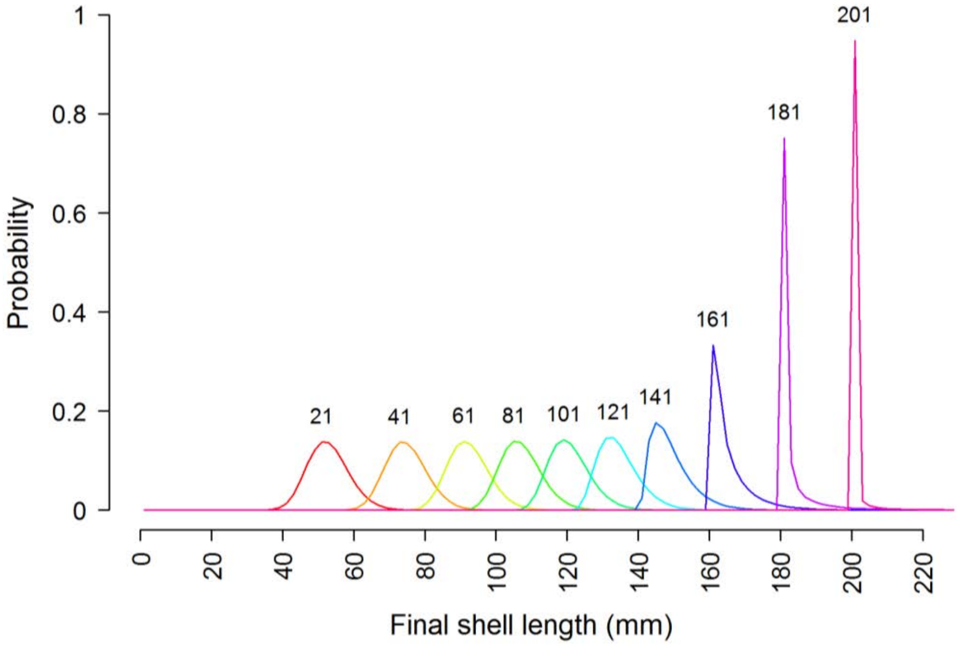


Figure 4.14: Probabilities of Brownlip abalone growing from a specified initial length (i.e. the numbers above each curve) to any other length at the next annual model time step, based on the model length transition matrix.

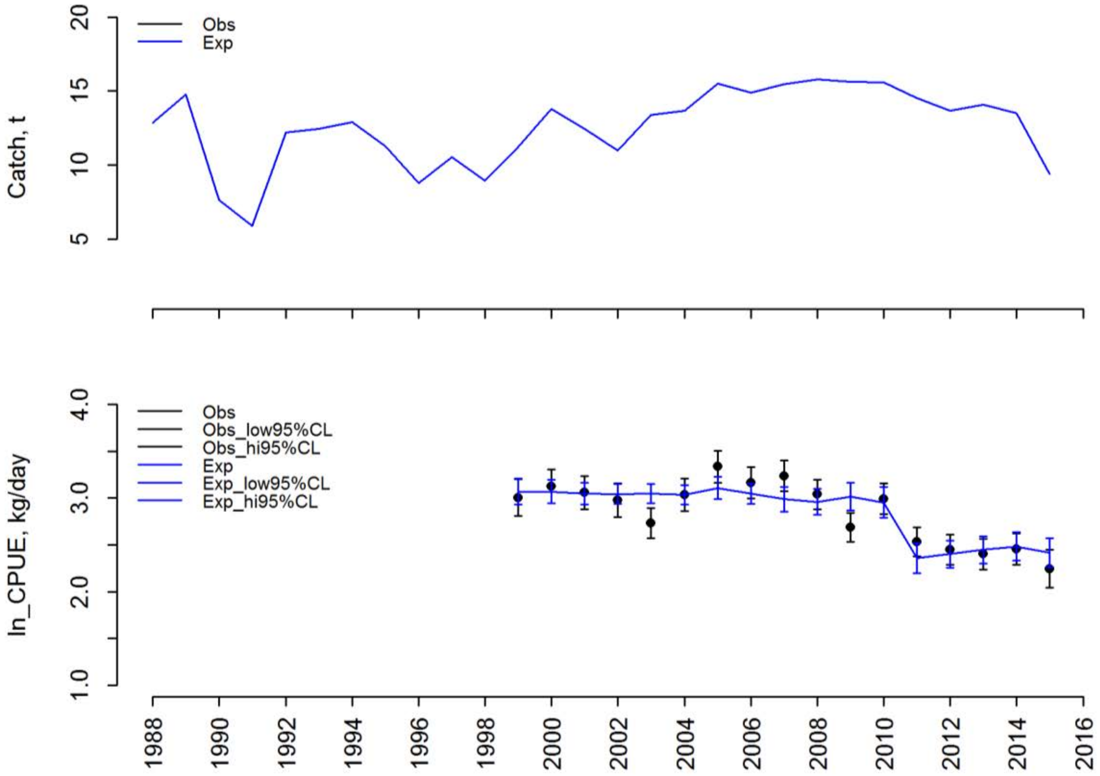


Figure 4.15: Commercial catches (t, whole weight) (top) and commercial catch rates (kg fishing day^{-1}) (bottom) for Brownlip abalone. Black points and blue lines represent observed and estimated values, respectively. Note that the estimated catches completely overlay the observed catches because, in the model, annual fishing mortalities are estimated as those values for which the estimated catches match the observed catches (top plot).

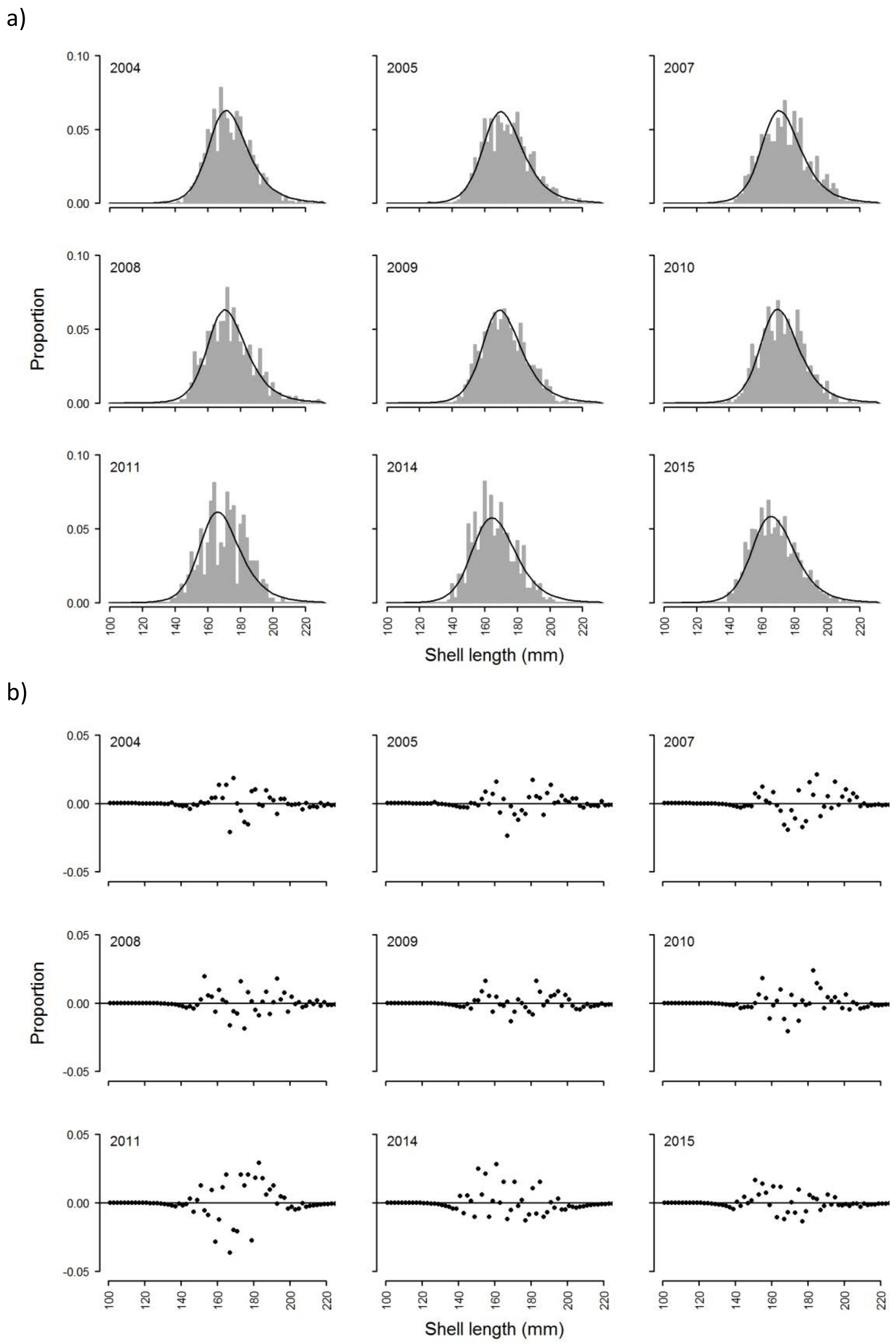
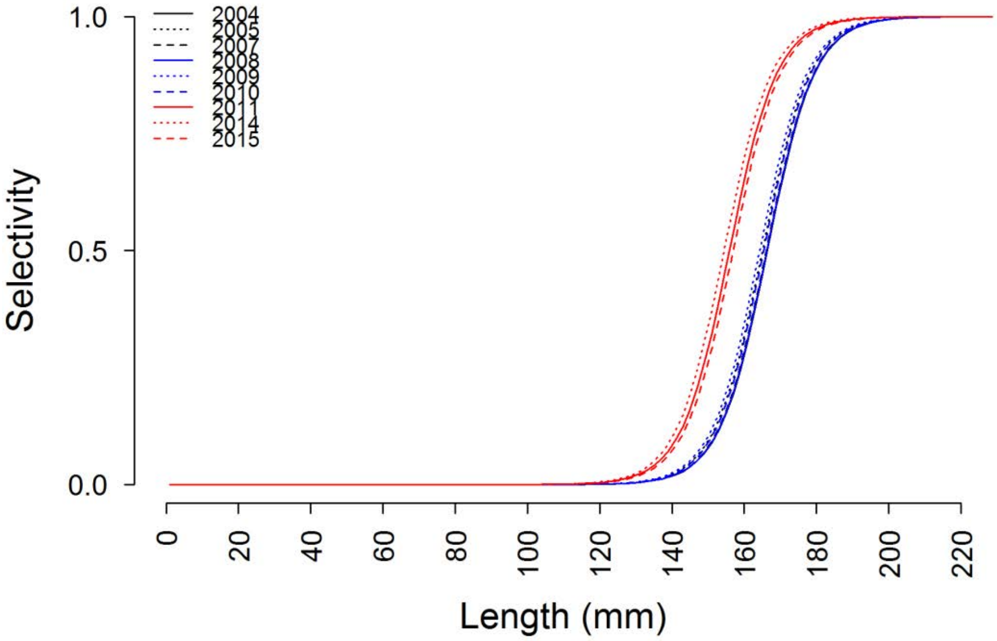


