

Abalone Stock Enhancement at Cape Recife, Eastern Cape Province of South Africa

Thesis submitted in fulfilment of the
Requirements of the Degree of
MASTER OF SCIENCE
Rhodes University



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2016

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ABSTRACT

The potential for restocking depleted natural reefs with hatchery abalone, *Haliotis midae*, to support a commercial ranching venture in the Eastern Cape Province of South Africa was investigated. A baseline stock assessment and analysis of historical fishery data provided compelling evidence of significant declines in the abalone stock, attributed to uncontrolled illegal fishing over the last 20 years at the study site. A ranching pilot study was undertaken where small-scale replicated seeding experiments were set up which quantified the effect of seed size, density and habitat on survival and growth of hatchery-reared abalone. Thirty-six experimental plots were seeded with 8400 abalone spread evenly over two broad habitats. Mean retrievals of seeded abalone were 17% ranging from 4 – 42% after a minimum of eight months at large. Release density and large-scale habitat had no significant effect on seed survival, but smaller seed size (40.0 ± 3.7 mm shell length) achieved higher ($F_{1,22} = 4.64$, $p = 0.042$) retrievals than larger seed size (53 ± 3.7 mm). Growth rates were an average of 30% higher in the shallow sites compared deeper sites ($t_{1,1091} = -2.79$, $p = 0.005$). There was seasonal component in growth with a 0.55 ± 0.04 mm per month higher rate in summer than during winter ($t_{1,1091} = -12.45$, $p < 0.001$). Abalone seed releases were also conducted on a larger scale, which focused on the economic potential for commercial-scale ranching. Over 160 sites were seeded with 1.4 million hatchery reared abalone or 30 metric tonnes. Seventeen sites underwent long-term monitoring of survival with repeated sampling events on sites over a period of up to 666 days. Nine of these sites were seeded with 140800 small abalone (29 – 40 mm), three sites with 25100 medium abalone (30 – 46 mm) and five sites with 14700 large abalone (60 – 84 mm). There was a significant difference in survival between the seed sizes ($F_{4,6329} = 304.3$, $P < 0.001$). The Generalized Linear Mixed Model (GLMM) calculation estimated the instantaneous apparent mortality rate for small, medium and large abalone at 1.19 yr^{-1} , -0.9 yr^{-1} and -0.67 yr^{-1} , which equated to a survival rate of 21%, 28% and 36% per year respectively. The weighted mortality rate calculated according to the seed size differential mortality and the number of seed released for those sizes was 1 yr^{-1} or 25% survival. In conjunction with a conservative somatic growth rate of 1.2 mm.m^{-1} and plausible emigration rates, a range of biomass harvesting estimates were obtained. Movement and mortality were investigated using video analysis which showed that hatchery seed had the ability to move considerably once released onto natural reefs and confirmed that mortality immediately following releases was due to the heavy predation pressure as confirmed by shell collections. This project has demonstrated that potential exists for ranching in South Africa and highlights critical factors that need to be addressed if ranching is to be an economically viable operation.

DECLARATION

I, Warren Witte, declare that this is my own unaided work hereby submitted for the degree of Masters of Science of Rhodes University in the Faculty of Science. It has not been submitted for any degree for examination in any other university.

Warren Witte, January 2017



ACKNOWLEDGEMENTS

The abalone ranching project at Cape Recife was undertaken on a scale not yet seen in South Africa. An immense amount was achieved from both a commercial seeding development and research perspective. There were many challenges and difficulties that arose throughout the study but these were overcome with the support and teamwork from a variety of entities, groups and individuals which I would like to thank.

Professor Peter Britz, my supervisor, for always being available for guidance and helping resolve issues that arose on a continuous basis. Thanks for all the insights and knowledge you provided me with over the years it's been a great pleasure. Brian Godfrey, the technical supervisor at Department of Ichthyology and Fishery Science (DIFS), provided vital insight and support to getting my feet off the ground. Your knowledge and practical experience was an invaluable tool for steering me in the right direction. Thank you for all the trips that you made down to Port Elizabeth, your hands on approach and always being available to answer any questions. Dave, the new technical supervisor of DIFS, thanks for help with various items and dive support.

Wild Coast Abalone who formed the central core of the project, providing the huge drive needed to make ranching a success. For supplying all the abalone spat for the experiments. Brendon Malan whom I have conversed with consistently over the course of the project, providing all the necessary information and expertise and having an open ear for any adjustments that needed to be made. Tom Swartz, head of the anti-poaching unit in PE, for skippering our vessel Naartjie for the research work. To the whole team at Tactical Task Force (TFF) for providing a safe and secure environment to work in, your hard work on and off the boat and for the great friendships forged.

Research divers, Andrew, Diane, Evania, Adrian, Cale, Alex and Matt who formed the core of the team and to the many others whom are too numerous to mention many thanks for the countless hours spent being washed around in often very tough conditions. Dive supervisors, Anton, Paul and Michelle many thanks for your support and ensuring the safety of the team. Morvan for always been on call and ready with Blue Pearl for research dives.

I owe a great sense of gratitude to Mike Berg for his invaluable time spent on many aspects of the data analysis and to Dominique Prinsloo for her input in structuring and

editing of this document and getting me over the finish line.

The Technology and Human Resources or Industry Programme (THRIP) as well as Lidomix (Pty) Ltd. for providing the funding which supported the research and myself over the duration of this project.

Thanks to my parents for the educational support platform you have provided me with to allow me to get to where I have and complete my Masters degree in science.

LIST OF ABBREVIATIONS

ATT	Abalone Task Team
DAFF	Department of Agriculture, Forestry and Fisheries
g	grams
GIS	Geographic Information System
<i>H. midae</i>	<i>Haliotis midae</i>
HMCO	Honorary Marine Conservation Officer
IUU	Illegal, Unreported and Unregulated
MLS	Minimum Legal Size
m ⁻²	per metre square
MCM	Marine and Coastal Management
MLRA	Marine Living Resource Act
mm	millimetres
mm.m ⁻¹	millimetres per month
MPA	Marine Protected Area
Kg	Kilogram
Pers. Comm.	Personal Communication
Pers. Obs.	Personal Observation
Pty (Ltd)	Propriety Limited Company
SAPS	South African Police Services
SCUBA	Self Contained Underwater Breathing Apparatus
SMB	Surface Marker Buoy
SOP	standard operating procedure
TAC	Total Allowable Catch
TTF	Tactical Task Force
TURFs	Territorial User Rights Fishery
SD	standard deviation
USD	United States Dollar

SANParks

South African National Parks

ZAR

South African Rand

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CHAPTER 1

1.1 General Introduction

The South African wild abalone fishery has experienced a dramatic decline over the last three decades, predominantly a result of heavy fishing pressure from the illegal catch (Raemaekers et al., 2011). Similarly declines have taken place worldwide, where Total Allowable Catches (TACs) have declined in almost every remaining abalone fishery (Shepherd & Rodda, 2001; Prince, 2005; Heasman, 2006; Cook & Gordon, 2010). The decline of wild abalone stocks has led to the use of farmed abalone to meet the global demand and as a result, the supply of abalone has increased and kept pace with world demand (Sales & Britz, 2001; Cook & Gordon, 2010). Nonetheless, the status of the wild abalone stocks remains an ecological, social and economic concern. The Food and Agriculture Organization of the United Nations (FAO) has identified the management of marine capture fisheries in a more responsible and sustainable manner as of priority concern on their agenda (Butchart et al., 2010; FAO, 2011). A fishery management tool that has received much attention for potentially increasing or sustaining coastal fisheries is stock enhancement and sea ranching which uses juveniles from a farm source to rehabilitate stocks in the sea (Munroe & Bell, 1997; Bartley, 1999; Liao, 1999; Liao & Leaña, 2003; Mustafa et al., 2003). The effectiveness of stock enhancement has increased in the last few decades as a result of significant strides made in hatchery management techniques which can now produce juveniles on large enough scales for release and the evolution of new methods of sea farming (Mustafa et al., 2003; Bell et al., 2008). In South Africa, while hatchery-rearing technologies for abalone are well established (Sales & Britz, 2001), knowledge about the factors determining the successful release of juveniles back into the sea is very limited (Sweijd, 1998; De Waal, 2002; Godfrey, 2003). To satisfy this knowledge gap, this thesis set out to explore the factors determining the viability and success of a pilot commercial abalone ranching program on the east coast of South Africa.