Figure 4.16: Length composition data for Brownlip abalone derived from random sampling of commercial catches from 2004 to 2015. a) Fits of the model (black lines) to the length composition data (grey bars). b) Residuals (points) associated with the expected and observed proportions at length for each annual length composition sample. A line at zero has been added to each plot.

a)



b)

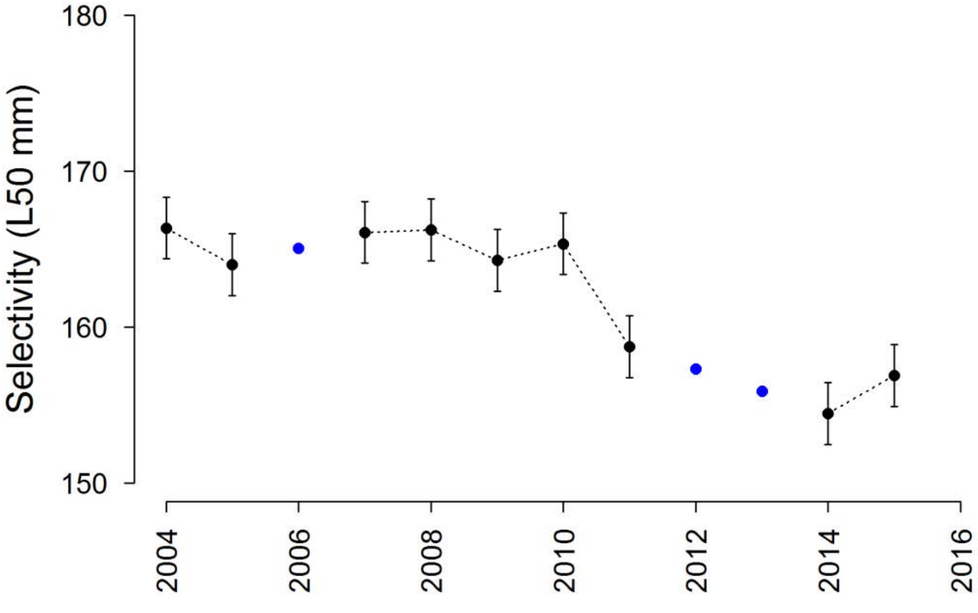


Figure 4.17: Estimated selectivity patterns for Brownlip abalone between 2004 and 2015. a) Fitted logistic selectivity curves for different years and b) estimates of the shell lengths (mm) at which individuals are 50% selected into the fishery (L_{50}). In b), black points denote model parameter estimates of L_{50}, black bars denote approximate 95% confidence limits for estimates of L_{50} and blue points denote estimates of L_{50} calculated for years without length composition data, using linear interpolation.

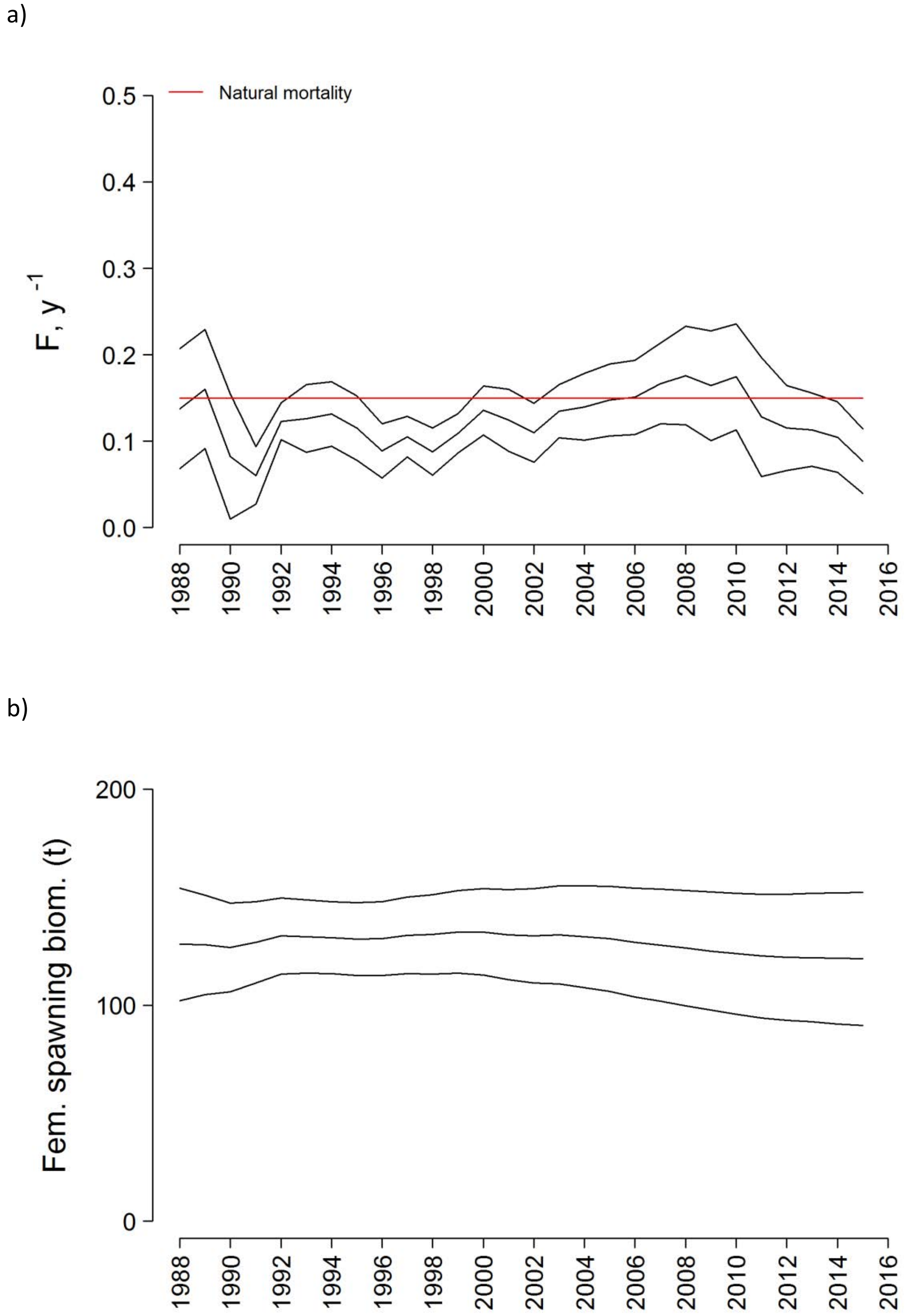
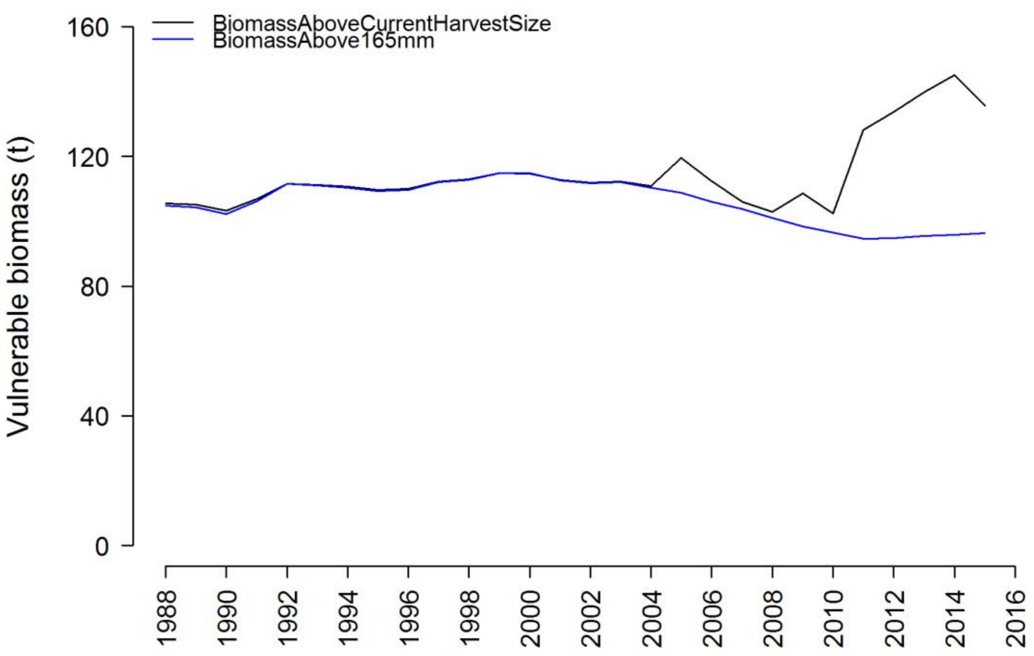