The South African abalone resource is considered heavily depleted (DAFF, 2014). The decline in the natural abalone fishery since the mid-1990s has been due to extensive illegal fishing causing many areas to suffer complete stock collapse (Hauck & Sweijd, 1999; Tarr, 2000).

Following a long period of stable catches in the quota managed fishery, a 'perfect storm' for abalone poaching in South Africa was created in the mid-1990s by exceptionally high prices and demand from Asia; a flawed post-apartheid fishery reform process and the porous nature of South African borders allowing illicit abalone to be easily exported (Raemaekers et al., 2011). The response of the state has been to reduce the fishing effort through reductions in legal fishing quotas, while also increasing anti-poaching compliance efforts (Hauck & Sweijd, 1999). Despite these steps, poaching by crime syndicates has persisted with a huge illegal catch of up to 2400 tons/annum (De Greef & Raemaekers, 2014).

A central problem for abalone fishery rightsholders is that very little incentive exists to invest in both protecting and rebuilding the resource due to lack of secure-long term rights (Britz pers. comm., 2015). The lack of ownership of this resource has created a "Tragedy of the Commons" scenario (Hardin, 1968), where individuals are compelled to harvest shared resources unsustainably, which is motivated entirely by economic self-interest. According to Hardin, this is because the costs of overharvesting are shared among all while the benefits are not (Hardin, 1968). The failure of the state to adequately fulfill their role as the regulatory institution has meant that even legal rights holders harvest more than their allocated quota. The rationale behind this mentality is that if the rightsholder does not take it, someone else (poachers) will and his or her quota will be reduced regardless. The primary fishery management response by the state has been to reduce legal quotas further, or suspending harvesting all together, alienating rights holders from participation in resource protection and rebuilding. Thus rights holders have no security of tenure in the fishery. The traditional resource-focused management approach by the state, which has been to cut legal quotas and attempt to increase compliance efforts, has in essence failed. Experience has shown that government alone cannot protect the abalone resource. Abalone stocks in certain areas have been said to be so heavily depleted that stock recovery is unlikely without an active restocking initiative (Britz pers. comm., 2013). Some abalone fisheries, such as the white abalone (*Haliotis sorenseni*), despite being closed to commercial fishing for over 30 years has failed to

recover on its own and immediate enhancement using hatchery juveniles has been recommended to rebuild populations (Stierhoff et al., 2012). It has been proposed that what is required is a collaboration between the government and the fishery stakeholders where there is a shared responsibility for investment and long-term commitment to rebuild and protect the resource (Britz et al., 2015).

Abalone ranching or stock enhancement is thus being tested in South Africa as a potential tool for rebuilding abalone populations in heavily depleted areas. In 2010, the Department of Agriculture, Forestry and Fisheries (DAFF) published guidelines for abalone ranching or stock enhancement in South Africa (Gov. Gazette 33470) and subsequently, in 2011 initiated an applications process to operate ranching programmes based on area bound access rights or Territorial User Right Fisheries (TURFs). In these areas, the allocation of long-term abalone ranching rights potentially provides a solution to the illegal fishing problem. Rightsholders are incentivised by means of long term (15 year) rights to invest in resource rebuilding in two ways: (1) through the release of hatchery seed to increase wild stocks and (2) providing protection to the resource (Britz et al., 2015).

Abalone can also be seen as a desirable species to use in stock enhancement, as it is in high demand and fetches very high prices. These TURFs remove the condition of common property; are site specific; limit or control access to the territory; allow the right to extract benefits and a reasonable time limit to allow the owner to capture satisfactory return on their capital investment (Christy, 1982). Such a framework is ideally suited to the relatively sedentary nature of the *Haliotis* species. TURFs provide a management framework within which rightsholders are provided an exclusive right to commercial abalone harvesting in a defined area. In South Africa, abalone ranching permits confer an exclusive 15-year use right to investors (such as interested parties, fishing communities or companies) that have shown commitment to resource rebuilding (Britz et al., 2002; Britz et al., 2003; DAFF, 2010). These investors are incentivised to rebuilding the resource through exclusive access to increased abalone yields from allocated areas.