Figure 4.18: Annual estimates and approximate 95% confidence limits for a) fishing mortality (F, y^{-1}), and b) female spawning biomass (t) of Brownlip abalone between 1988 and 2015. The red line in a) denotes the assumed value of natural mortality (M) of 0.15 y^{-1}. The above results assume that the steepness parameter of the stock-recruitment relationship (h)=0.6.

a)



b)

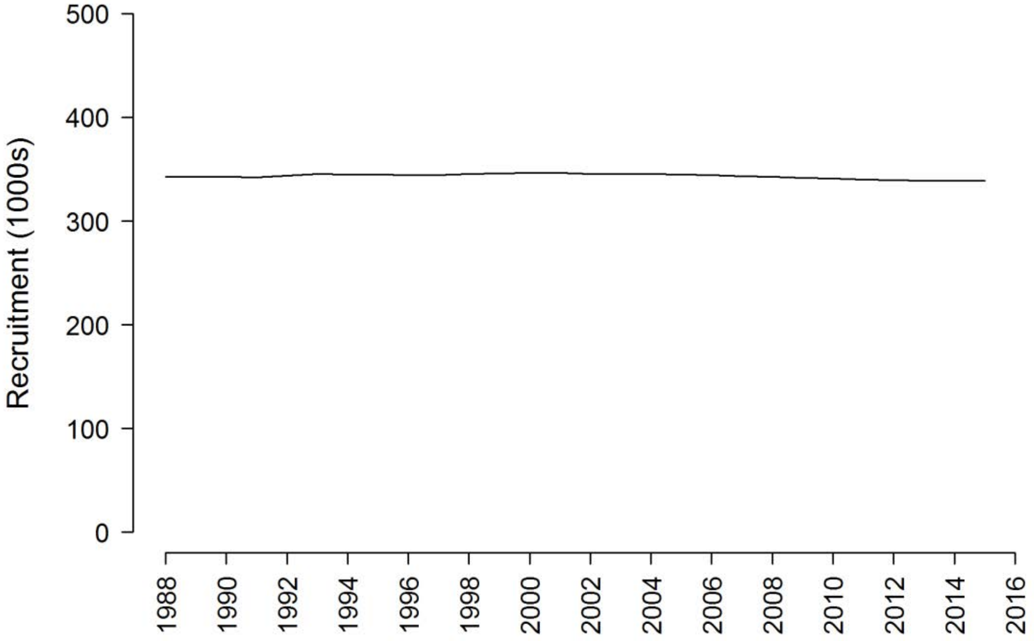


Figure 4.19: a) Estimates of vulnerable (or exploitable) biomass (t) of Brownlip abalone above the estimated harvest sizes for each year (black line) and above 165 mm in all years (blue line). b) Estimated Brownlip abalone recruitment (1000s) between 1988 and 2015, based on the Beverton and Holt stock-recruitment relationship (assumed steepness=0.6).

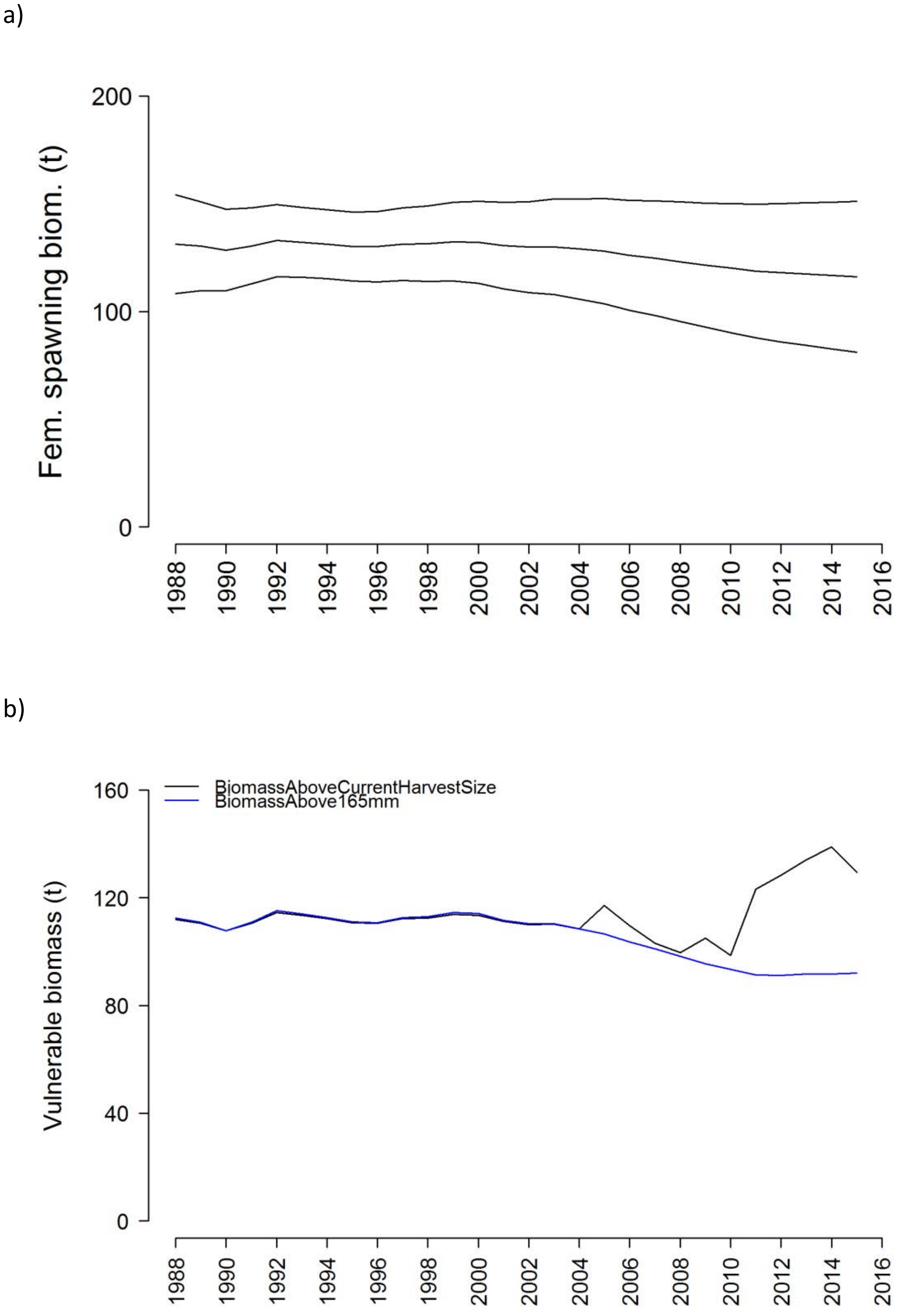


Figure 4.20: a) Annual estimates and approximate 95% confidence limits for female spawning biomass (t) of Brownlip abalone between 1988 and 2015. b) Estimates of vulnerable (or exploitable) biomass (t) of Brownlip abalone above the estimated harvest sizes for each year (black line) and above 165 mm in all years (blue line). The above results assume that the steepness parameter of the stock-recruitment relationship ($\boldsymbol{h}$)=0.4.

5 Discussion

5.1 Tag-Recapture Study

The tag-recapture study had sites across the WA AMF and a substantial number of Brownlip abalone were tagged within these sites. These animals were tracked for multiple years to complete a rigorous assessment of the growth and survival (converted to mortality) of wild Brownlip abalone. During the study, over 50% of Brownlip abalone tagged were recaptured, as was the case for 4 out of the 5 sub-areas surveyed. The Augusta sub-area was the only exception and this was due to one of the sites having a negligible recapture of Brownlip abalone between the initial and first recapture period. There is uncertainty as to why, but given this did not occur at any of the other 18 sites it would point to either natural or fishing related causes rather than any issues with the capture and tagging methodology. There was both tag returns and anecdotal evidence from commercial divers that the Brownlip abalone were fished, but in the study, only 2.8% of animals were reported as dead, indicating a possible under reporting of fished animals by the commercial industry.

Across all sub-areas surveyed in the tag-recapture study there were very few animals captured with a size less than 100 mm shell length. The lack of small captured Brownlip abalone was similar to that experienced by Wells and Mulvay (1992), where only 1% of animals tagged in Augusta sites and 6% in the Esperance (Town) sites were less than 100 mm. This reflects the highly cryptic nature of the animal living in caves and crevices, and the difficulties associated with accessing wild juvenile Brownlip abalone. In contrast, the relatively high frequency (>62%) of Brownlip abalone recorded between 150 and 170 mm shell length demonstrated that large, legal size adults formed the dominant component of this tag-recapture survey. Wells and Mulvay (1992) also found this to be the case with the modal size class of Brownlip abalone being 160 to 179 mm for sites at both Augusta and Esperance (Town), but did show Augusta sites to have animals with a larger mean length (~9 mm). In this study the mean lengths were the opposite, where Brownlip abalone in Area 2 (Esperance) had a larger mean length (~7 mm) than those in Area 3 (Augusta). This could be a reflection of a change in size distribution over time, or attributed to a greater number and/or different tag-recapture sites used in this study, or possibly the fact that the Town sub-area had 50% of the Brownlip abalone tagged with a shell length greater than 170 mm which skewed the data. Length frequency data for Greenlip abalone in WA derived from fishery-independent surveys show that this species has a much lower average shell length than Brownlip abalone, with 117 mm in Area 2 and 124 mm in Area 3, while juveniles are able to be captured down to 25 mm shell length (Hart et al. 2013a). Blacklip abalone in the Western Zone Abalone Fishery (SA), from a couple of the spatial assessment units in only a few years surveyed, have been shown to have a length-frequency distribution with modal size classes of around 150 mm or greater and a small proportion of animals surveyed below 100 mm shell length (Stobart et al. 2012).