Attempts at abalone stock enhancement programs have been undertaken on experimental scales in countries such as Australia (McCormick et al., 1994; Dixon et al., 2006; James et al., 2007; Chick et al., 2013), USA (Tegner & Butler, 1985) and New Zealand (Schiel, 1993; Roberts et al., 2007). The degrees of success have been variable

and never fully commercialised. In Japan however, large-scale stock enhancement programs have been undertaken since the late 1960's, where state funded hatcheries have attempted to restore depleted stocks (Imamura, 1999; Hamasaki & Kitada, 2008). While on a national scale, these releases have been unable to sustain the total production, at a local scale, it is suggested that hatchery releases augment total production at some locations (Hamasaki & Kitada, 2008). To date, abalone ranching in South Africa has been undertaken on an experimental basis (Sweijd et al., 1998; De Waal, 2002; Godfrey, 2003). Although these results are promising, existing ranching protocols need to be improved, scaled up and commercialised. The need to determine the feasibility of ranching on a large-scale is paramount because most studies have been conducted on a small scale with variable results. Whether stock enhancement or ranching is commercially viable in South Africa is unknown and thus there is a need for the appropriate scientific assessment. This will provide fishery managers with valuable information on advancing the science and establishing the potential for its use as a fishery management tool which has been well documented in the film ["White Gold"](#), produced as a product of this thesis. The present research project formed part of a large pilot commercial ranching operation in the Eastern Cape Province and was designed to improve the existing seeding techniques and monitor its effectiveness.

This remainder of the chapter briefly describes the global trends in abalone fisheries, the South African abalone fishery, and abalone stock enhancement in order to contextualise and motivate the present research approach and objectives.

1.2 Literature review

1.2.1 Abalone and Global Trends

The name "Abalone" refers to a group of large sea snails that belong to the family Haliotidae and are found along the coastlines of almost every continent, except Antarctica. These marine gastropods have been known as a food delicacy since historic times (Shepherd et al., 1992b). As a result of their high commercial value, abalone are among the most intensively studied exploited marine invertebrate species (Day & Shepherd, 1995). These molluscs are herbivorous that feed on drift algae in mostly shallow reef environments (Prince, 2005). They are characterized by their ear-like shape and a row of respiratory pores running around the whorl of the shell (Prince, 2005). Abalone mostly live a sedentary lifestyle only moving when forced to by insufficient

space, food limitations or disturbance (Tarr, 1995). This dioecious broadcast spawner depends on the proximity of con-species for successful reproduction (Tarr, 1989). Thus, the larger more fecund individuals aggregate in high-density beds, which occur in shallow diving depths (Shepherd, 1986; McShane, 1995). Their broadcast spawning behaviour and subsequent planktonic larval stage are highly susceptible to the vagaries of the environment making recruitment unpredictable (Tegner & Butler, 1989). As a result of their natural life history, abalone are highly vulnerable and susceptible to overfishing (Tegner & Butler, 1989). Worldwide abalone have demonstrated a propensity towards abrupt stock collapse (Shepard et al., 1992). Its demise has been largely attributed towards unsustainable levels of legal harvesting, and increasing levels of illegal, unreported and unregulated (IUU) fishing (Cook & Gordon, 2004; Raemaekers & Britz, 2009). Total Allowable Catches (TACs) have gradually been decreasing in almost every remaining abalone fishery (Shepherd & Rodda, 2001; Uchino et al., 2004; Heasman, 2006). Legal landings from abalone fisheries have declined from almost 20,000 tons in the 1970's to less than 8000 tons in 2013 (Cook, 2014). The decline in abalone populations is primarily fuelled by the exceptionally high demand and high prices fetched from certain South East Asian countries namely China, Hong Kong, Japan, Taiwan and Singapore (Raemaekers et al., 2011). Despite the myriad of laws and penalties in many countries, the illegal catches have continued at an unprecedented rate (Gordon & Cook, 2004). This has been a major factor that has affected the world abalone market during the last decade or so - in 2008, the illegal catch of 5300 tons represented 65% of the total legal catch of 7869 tons (Cook & Gordon, 2010). With the ever-growing demand and lack of sizeable abalone, more undersized individuals are being targeted creating a constant threat to entire populations.

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Table 1 Total global production of abalone from legal capture fisheries and from farms. Source: The Worldwide Abalone Industry by P. A. Cook, 2014, *Modern Economy*. 5, 1182. 2014.