The limited number of Brownlip abalone captured that were <100 mm shell length and the relatively high proportion of larger slower growing animals makes fitting appropriate growth models difficult. Consequently, growth rates of Brownlip abalone produced in aquaculture were required to estimate juvenile Brownlip abalone growth and incorporated as part of the tag-increment data for the growth models. Discussion of Brownlip abalone growth occurs in the Growth and Mortality Model Section below.

The apparent survival and recapture estimates produced by the MARK program for Brownlip abalone in the tag-recapture study, were derived by weighted averaging of the estimates from the candidate set of models, after the variance inflation factor was incorporated to calculate the QAICc. The GOF tests did reveal minor over-dispersion of the data and this has been attributed to the violation of the assumption that all animals have equal probability of capture, given the highly cryptic nature of the species. However, violation of this assumption does not render a tag-recapture analysis useless as survival estimates from CJS models are robust to heterogeneity in data (Pollock et al. 1990). The survival probability estimates ranged from 0.6 to 0.9 y^{-1} across sub-areas, with no differences between recapture periods for individual sub-areas. These survival estimates are similar to those produced by the same statistical methodology for a stock enhancement release of juvenile Greenlip abalone in Augusta, where at 12 and 18 months post-release the survival probabilities of 0.6 to 0.85 were not considered a product of release mortality (Hart et al. 2013b). Obviously these two tag-recapture studies are on different size classes and species of abalone, therefore different factors affect survival, including juvenile predation, emergence, density dependence for the juvenile Greenlip abalone and fishing pressure for the Brownlip abalone.

In this tag-recapture study, the Brownlip abalone across the 19 sites are known to have experienced some level of fishing pressure, as evident by tag returns, noting on CDRs and anecdotal evidence from commercial divers. Therefore, the inverse of the survival probability estimates (ϕ) produced by MARK cannot be assumed to equate to natural mortality (M). To convert the survival estimates (ϕ or S) to mortality estimates (M, F or more appropriately Z) a basic transformation was used, noting that the MARK estimates do not account for fishing mortality through growth and length based selectivity patterns. Given that 77.5% of Brownlip abalone tagged were over legal minimum length (140 mm) and the highest length frequencies were between 150 and 170 mm shell length, it is likely that the mortality estimates are a combination of both natural and fishing mortality. The fishing pressure experienced would vary between sites depending on the size distribution of the tag-recapture abalone at the sites and the accessibility of each site.

The transformed mortality estimates ranged from 0.12 to 0.39 y^{-1} between sub-areas, which encompassed the range of total mortality estimates produced by the catch curve analysis (0.18 to 0.26 y^{-1}, Section 4.3.2). Four of the five sub-areas surveyed were at the upper end or higher than the range of catch curve analysis total mortality estimates, while the mortality for the Town sub-area was lower, suggesting a varying level of fishing mortality between sub-areas. The Windy Harbour sub-area had the highest level of mortality, which is also the sub-area that produces the greatest annual catch of Brownlip abalone in the fishery (Figure 1.4). The high mortality estimates imply that the sites in Windy Harbour, in particular, receive substantial commercial fishing pressure. Conversely, the Town sub-area had a lower level of mortality than produced by the catch curve analysis, which could be attributed to these sites receiving very little fishing pressure. Thus, the Town sub-area mortality estimate may be close to the value of natural mortality. This was supported by 50% of the Brownlip abalone captured at the Town sub-area sites having a shell length greater than 170 mm (LML 140 mm), which was nearly double the frequency of the 170 mm plus abalone in the other 4 sub-areas (Figure 4.3). Therefore, the Town sub-area mortality estimate may provide the most reliable indication of the true level of natural mortality for this species.

In the past, natural mortality (M) of adult Brownlip abalone in WA has been assumed to be similar to that for Blacklip abalone (0.25 y^{-1} for >3 years old) in the Western Zone Abalone Fishery of SA (Shepherd and Breen 1992; Mayfield et al. 2003; Hart et al. 2013a). Estimates of M for adult Greenlip abalone range widely, between 0.13 and 0.4 y^{-1}, but in WA's commercially Greenlip fished population M is generally assumed to be 0.25 y^{-1} (Shepherd and Barker 1998; Mayfield et al. 2003; Hart et al. 2013a). For Brownlip abalone the assumption could be made that a relative natural mortality estimate of 0.12 to 0.15 y^{-1} would be appropriate. Given that these mortality estimates transformed from survival probability estimates produced from the tag recapture study are lower than the total mortality estimates produced by the catch curve analysis, and are at the lower end of the natural mortality estimates for Blacklip and Greenlip abalone.

5.2 Aquaculture Trials

Brownlip abalone have been successfully spawned and reared in commercial aquaculture systems. Spawning procedures followed those used for Greenlip abalone in WA with very little variation, and therefore could be used successfully for the commercial production of Brownlip abalone (e.g. Daume 2007; Strain et al. 2016). Baseline growth rates of juvenile Brownlip abalone from settlement to harvest (6-8 months) in the nursery system were shown to average 62.2 ± 0.5 $\mu m.d^{-1}$. This is comparable to juvenile growth rates recorded for Greenlip abalone in WA and Blacklip abalone in Victoria using the same system and diet (Daume et al. 2004; Strain et al. 2006; Daume et al. 2007). Given that growth of Brownlip abalone in the nursery system was similar to the growth of commercially produced Greenlip abalone in WA, the current commercial nursery system was deemed suitable for the production of juvenile Brownlip abalone.

In the grow-out system, the concrete slab tanks utilised for Greenlip abalone were shown to be ineffective at housing Brownlip abalone, as their use resulted in high mortality with the abalone either walking out of the tank or showing distinct clustering behaviour which can lead to either stunted growth or mortality. Given Brownlip abalone's highly cryptic nature, a change in tank design to a deeper tank with hides was needed to reduce mortality, clustering and improve growth rate. The Brownlip abalone in the hide tanks initially produced considerably slower growth rates than when they were in the nursery system (36-42 $\mu m.d^{-1}$ for 25-45 mm *vs* 62 $\mu m.d^{-1}$ for 0-15 mm animals). This could be a potential product of the different tank designs, but the effects of harvesting and weaning from a natural to artificial diet also plays an important role in early growth and survival of abalone in the grow-out system. There have been many studies worldwide that have compared growth of juvenile abalone consuming natural or artificial diets with varying results, however, in Australian abalone aquaculture the weaning process generally produces slower growth rates and higher mortality (e.g. Daume 2007; Strain 2012).

To improve growth rates in the hide tanks, the Brownlip abalone were harvested and graded, which subsequently resulted in an increase in growth rate to 67-70 $\mu m.d^{-1}$ for animals 30-55 mm shell length. Effects of stocking density on growth of a range of abalone species has shown that as stocking density decreases growth rate increases, while Blacklip abalone of a similar size range reared in raceways was shown to exhibit slower growth rates than in hide tanks (e.g. Huchette et al. 2003, Table 3). However, the ability to reduce stocking density and improve growth rates requires the abalone farm to either have more tanks available to hold the two grades of stock or the lower size grade of stock is of surplus requirement and disposed of. To ascertain if the larger sizes of Brownlip abalone could be accommodated in the concrete slab tank animals of 60-75 mm were stocked in this design, but the growth rate reduced (44 $\mu m.d^{-1}$) and the abalone still exhibited walk out and clustering behaviour. To overcome this, the Brownlip were placed in slab tanks interspersed with Greenlip abalone, which reduced the movement and crawl out of Brownlip abalone.

To determine the conditions required to achieve optimal growth rates of Brownlip abalone in a grow-out system, experimental trials were conducted on the deeper hide tank design by examining variations of its design and using two different size cohorts at commercially acceptable stocking densities. On average, the growth rates (in terms of length and weight gain) of the 71 mm Brownlip abalone cohort trial were higher than the 45 mm cohort. It is generally recognised for abalone that there is extensive variation in growth, both within age cohorts and as the animal ages (e.g. Section 4.3.1; Day and Fleming 1992; Shepherd et al. 1992). Note also that, given the relationship between weight and length conforms well to a power relationship (Hart et al. 2013a) it is not surprising that the larger animals had greater weight gain. The tank design treatments also exhibited a different order in growth parameters, indicating that Brownlip abalone growth potential differs depending on size. The survival of Brownlip abalone in both trials was similar and thus the results gave no indication as to which hide tank design was optimum. Given these results, tank design can be considered an important factor in the production of Brownlip abalone through the grow-out stage and, at present, the hide tanks either with or with-out higher water flow are the most appropriate design to be used on a commercial abalone farm.

Brownlip abalone can be commercially produced to market size in aquaculture within WA given slight alterations to current practices. However, more research needs to be undertaken to optimise all aspects of its production. The future increase in aquaculture production of Brownlip abalone within WA may be largely dependent on market demand rather than production capacity. An important aspect worth considering would be the hybridisation of Brownlip abalone with Greenlip abalone, which is known to happen in the wild between Brownlip/Greenlip and Blacklip/Greenlip abalone (AIAWA pers. comm.; Brown 1991; Brown 1995). This hybridisation could produce abalone with potentially higher meat yield and faster growth than the current commercially produced Greenlip abalone.

5.3 Growth and Catch Curve Models

Growth models

Prior to this study, the only available information on the growth of Brownlip abalone in WA was that presented by Hart et al. (2013a), who fitted a von Bertalanffy growth equation to preliminary tag-recapture data. The data they employed were those collected during the early stages of this study from 2 of the 19 sites ultimately sampled (Section 3.1). The large increase in number of sites sampled greatly increased the representativeness of the growth data for Brownlip abalone. In addition, as described in Section 5.1, because the smaller (below ~100 mm shell length) individuals of this species are highly cryptic and virtually impossible to sample (e.g. Wells and Mulvay 1992), useful data was able to be obtained on these smaller individuals by monitoring the growth of hatchery-reared individuals. In combination, the growth data for wild and hatchery-reared individuals cover essentially the full size range of this species, thereby enabling growth to be modelled throughout all stages of life. Although it is recognised that the growth of cultured juveniles reared within a hatchery may not be the same as that of such individuals in the wild, in the case of Roe's abalone (*Haliotis roei*) in WA, a far less cryptic species than Brownlip abalone, concurrent studies are demonstrating similar growth between their juveniles in these two environments (Strain et al. in prep. b). In that study, the juveniles of Roe's abalone were reared in the same hatchery under the same conditions as the juveniles of Brownlip abalone in this study.

Recognising that a range of models other than the von Bertalanffy growth equation have been used for describing the growth of abalone species, such as the Gompertz model (Troynikov et al. 1998; Bardos 2005; Hart et al. 2013c), a Gaussian function (Rogers-Bennett et al. 2007; Hart et al. 2013c) and an inverse logistic equation (Haddon et al. 2008; Helidoniotis et al. 2011), this study compared four alternative models. Those comparisons demonstrated that two of these models, namely a Gaussian function and a 'double logistic' function, provided far better statistical fits to the tag-recapture data than the von Bertalanffy growth equation model. Note that, the inverse logistic equation by Haddon et al. (2008) to describe the growth of Blacklip abalone, would have been likely to provide a good description of the growth of the larger individuals of Brownlip abalone measured in the wild, most of which were >100 mm. However, the hatchery data indicated that the growth rates of small (<50 mm) juvenile Brownlip abalone are less than those of larger individuals, which was accounted for in this study by applying either the Gaussian function or double logistic function. In the case of Blacklip abalone, Haddon et al. (2008) likewise found that small (<50 mm) juveniles were also very cryptic and it was for this reason that they did not sample such individuals.

Given the species of abalone most similar to Brownlip abalone is the Blacklip abalone from the south-eastern coastline of Australia (Section 1.2), it would appear reasonable to compare the growth of these two species. On the basis of the (simulated) growth curves, using estimates of annual growth relative to initial length, on average, Brownlip abalone are expected to attain maturity (120 mm) at 4-5 years of age, the current LML (140 mm) by about 6 years of age and to enter the fishery at the current lengths at which commercial fishers are harvest this species (150-155 mm) at 7-8 years. By comparison, Helidoniotis et al. (2011) concluded that, for Blacklip abalone in Tasmania, the average size and age at maturity is variable among populations, ranging from 95-128 mm shell length at ~4-7 years. On the basis of wild tag-recapture data, Haddon et al. (2008) concluded that in the most productive areas of the Blacklip abalone fishery in Tasmania, this species recruits into the fishery at 138 mm, which is about 8 years, i.e. slightly older than that recorded in this study for Brownlip abalone. It should be noted, however, such differences may also reflect the fact that tag increment data for modelling the growth of small juveniles were not available for the study by Haddon et al. (2008). More recently, Helidoniotis and Haddon (2012) presented information on the growth of very small juvenile Blacklip abalone sampled in the wild from Tasmania. On the basis of modal length frequency progression analysis, they showed that this species attains a mean length of just over 20 mm by 1 year of age. In the hatchery, the present study showed Brownlip abalone were slightly larger at around 24 mm.

Future research on growth of Brownlip abalone in WA could be aimed at better describing variation in growth among different populations. Preliminary analyses of tag-recapture data separated by the two main management areas (Areas 2 and 3), indicated that at this broad level growth was similar, but with the estimated increments, at a given initial length, being slightly greater in Area 3 than Area 2.

Length-based catch curve models

The Department of Fisheries Western Australia (DOF) employs a “weight of evidence” approach to stock assessment, i.e. stock status is evaluated using all available information within a risk-based assessment framework (see Fletcher 2005). Using this approach stock status would ideally be determined from the results of a range of quantitative analyses (and by analysing signals in the underlying data used for such analyses). As part of this overall weight of evidence framework, DOF considers five “levels” of assessment, which vary depending on the available data for assessment and level complexity of analysis. These range from simple analyses of annual trends in catch (level 1) through to the more complex integrated models (level 5). Noting that if the highest level of assessment possible for a fishery given the available data is level 5, ideally, in addition to considering outputs from the integrated model, the assessment should provide results based on all lower levels of assessment. The equilibrium, length-based catch curve and per recruit models described in this report (Section 3.3.2 and 3.4) are categorised by the DOF as a level 3 assessment. For the catch curve assessment analyses, the key data providing signals in relation to any change(s) in stock status are the length composition data, which provides information on mortality and the sizes over which individuals become selected into the fishery. Note also that for length-based catch curves, reliability is highly dependent on the description of growth.

The catch curve-based estimates of mortality for Brownlip abalone in WA are likely to be the most reliable available for this species from any study. Previously, mortality estimates were provided by Hart et al (2013a) based on the length-based catch curve model of Pauly (1984), using estimates of growth according to a von Bertalanffy growth model. As discussed above, the von Bertalanffy growth model provided a relatively poor fit to the tag increment data (Section 4.3.1). The analyses undertaken in this study demonstrated that the level of uncertainty in estimates of mortality derived using the Pauly (1984) method was extremely large when compared with the alternative method adopted based on the Baranov catch equation (but which yielded similar point estimates). As an example the Pauly (1984) equation has also been used to estimate mortality for the red abalone (*Haliotis rufescens*) in northern California (Rogers-Bennett et al. 2007), but uncertainty was not assessed. The greater precision associated with the model based on the Baranov catch equation may be related to the fact that, by incorporating a selectivity function, this model is fitted to a much wider range of lengths (i.e. the full set of lengths in each commercial sample), compared with the Pauly (1984) model, which is fitted to a subset of the data for individuals above the size at which it is assumed Brownlip abalone become fully-selected into the fishery. Note also that, as fishers target a relatively narrow size range of this species, i.e. only relatively large individuals well above legal size, the restriction of this size range means that the Pauly (1984) catch curve is fitted to very few data points.

Although the results of the catch curve analyses provided no clear trends in total mortality, with the 95% confidence limits for different time periods overlapping, they did show clear evidence of a decline in mean size at which Brownlip abalone become selected into the fishery (i.e. L_{50}). This trend is consistent with the trends in selectivity estimated by using the length-based integrated model (Section 5.5). The apparent decline in the sizes at which fishers now harvest Brownlip abalone may reflect a change in fishing patterns in response to reductions in the abundance of large individuals, a conclusion consistent with discussions held between commercial fishers and DOF (AIAWA pers. comm.). In evaluating the results of the catch curve analyses, it needs to be recognised that the mortality estimates relate to the mortality experienced by only those individuals that have become fully-selected into the fishery. As Brownlip abalone mature at a considerably smaller size (~120 mm) than the length at which it becomes fully-selected into the fishery (>~160 mm, see Table 4.6), the mortality that, on average, is experienced by the breeding stock will be substantially lower. For this reason, it is not informative to relate estimates of fishing mortality (F) for fully-selected individuals, resulting from catch curve analysis, to F-based references points (e.g. $F_{\text{Target}} = 2/3M$ or $F_{\text{Limit}} = 3/2M$), as this would not fully account for the level of protection provided to the breeding stock due to the fishery strategy adopted by fishers. Consequently, for a level 3 assessment of Brownlip abalone, it is necessary to undertake a form of analysis that accounts for the lower levels of fishing mortality experienced by smaller individuals, such as the per recruit (and related) analyses undertaken in this study. Note that, to provide estimates of current yield and/or spawning potential ratio using per recruit analysis, it was first necessary to undertake catch curve analyses to provide current estimates for selectivity parameters and mortality.

5.4 Per Recruit and Related Equilibrium-based Models

Influence of alternative modelling assumptions on results

The results obtained using the traditional per recruit model suggest that at the current estimated level of fishing pressure, YPR could potentially be increased by reducing the sizes at which Brownlip abalone are currently fished. Even if a lower value for M than used for the base case scenario (0.15 y^{-1}) was assumed in the analysis. They also suggest that, if fishers continued to harvest Brownlip abalone at the same sizes as currently fished, YPR would continue to increase even at extremely high levels of F (up to at least 6.0 y^{-1}). Traditional yield per recruit models are relative simplistic models that consider only the possibility of 'growth overfishing' (i.e. direct impacts on yield due to fishing), that results from excessive removal individuals from the population before they have had sufficient time to grow. They lack biological realism in that they do not account for the possibility of 'recruitment overfishing', i.e. the potential for recruitment to be impacted due to declines in spawning biomass. In other words, traditional YPR models do not take into account sustainability of the fishing rate when estimating maximum yield from predicted optimal F values (e.g. Sainsbury 1982).