Year	Fishery production (tons)	Farm production (tons)
1970	19720	50
1989	14830	1200
2002	10146	8700
2008	7869	30760
2010	7424	65344
2011	7424	85344
2013	7486	103464

To fill the void of reduced capture fishery landings in conjunction with the growing demand, farm production has been rapidly rising (Table 1) in countries such as China, South Korea, South Africa and Australia (Cook, 2014). Farm production in the 1970's was negligible compared to recent years where increases have been massive, largely a result of the dramatic expansion of Chinese aquaculture (FAO, 2014). In the eight years preceding 2010, farm production increased by more than 750%, which culminated with an estimated output of 65,360 tons in 2010 (Cook, 2014). The total supply of abalone to

the world markets from all sources (legal, illegal and cultured) was estimated to be 20,370 tons in 1970, 22,667 tons in 2002, 44,510 tons in 2008, 73,206 tons in 2010, and 115,692 tons in 2013 (FAO, 2009; Cook, 2014). Recent statistics presented at the 9th International Abalone Symposium in South Korea in October 2015 showed that current production is 140,976 tons - an increase of 215% from 2010. The development of hatchery technology has provided the platform needed to engage in stock enhancement initiatives, where juvenile abalone (hereon referred to as juveniles) can be produced on a scale necessary for restocking initiatives. Development of hatchery technology has provided the platform.

1.2.2 South African Abalone Fishery

An overview of the South African abalone fishery is presented describing scientific work used to inform the current management of the fishery. The evolution of the commercial fishery pre- and post-apartheid is addressed, shedding light on the complex dynamics of the abalone fishery in South Africa.

The commercial abalone fishery in South Africa is reliant on a single exploited species, *Haliotis midae* (Tarr, 1995), or 'perlemoen' as it is locally known. It is one of the largest of the Haliotids after the Californian *H. rufescens* (Tarr, 1992). Its natural range (Figure 1.1) is between Cape Columbine on the West Coast of South Africa (Muller, 1984) to Mbashe River on the East Coast (Fielding, 1995). The adult populations are mostly non-cryptic, readily visible and found mostly in depths shallower than 10 m (Tarr, 1992). The abalone fishery in South Africa is one of the smallest in terms of yield but most lucrative in terms of unit value.



Fig. 1.1 The dark grey line along the Western Cape indicates the extent of the commercial abalone fishery in South Africa, located between Cape Columbine and Quoin point. The light grey area is the distribution range of *H. midae* along the coastline.

1.2.2.1 Summary of scientific work informing abalone fishery management

Newman (1966, 1967, 1968) first initiated studies on *Haliotis midae* ecology, when he described its movement, reproduction and growth as well as differences in productivity related to distribution (Newman, 1969). Barkai and Griffiths (1986) went on to assess the diet and found that *H. midae* selected for a wide group of seaweed species according to the abundance in the surrounding habitat. *Ecklonia maxima*, a fast-growing brown kelp species, was the dominant food source for abalone along the West Coast, whereas the dominant food source along the South Coast were members of the *Plocamium* genus. Barkai and Griffiths (1987) investigated the consumption, absorption efficiency, respiration and excretion before describing the energy budget of the species (Barkai & Griffiths, 1988). The increasing interest in abalone aquaculture led to studies on behavioural thermoregulation, with an important finding that warmer sea temperatures for optimum growth were calculated to be 22.6°C. This factor would be more favourable for intensive aquaculture as opposed to areas of highest natural abundance, (Hecht, 1994). Tarr (1995) undertook tagging experiments on a number of *H. midae* populations

from the West Coast to the East Coast to better understand growth and movement, where he found higher growth rates than what was previously published - the minimum legal harvest size (MLS), was reached at around eight years as opposed to the 13 or so years previously reported and full sexual maturity occurred at around seven years, which was four years earlier than previously considered. Tarr (1995) compared growth of populations at Bird Island on the East Coast and Robben Island on the West Coast and found growth rates to be similar. This is in contrast to Woods (1993) study which found faster growth rates in Eastern Cape than the South-Western Cape but his study was conducted in shallower water areas compared to Tarr (1995) study at Bird Island which was in deeper water which could possibly influence growth rates.

The limited knowledge on abalone in the Eastern Cape prompted Fielding (1995) to investigate this resource along the Transkei Coast. Abalone were found to reach sexual maturity at a size smaller than those along the Southwestern Cape. A reduction in the MLS for abalone in this area would have implications for the management of the fishery, however a number of problems were identified. These included poor information on natural levels of mortality and growth, spatial patchiness of resources and the uncertain relationship between standing stock and recruitment, thus the recommendation was for the MLS to remain at a shell width (SW) of 114 mm (Fielding, 1995). Subsequently, in 2015 the MLS was reduced to 90 mm SW for *H. midae* in the Eastern Cape. Aspects of the feeding biology (Wood & Buxton, 1996a) and reproduction (Wood & Buxton, 1996b) along East Coast were also investigated.

In the Southwestern Cape, the abalone resource was threatened by an ecosystem shift in the form of the invasion of rock lobster, *Jasus lalandii*, into the kelp bed regions in the early 1990's (Tarr et al., 1996). This caused dramatic declines in the populations of sea urchins, *Parechinus angulosus*, which provide refuge for juvenile abalone (Tarr et al., 1996). The relationship between juvenile abalone and urchins was further investigated and it was found that 98% of juveniles were found dwelling beneath sea urchins and that the continued recruitment of abalone and thus, survival of viable populations was tightly linked to available refuge provided by urchins (Day & Branch, 2000a; Day & Branch, 2000b; Day & Branch, 2002).

Dichmont et al. (2000) expressed reservations about the current approaches to the management of the fishery by using Catch-Per-Unit-Effort (CPUE) as the sole index of

abundance when assessing the fishery due to the highly aggregative behaviour of abalone. This was due to the fact that the more the animals aggregate, the higher the CPUE is likely to deviate from its linear relationship with biomass (Walters & Maguire, 1996). One of the major issues encountered was that the high catch rates of abalone could be maintained while the population is in decline. If the CPUE is used solely as an abundance index for setting zonal TACs then sustainable utilisation of the abalone as a resource cannot be guaranteed. Adaptive management approaches to the fishery included investigating simple simulation models instead (Dichmont et al., 2000). Following on from this, a model was developed as an extension to the more standard age-structured assessment models, which accounted for spatial effects and incorporated ecosystem shifts and estimates of illegal catches. For this model, Plagányi and Butterworth (2010) collated CPUE data and Fishery Independent Abalone survey abundance data, as well as several years of catch-at-age data from a variety of sources. This model provided the basis for management advice in recent years by projecting the abundance trends under alternative catch levels. Plagányi et al. (2011) quantified illegal catches by combining and using all available information from confiscations and police information into the stock assessment model. These models showed what the projected stocks would likely be under various scenarios of illegal fishing pressure. It suggested that the abalone is unlikely to recover in the areas invaded by rock lobsters in the next ten years but there are still viable populations that could be safeguarded for future generations if illegal fishing effort could be brought under control (Plagányi et al., 2011).

1.2.2.2 Historic overview of the abalone fishery

Commercial harvesting of abalone began in 1949 (Tarr, 1992). Although the biogeographical range for abalone extended to the Eastern Cape province, the commercial fishery was restricted to the Western Cape with the highest densities occurring between Cape Hangklip and Quoin Point (Raemaekers et al., 2011). No total allowable catch or catch quotas were imposed in the initial years.