The traditional yield per recruit model is often extended to calculate values of spawning potential ratio (SPR) based on spawning stock biomass per recruit or eggs per recruit, as a measure of the extent to which population reproductive potential has been reduced from its initial, unfished state (e.g. Haddon 2011). Typically, values of SPR are then used as a performance indicator, and compared against specified target (e.g. 0.4) and limit (e.g. 0.2) reference levels (e.g. Sluczanowski 1984; 1986). Per recruit analyses that derive estimates of both YPR and SPR have been used widely in the assessment and management of abalone fisheries throughout the world, as these models are relatively easy to apply and have direct applications for management (Breen 1992). These models are thus considered to have utility for exploring potential effects of changes to management and fishing operations, such as variations to size limits and to the sizes of animals that are harvested, impacts of seasonal and/or pulse fishing operations, as well as alternative assumptions about biology (e.g. levels of natural mortality, etc.). Per recruit analysis was used relatively recently to model effects, on YPR and SPR, of changes to minimum size limits for Greenlip abalone in WA (Hart et al. 2013a). The results of such analysis for Brownlip abalone in this study indicated that, even at high levels of F, the values of SPR would not decline below ~0.2 for any of the alternative scenarios considered relating to the different selectivity schedules and assumed values for M. Suggesting that under the current policy adopted by industry to only harvest relatively large individuals of Brownlip abalone (that are larger the current legal minimum size), the stock is relatively resilient to fishing pressure. However, as discussed below, these results should be treated with caution.

A key limitation of the latter type of per recruit model is that, even though it considers impacts of fishing on spawning biomass, it does not account for any indirect fishing impacts on yield or spawning biomass, as may occur if spawning biomass is reduced to a level where recruitment is impacted (e.g. Breen 1992; Punt et al. 1993). That is, per recruit models by definition, assume constant recruitment. For this reason, it was considered important to explore the extent to which recruitment (and thus ultimately yield and SPR) might be impacted by fishing mortality, by extending the model further to incorporate a stock-recruitment relationship (with an assumed value for the steepness parameter, h, for this relationship) (Shepherd 1982). The results obtained using this latter model (which, in general, may be described as either a 'dynamic pool model' or 'equilibrium, age-based model', but no longer a 'per recruit model') were less optimistic than the traditional per recruit model. This extended model with a stock-recruitment relationship (hereafter in this discussion, termed the 'extended model') indicated that, at high levels of F, yields should decline relative to those at $F_{\max}$, but to varying degrees depending on the scenario for selectivity, M or h. Moreover, for some of the alternative scenarios considered relating to different selectivity patterns, and M

and h values, the model predicts that it is possible to breach the limit reference point when fishing pressure becomes excessive.

Despite having extended the per recruit model considerably to incorporate a stock-recruitment relationship, the results of this type of analysis are still impacted by several strong assumptions, including that the population is at equilibrium under constant fishing mortality and that recruitment does not fluctuate annually about the mean levels predicted by the stock-recruitment curve. The variation in abundance of spawning biomass may also contribute little to the variation in recruitment given the number of environmental factors that could impact strongly on certain abalone life stages (McShane 1995). Although the results are potentially useful, they should be treated with a level of caution. The integrated model described in this report overcomes some, but not all, of the strong assumptions made by this 'extended model' and per recruit models.

Sensitivity analyses

The results of the sensitivity analyses employing the extended model with the stock-recruitment relationship, highlighted that estimates of YPR and SPR were sensitive to different values of the selectivity parameters, and M and h. The results were always more pessimistic when the values of the selectivity parameters were lowered and when h was lowered. In the case of M, the results suggested that when M is low, YPR increases (relatively to values for higher M values) unless F becomes very high. The values of the selectivity parameters considered for the base case scenario are considered feasible given that these have been estimated using catch curve analyses fitted to recent length composition data (Section 4.3.2). Likewise, as the value of M considered for the base case scenario was based on an estimate derived from tag-recapture data for Brownlip abalone in WA (Section 4.1.2), the value is considered feasible. However, given that previous studies on Greenlip and Blacklip abalone populations have indicated that M varies and is length/age-dependent (Shepherd and Breen 1992; Shepherd and Barker 1998), there may be value in exploring the impacts of assuming such trends in natural mortality on the results of this type of modelling. In the case of h, the true value is far less certain. The value of 0.6 used for the base case is similar, but higher than the 0.5 assumed in a recent MSE study undertaken by Haddon et al. (2013). Given that the results produced by the sensitivity analysis for h were far more pessimistic when a lower value of 0.4 was used, it may be prudent for future management of this species to base assessment results on a more conservative value of h such as 0.5 or 0.4, than that considered in this study for the base case scenario. However, further consideration needs to be given as to whether these values of h suggest that the current level of spawning stock is affecting recruitment.

Stock status

Employing the extended model, at the current estimated value of F of 0.11 y^{-1}, the estimate of SPR for the basis case scenario (h=0.6, M=0.15 y^{-1} and selectivity as estimated for 2013-15) was 0.54. If it is assumed that h=0.4, SPR is estimated at 0.39. Taking into account uncertainty in h, i.e. the parameter considered least well known, SPR is considered to range between 0.39 and 0.54. From previous assessments of abalone fisheries, a value of 0.5 for SPR has often been used to represent an optimum (i.e. target) level of egg production (e.g. Breen 1986; Hart et al. 2013a; see also Breen 1992) and a value of 0.2 considered unacceptable (i.e. as a limit reference point) (Breen, 1986). However, the revised harvest strategy for abalone species in the WA AMF specifies Area-specific target, threshold and limit reference levels that correspond to 40% (0.4), 30% (0.3) and 20% (0.2) of unfished stock levels, respectively, all be it for catch rate as a proxy for biomass rather than SPR (DOF 2017). On the basis of the SPR results, it would appear highly likely that current SPR of Brownlip abalone is above the limit and threshold reference points of 0.2 and 0.3, respectively, and may be at or above the target of 0.4.

Previous experience has shown that, because of uncertainties associated with estimates of parameters from equilibrium models, $F_{\max}$ is too high as a target reference point and a more conservative reference point (e.g. $F_{0.1}$) is more appropriate (Hilborn and Walters 1992; Haddon 2011). For the extended model using the base case scenario, the point estimate for the current estimate for F of 0.11 y^{-1} is below both $F_{\max}$ (0.28 y^{-1}) and $F_{0.1}$ (0.15 y^{-1}). For the extended model assuming h=0.4, the current estimate for F is about the same as $F_{\max}$ (0.11 y^{-1}) and thus above $F_{0.1}$ (0.08 y^{-1}). On the basis of the yield results from the extended model, and accounting for uncertainty in h, F is unlikely to exceed $F_{\max}$ but it is possible that F exceeds $F_{0.1}$.

Fishing size limits, optimal harvest sizes and harvest potential

Using the extended model, the sensitivity analyses associated with minimum harvest size indicated that if commercial fishers elected to target Brownlip abalone at 140 mm (current LML) rather than 150 mm (current minimum commercial harvest size), this would not impact yield greatly at the current estimated level of fishing pressure. As commercial fishers receive payment for their catches relative to total weight (i.e. not graded according to size), a reduced size composition would not be expected to impact on their income. Similarly, the prices received for Brownlip abalone by local fish processors would not be expected to vary greatly if this species was harvested at slightly smaller sizes (above 140 mm), because it would still be regarded as large wild-capture product. Note that, for abalone species in general, small animals (e.g. Roe's abalone) and aquaculture product receive considerably lower market price, but this is currently not relevant to Brownlip abalone. However, the sensitivity analyses also demonstrated that the modelling results are very sensitive to values of both M and h. For example, if the value of h for Brownlip abalone is set at 0.4 rather than 0.6, harvesting this species at the current L_{50} of 150 mm and current estimated level of fishing would result in a substantial decline in yield. If the minimum harvest size was reduced to 140 mm, under this scenario for h, not only would the yield decline markedly, but spawning potential (SPR) of the population would be expected to decline to a level that would pose a considerable risk to sustainability. If fishers have reduced the minimum harvest size for Brownlip abalone (from 160 mm to 150 mm) due to declines in the abundance of large individuals in the population, fishing pressure would need to be reduced in order to obtain good yields in the longer term. Given the above, it is suggested that commercial fishers would benefit by maintaining the current minimum harvest size of 150 mm, and not allowing any further increase in fishing effort. This, indicates that the TACCs that had been set in recent years (up to 2012) prior to effort reductions, may have exceeded the upper limit for the long term harvest potential of the population.

5.5 Preliminary Integrated Length-based Model

Model structure/assumptions

The preliminary size-structured integrated model developed in this study provided good visual fits to both the commercial catch rate and size composition data. This therefore provides some indication that the two data sets provide a similar signal in terms of stock abundance, i.e. that there is limited ‘tension’ between the two data sets and that the model structure was appropriate given the data. In terms of model structure, two important aspects were 1) time-varying selectivity and 2) allowing for a change in catchability when the fishery began to employ two divers (rather than just one) on a single day of fishing.

The importance of incorporating time-varying selectivity to avoid model misspecification (which can otherwise lead to biased estimates of abundance and mortality rates) is now well recognised (e.g. Gudmundsson et al. 2012; Piner et al. 2013; Martell and Stewart 2014; Maunder et al. 2014). Evidence to suggest that time-varying selectivity was important included that the selectivity pattern appeared to have changed markedly in recent years from the catch curve results, as was also understood from anecdotal evidence from commercial fishers. Furthermore, the fit of the integrated model to the length composition data improved markedly once time-varying selectivity was assumed. The time-varying nature of selectivity does raise an issue with respect to the catch rate data for this species. That is, the catch rates estimated for each year would be influenced by changes to fishing operations such as minimum harvest size and this could impact on interpretation of such data series (when viewed in isolation). This type of issue represents one reason why analysis of such data within an integrated model may be beneficial.

Assuming a change of catchability, i.e. estimating separate catchability coefficients (q) for the two catch rate time periods (single diver vs two divers fishing days), was important for improving the fit of the model to the annual catch rate time series and indeed overall model fit (introducing the second q reduced the overall negative log-likelihood by about 14). Some improvements could be made, however, with respect to how the catch rate data for Brownlip abalone are analysed prior to their use in the integrated model. In this study, the catch rate data were analysed using a catch rate standardisation model which accounted for the influence of fishing season, month, sub-area and diver (see Hart et al. 2009; Hart et al. 2013a). In an attempt to avoid those catches where fishing was targeted towards the main target specie (Greenlip abalone), the data were also ‘pre-treated’ by only including information relating to abalone catches from fishing days using a ‘qualification level’ for a minimum amount of Brownlip catch (based on the approach of Biseau 1998). Prior to standardisation, a ‘correction factor’ was also used to adjust the nominal Brownlip catch rate data for the effects of technology changes (i.e. GPS) (see Hart et al. 2009, Table 2). More recently, however, the nominal catch rates were further adjusted prior to standardisation, using a correction factor that attempted to account for the effect of the change in fishing efficiency that would have resulted from the use of 1 verse 2 divers per fishing day. However, the data available to estimate that correction factor for Brownlip were minimal (i.e. there were limited days where both 1 and 2 divers were used). The requirement, in the model, to estimate separate catchability parameters for the two catch rate periods to provide a good fit to the catch rate data, implies that this correction factor may not have been well estimated in the catch rate standardisation model. A better alternative, in future, may be to treat the catch rate data based on 1 or 2 divers as separate time series (still assumed to have separate catchabilities) and not estimate a correction factor for the 1 verse 2 diver effect in the catch rate standardisation model. Another consideration for future research is that, beyond the impacts of changes in technology and fishing operations (1 verse 2 divers), fishing efficiency is assumed to have remained constant. The impacts of alternative assumptions relating to potential 'creep' in fishing efficiency could be considered.

One aspect of this model which differs from many traditional integrated models, is that the composition data were not analysed using the multinomial distribution. The use of the Dirichlet distribution enabled internal estimation of effective sample size (thereby preventing the need to apply a data weighting procedure outside the model) (Schnute and Haigh 2007; Francis 2011; Francis 2014). One issue that has been raised with the Dirichlet distribution is that it does not account for positive correlations in the data (Francis 2014). Examination of the residuals associated with the observed and expected proportions of Brownlip abalone in successive length classes did demonstrate at degree of correlation in the data in a few years. One alternative distribution that can account for both over dispersion and correlation is the logistic normal distribution. According to Francis (2014), this latter distribution is most easily applied to models that are not sex-structured, as is the case for Brownlip abalone (noting that length samples taken from commercial fishers comprise only the shell and thus it is not possible to determine the sex of the individual). For future modelling, the use of this distribution for abalone composition data appears worth exploring.

As discussed by Haddon et al. (2008), the manner in which growth is described within a size-structured model can substantially impact on model results. Earlier in this study, considerable attention was paid towards identifying an appropriate model for describing the growth of Brownlip abalone (Section 4.3.1). This involved statistically comparing alternative models for describing the available tag-recapture data for this species, i.e. based on Akaike's Information Criteria (AIC) (Burnham and Anderson 2002). Despite this, an important limitation of the modelling undertaken for Brownlip abalone is that the data are pooled across management areas and thus also the sub-areas. As discussed by Haddon (2011) in regard to a model for Blacklip abalone, growth of individuals in abalone populations is notoriously variable and a model that attempts to capture population dynamics over a large area essentially averages over much of the variation between the different populations. As considered, for example by Breen et al. (2003) with respect to their use of commercial catch rate data for their length-based modelling of New Zealand abalone (*Haliotis iris*), by modelling at a broad scale, there is a danger of productivity being overestimated if fishing is causing serial depletion and/or if fishing has led to some populations becoming unproductive. Ideally, modelling in future should be undertaken at smaller spatial scales, but given the relative low economic value of this species there may be insufficient data. For this reason, the results needed to be treated with a degree of caution (see Haddon 2011).

The modelling of Brownlip abalone was also influenced by the lack of any marked signal in the catch rate time series, resulting in more uncertain outputs in relation to stock status. A final limitation worth mentioning is that the models developed in this study currently assume, based on the work of Well and Mulvay (1992), that the attainment of maturity of Brownlip abalone is 'knife-edged' at 120 mm and that this size is common to both sexes. Sampling is currently underway to refine the estimates of size at maturity for this species.

Key results/assessment outcomes

In broad terms, the outputs of this preliminary integrated assessment model suggest that the overall stock status of Brownlip abalone is at an adequate level. In particular, the estimates of the ratio of spawning biomass in 2015 relative to the unfished level (and associated 95% confidence limits) are above 0.5. The lack of any marked decline in estimated female spawning biomass (as is consistent with the annual trends in the catch rate series) implies that, at least recently, this has not declined greatly. The results are also broadly consistent with the catch curve and per recruit (and extended per recruit) modelling, albeit slightly more optimistic. It should be noted, however, that the outputs of the integrated model account for only some of the uncertainty that exists, i.e. for one influential parameter, by specifying different values (0.4 and 0.6) for the steepness parameter (h) of the stock-recruitment relationship. Given that the objective to develop an integrated assessment model was only added late in the project, time was limited. For future work, further sensitivity analyses could be used to explore the sensitivity of the model to alternative assumptions relating to uncertainty in other parameters (e.g. M and efficiency creep – see earlier).

An important question raised from the outputs of the modelling undertaken in this study is the reason as to why fishers are now harvesting smaller Brownlip abalone. One possible explanation is that, due to declines in biomass of abalone above the size at which this species was historically harvested (~165 mm), commercial fishers elected to start harvesting smaller individuals to maintain their catch rates and achieve their quota. Noting that the commercial industry self-imposes minimum size limits that are in excess of the legal size limits set by DOF, and which are well above the estimated size at maturity. Even if this scenario was true, this does not necessarily reflect a sustainability issue. However, if maintenance of relatively large individuals within the breeding stock is considered desirable, then potentially, the catches in more recent years were too high. Indeed, this was already the view taken by the commercial fishing industry and the DOF (given the declines that had been observed in the abundance of larger individuals through meat weight analyses), which resulted in the TACC for Brownlip abalone in WA being reduced from 14.4 t in 2014 to 10 t (meat weight) in 2015. The model developed in this study is potentially of use for informing, through simulation projections, whether the level of reduction in TACC is likely to be sufficient to result in a desired level of increase in abundance of Brownlip above the historic minimum harvest size.

6 Conclusion

The overall aim of this project was to address knowledge gaps relating to the biology and population dynamics of Brownlip abalone, while at the same time looking to improve the management of the WA Brownlip abalone fishery. To achieve this, the specific objectives of the project were to determine growth and mortality of wild populations, growth rates and mortality of cultured animals, habitat identification for potential stock enhancement, develop fishing size limits and a preliminary integrated length-based model. All but one of the objectives were fully achieved. The objective of habitat identification to determine release mortality, growth, survival and recapture parameters for potential Brownlip abalone stock enhancement was only partially completed. Suitable habitat was identified in the tag-recapture study and the systems developed to complete the objective, but due to AIAWA withdrawing their support for releases of hatchery-reared juveniles into wild populations, any assessment on the potential of stock enhancement of Brownlip abalone was unable to be undertaken. This position on stock enhancement is still upheld by the AIAWA and until such time as their stance changes this objective cannot be completed. To offset this and add significant value to the project, the objective to develop a preliminary integrated length-based model was incorporated during the latter stages of the project, which is considered to have substantial benefits for the management of the Brownlip abalone fishery within WA.

This project provided a unique opportunity to facilitate research on the, relatively unknown, previously considered “by-product”, Brownlip abalone species in the WA AMF. Until now there has been very limited information on basic biological characteristics of Brownlip abalone. This project has produced a range of useful information on Brownlip abalone and developed approaches for the management of Brownlip abalone in WA, including:

a) The most reliable estimates of natural and fishing mortality for this species.

b) Demonstrated the species ability to be commercially produced in aquaculture, while also evaluating different grow-out system designs.

c) Utilisation of both wild and aquaculture tag-recapture data to model growth throughout all stages of life.

d) The development of a per recruit model for Brownlip abalone, extended to incorporate a stock-recruitment relationship. The model has been used to evaluate the implications of different fishing size limits, and alternative assumptions for natural mortality and the steepness parameter of the stock-recruitment relationship.

e) Development of a preliminary, length-based integrated model that utilises the biological parameters estimated in this study, together with commercial catch rate and size composition data to evaluate the current stock status of the Brownlip abalone stock.

f) Identification of influential commercial fishing practices such as temporal changes in selectivity and the shift from using 1 to 2 divers per fishing day, plus their effects on the WA Brownlip abalone population and implications for interpretation of data.

This study is the most comprehensive evaluation of Brownlip abalone biology and fisheries assessment, and will provide a solid research foundation for future management of the Brownlip abalone fishery in WA. The approaches developed are in the process of being modified for the two other commercial abalone species (*Haliotis laevigata* and *H. roei*) in WA, to help inform future management of the AMF. Overall the risk-based "weight of evidence approach" used by the DOF indicates that the current stock status of the Brownlip abalone fishery in WA is at an adequate level. However, more research is still required to improve estimates of some biological parameters, such as those defining the size-based relationships for maturity and fecundity. Future research will also involve applying, where possible, the analyses described in this project to WA abalone species at smaller spatial scales to coincide with AMF management areas and sub-areas, thereby better assessing if localised depletions have/are occurring.

7 Implications

In the project agreement three planned outputs were detailed and the research has met these as follows:

1) Deliver original scientific knowledge on the biology (habitat identification, natural mortality, growth, size distribution etc.) of Brownlip abalone in Western Australia.