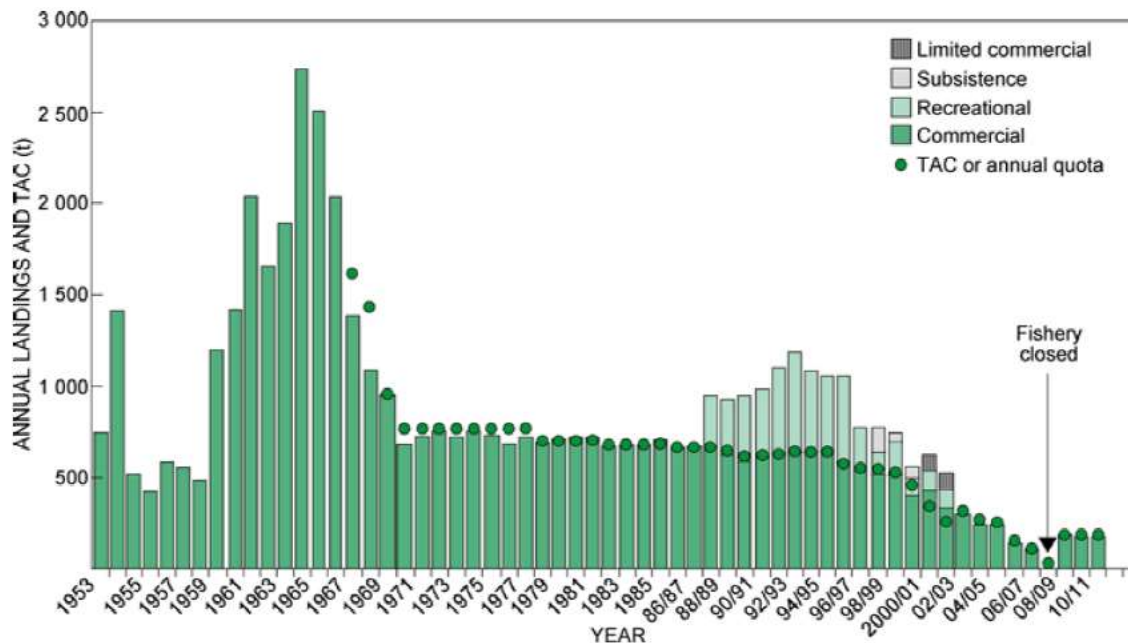


Fig 1.2 Annual commercial catch landings in tons from 1953 when records were first kept until 2014.
Source: Status of the South African marine Fishery Resources 2014. Department of Agriculture Forestry and Fisheries (Cape Town, South Africa).

Records of the quantity of abalone marketed after processing are available from 1953 where 770 tons of abalone were harvested (Tarr, 1992). The catch rose to 1500 tons in 1954, but then fluctuated around 500 tons until 1959 due to the decreased demand (Tarr, 1992). By the mid 1960's, landings had risen to a record high of 2800 tons (Figure 1.2), with subsequent years reporting declined catch rate due to the depletion of the dense beds or accumulated stocks of abalone. In a bid to stem this overexploitation, an annual quota was imposed in 1968 and gradually reduced over the next few years to around 700 tons remaining stable until the early 1980's when the annual quota was again reduced to 615 tons until the mid-1990s (Tarr, 1992; Raemaekers et al., 2011). The period between the 70s and the 90s was described as a stable quota-managed fishery (Tarr et al., 1996). In order to better manage the commercial fishery in 1986, the abalone fishing grounds were subdivided into seven zones - each with its own TAC, which was based on divers' previous catches. The measures put in place seemed to be successful because divers reported improving CPUE (Tarr, 2000). Concurrently, a recreational fishery was operating as an open access fishery with daily bag and size limits, and this assisted in ensuring that the quota-managed fishery remained stable. In 1983, recreational fishermen were required to buy permits and additional management strategies, such as closed seasons, were put in place.

1.2.2.3 The Post-apartheid Abalone Fishery

With the advent of democracy in 1994, came heightened expectations of access to marine resources among the disadvantaged coastal communities that did not receive fishing rights due to exclusion policies during Apartheid (Hauck & Sweijd, 1999; Sowman, 2006; Raemaekers, 2011). Fishery managers were faced with a difficult task of accepting more entries and redistributing access to those people previously denied rights to the abalone fishery, which then suffered due to extensive over fishing and illegal harvesting. Since the early 1990's, the abalone fishery has become the most challenging fishery to manage in South Africa (Branch & Clarke, 2006). Subsistence rights were introduced in 1998/1999, which were then replaced by two-year medium-term rights (DAFF, 2014). In 2003/2004, 10-year long-term rights were allocated, which increased participation in the fishery to 300 rightsholders (DAFF, 2014).

Authorities made an attempt to address the root causes of poaching by drafting a new abalone policy which was adopted in 2003 (DEAT, 2003). One key intervention of the policy was the implementation of TURFs, which gave rightsholders exclusive access. However, the TURF system was ineffective in its implementation as it allowed rightsholders to fish in zones other than their own and thereby undermined the sense of resource custodianship - the pillar defining the TURF system (De Greef & Raemaekers, 2014). Despite the introduction of TURFs, increased compliance effort, harsher penalties for offenders and tightening controls on international trade, illegal fishing remained high (DAFF, 2014). A brief look at the dynamics governing illegal abalone fishing and the response by the government in reducing quotas is presented below.