Significant original scientific knowledge has been attained on Brownlip abalone in WA through this research. The biological parameters established in this study are either the first estimates produced, i.e. natural/fishing/total mortality, or the most reliable estimates to date, i.e. growth, habitat identification, size distribution, etc. For example, before this research, estimates of mortality had generally been assumed from Blacklip abalone populations in SA. Now species-specific estimates of total mortality have been produced by length-based catch curve analysis of commercial catch composition data and the integrated model, while natural and fishing mortality have been derived from a comprehensive tag-recapture study. The incorporation of both a wild tag-recapture study and assessment of Brownlip abalone in aquaculture within this research, has provided information relevant to each industry. The combined data for wild and cultured individuals was also valuable for providing biological information on this species throughout all life stages. This new knowledge on Brownlip abalone will significantly aid the management of the resource by providing informative data for this and future stock assessments.

2) Establishment of a Brownlip abalone research capacity to fill the needs of both the industry and Government.

Given the limited biological information and fisheries assessment undertaken on Brownlip abalone before this project, the establishment of a Brownlip abalone research capacity was considered a key component of the project and will only benefit the future management of the Brownlip abalone fishery in WA. The research project has resulted in not only original scientific knowledge on the biology as described above, but also developed and initiated assessment methods for better evaluating stock status. During this project there was considerable conjecture within the commercial industry and concern over the stock status of the fishery. This assessment has clarified the stock status and supported recent management action.

The DOF currently employs a "weight of evidence" approach to stock assessment by evaluating the stock status using all available information within a risk-based framework. Previously the only information available for Brownlip abalone was derived from lower levels of assessment (annual trends in catch). The development and implementation of length-based catch curves, the extended per recruit model and the preliminary integrated length-based model, provides greater range of assessment methods for evaluating stock status. These analyses provide researchers with a range of tools to assess the stock status of the Brownlip abalone fishery and thereby produce appropriate advice for management to achieve a sustainable fisheries resource.

3) Determine the overall profitability of the Brownlip fishery and focus on enhancing the wild and developing the cultured or ocean grown Brownlip abalone industries.

Even though the assessment of the Brownlip abalone fishery and aquaculture in WA was able to determine the status of each industry, it was difficult to extend the research into stock enhancement or sea ranching. The assessment of the Brownlip abalone fishery showed the overall stock status to be at an adequate level. It also suggested that further reductions to minimum harvest size or any increase in quota (at least in the short term) to improve catch would not be consistent with precautionary management. For the commercial fishery, it was originally proposed that profitability could potentially be improved by implementing a sustainable balance of changes, including modifying minimum harvest sizes, increasing quotas and introducing stock enhancement. It was considered that reducing minimum harvest size or shifting to length-width limits may reduce the level of effort required by commercial fishers to catch their quota, and in turn reduce costs by approximately $5 per kg Brownlip whole weight. An increase from 42 to 50 t in the TACC was expected to result in an estimated additional $280,000 annual income to the fishery (8 t at $35 per kg).

At the start of this project there was an emphasis on applying the research undertaken to improve profitability. More recently, the focus of AIAWA and DOF has shifted towards sustainability concerns, and this has coincided with quota reductions. The outputs of this project have provided strong evidence that currently, long-term profitability would not be increased by either, further reducing the minimum harvest size or increasing the quota for Brownlip abalone. Introducing stock enhancement as a management tool could still be of benefit by improving profitability and increasing stock biomass (Hart and Strain 2016). As detailed above, the AIAWA removed their support for the release of hatchery-reared juveniles into wild populations, and therefore made any assessment on the potential of stock enhancement of Brownlip abalone a long term prospect.

In aquaculture, Brownlip abalone can be produced to market size and this research has identified the systems and limitations associated with achieving this. Even with faster production and subsequently reduced cost, the expansion of this industry is not necessarily limited by the production rates of Brownlip abalone but rather the market options and sale price available. Diversification into other areas such as sea ranching is entirely possible with this species, but it is likely that this would be determined by markets rather than production. However, significant research would need to be undertaken to assess the potential of Brownlip abalone for sea ranching, but the industry itself is still very much in its infancy.

8 Recommendations

The scientific information and assessment analyses delivered in this research are considered extremely useful and will be incorporated into the DOF management of the Brownlip abalone fishery within WA. Continuing these assessments over time will provide a better understanding of not only the stock status of Brownlip abalone but also the influence of fishing practices and possible environmental factors on the population. To maintain the most relevant assessments, the biological and fisheries data that feed these assessments need to be kept up to date, and also refined to a scale that best suits management but also the intrinsic nature of the species.

Given the models/assessment methods developed in this research are going to be implemented for Brownlip abalone, they should also be extended to the other two abalone species in the WA AMF. This process has already commenced with both Greenlip and Roe's abalone growth and mortality being examined. In the future, integrated length-based models of essentially the same structure will be applied in assessments of these other two species. As all 3 species are managed within the same fishery it would be beneficial to apply common assessment approaches. Therefore, the approaches developed are going to be used for all abalone species in WA and their benefits incorporated into the management of the WA AMF.

8.1 Further Development

Even though much of the scientific information used in the assessment analyses were either the first or most reliable estimates for this species, more research is still required to improve estimates of the relationships between maturity and fecundity with size. Although the parameters used were based on good research, that work was undertaken about 3 decades ago. Since that time, some methods of analysis have improved and it is possible that some aspects of the biology of the stock have changed considerably over time, particularly with the changing environmental conditions. The other refinement to data input to be considered is the scale this assessment was based on. In this report, the analyses were based on data combined for samples collected across the whole fishery. Although the spatial scale to which assessments can be applied is dictated, to a large degree, by data availability, there would be merit in exploring whether it is possible to conduct assessments at a smaller spatial scale to better account for variation in the biological attributes among different the populations of Brownlip abalone within the fishery. This investigation is currently being undertaken with the preliminary analyses of tag-recapture data separated by the two main management areas (Area 2 and 3). The results of these preliminary analyses indicate that, at this still relatively broad spatial scale, growth is similar but slightly greater in Area 3 than Area 2. If growth and other parameters can be estimated at smaller spatial scales, these can be input into the various assessments to assess if there is any evidence of localised depletion.

Regarding further development of the modelling in this research, it was identified that improvements could be made in the catch rate data used in the preliminary integrated length-based model. Particularly in relation to estimating how the change from 1 to 2 divers per fishing day influenced catchability. Given the intention to fit integrated models to the data for both Greenlip and Roe’s abalone, further development of the model will be required to incorporate the additional (fishery-independent) data available for these species.

It has been stated earlier in the conclusion (Section 6) that due to external factors, one of the objectives of this research was not fully completed. The potential of stock enhancement of Brownlip abalone remains relatively unknown, and until AIAWA changes its position on the release of hatchery-reared abalone into the wild it will remain so. Information can be inferred from recent research on stock enhancement of Greenlip abalone in WA (Hart and Strain 2016), but even basic information on variables such as growth and survival of released juvenile Brownlip abalone needs to be understood before an evaluation can be made of the potential for Brownlip abalone stock enhancement.

Utilising Brownlip abalone for sea ranching has been identified as a potential avenue for increasing the overall profitability of the species. Even though Brownlip abalone can be produced to market size in aquaculture, further research could be conducted to improve production rates. Substantial research would be required to incorporate Brownlip abalone into current sea ranching practices in WA, as at present this industry is only in its infancy with Greenlip abalone. Particular attention would need to be paid to the highly cryptic nature of Brownlip abalone when designing suitable artificial habitat.

9 Extension and Adoption

Key research and outcomes of this project have been disseminated to the target audience, which includes the WA Brownlip abalone fishery, the WA aquaculture industry and resource managers at the DOF. This has included, providing industry and Government in WA an evaluation of specific biological, aquaculture, enhancement and harvest strategy outcomes. Specifically, information has been provided on methods for assessing wild Brownlip abalone stocks and the protocols involved in the development of commercial Brownlip abalone aquaculture.

Both AIAWA and the Brownlip abalone licence holders/fishers are the primary audience for this research, with the most up to date project results and outcomes conveyed to them throughout the duration of the project. This has occurred through presentations and discussions at Annual Management Meetings and quarterly Scientific Advisory Group meetings between the DOF and industry stakeholders, as well as ongoing discussions directly with licence holders and fishers.

The WA abalone aquaculture industry, and more specifically the commercial abalone farm 888 Abalone Pty Ltd have been involved in this research throughout the project, with all aquaculture components of the project being conducted at their facility. This has allowed instant communication of the research results to the industry and their extension into commercial practices.

Administrators of fisheries management at the DOF including both the researchers and the managers have been involved in the project. A detailed overview of the research will be provided to the managers and the likely implications for the future management of the Brownlip abalone fishery within WA.

The expanded audiences the project research and outcomes are relevant to include, national abalone wild stock and aquaculture industry bodies, Australia-wide Fisheries and Aquaculture Research Institutions, regional managers and national/international abalone scientists and biologists. To extend and communicate the project results to the expanded target audience, presentations will be given at an appropriate National and/or International Conferences and scientific manuscripts published in due course.

9.1 Project Coverage

A media release entitled “Brownlip abalone – growing out of the greenlip’s shadow” was released on the Department of Fisheries Western Australia website in October 2012.

A media release will be produced when the final project report is published.

9.2 Project Material Developed

Several scientific manuscripts are currently under preparation and intend on being submitted to international peer-reviewed journals.

10 Appendices

10.1 Appendix 1: Intellectual Property

The results of this project have become public domain and will be published, widely disseminated and promoted with training and extension provided if required. There is no intellectual property associated with this research report and it is not anticipated that any patents will arise from this project.

10.2 Appendix 2: List of Staff

The following Research Scientists conducted this project.

Dr Lachlan Strain

Dr Alex Hesp

Dr Anthony Hart

Dr Nick Caputi

Professor Norm Hall

The following Technical Officers were engaged on this project.

Mr Frank Fabris

Mr Jamin Brown

Mr David Murphy

Mr Mark Davidson

The following contributed significantly to this project.

Mr Shane Smith

Mr Vincent Encena

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