Hauck (1997) began research in 1995 into the illegal trade of abalone and it became immediately apparent that these poaching activities were complex in nature with strong political underpinnings: firstly, the communities involved were impoverished and illegal abalone fishing became a means in which they could provide for their families; secondly, the lucrative nature of abalone lured many from legitimate paying jobs into the industry; and lastly, the political injustices of the past regarding the exclusion of non-whites partaking in the fishery despite their historical involvement. The poaching problem has been further compounded by the involvement of syndicates, which fuel the illegal exploitation by providing lucrative incentives and trade routes to overseas markets (Hauck & Sweijd, 1999; Steinberg, 2005). As poaching continued through the 1990's and 2000's, the legal quota continued to drop from 615 tons in 1995/6 season to just 75 tons

in 2007/8 season - a response by the state to adjust for the rampant illegal harvest taking place. The recreational fishery was closed in 2003 as law enforcement officials struggled to contain the high levels of illegal fishing. This fishery remains closed to date.

In addition to the huge illegal fishing effort, ecosystem shifts were also taking place causing a collapse in recruitment of abalone. Fishery managers grew increasingly worried of a possible collapse in this commercial fishery due to the rock lobster invasion, as it was the most productive abalone fishing grounds in the Western Cape (Day & Branch, 2000a). Amid fears of a total (non-recoverable) collapse, scientists and fishery authorities made a decision to close the commercial fishery in 2008 (Hauck, 2009). This sparked outrage amongst rightsholders whose livelihoods depended on abalone. This decision was made by the Minister of the Department of Environmental Affairs and Tourism (DEAT) and was challenged in the Cape High Court. The rightsholders argued that the decision to close commercial harvesting due to over-exploited stocks was discriminatory when an illegal fishery continued to thrive. Their legal battle was unsuccessful as the judge upheld the Minister's decision (Raemaekers et al., 2011). Nevertheless two years later, the Minister responsible for fisheries announced the re-opening of the commercial abalone fishery with an allocated experimental quota of 150 tons (Britz pers. comm., 2013; DAFF, 2014). The reopening of the fishery was based on one main condition – there had to be a reduction in poaching levels of 15% per annum. This formed a priority management objective for the sustainable utilisation and recovery of the abalone resource (DAFF, 2014). However, the required reduction has still not been achieved and estimates four years after reopening the fishery indicate that poaching actually increased by around 150%, whilst a net 50% reduction was required under the rebuilding plan (DAFF, 2014). This paints a bleak future for the wild abalone fishery in South Africa. A drastic change in the management of the fishery is needed if government is to bring the illegal fishery into legal standing.

1.2.3 Abalone Fishery in the Eastern Cape Province

Historically, the abalone fishery focussed solely on the productive fishing grounds of the South-Western Cape whilst the Eastern Cape was largely overlooked. The Eastern Cape never had a commercial abalone fishery established because marine resource managers believed the distribution pattern and abundance of the abalone to be too patchy and discontinuous to justify commercial exploitation (Tarr, 2000). A thriving illegal fishery took root in the province in the absence of a legal commercial fishery in the mid-1990s.

The context of poaching within the province, and specifically at the study site (ranching area Eastern Cape one or EC1) at Cape Recife (Figure 1.3) is discussed below which highlights the dynamics, social drivers and scale of poaching. This provides a rationale for the stock enhancement and TURF based management approach at the study site.



Fig 1.3 An aerial shot of Cape Recife at the western boundary of the abalone ranching area EC1, which extends 18km to the East. Abalone seeding operations have focused predominantly on the offshore reef between the Cape Recife and Thunderbolt reef 4 – 9 m deep. The lighthouse provides a tactical position at which the private security company operating quarters are situated.

1.2.3.1 Fisher profile

The social-political characteristics of the illegal fishery in the Eastern Cape differ to that of the Western Cape (Hauck & Sweijd, 1999). Areas along the former Transkei and Ciskei coasts of the Eastern Cape have had long standing traditional fishing links to abalone, where large numbers of rural people without diving gear wade from shore as a means to access the resource (Godfrey et al., 2005). Poaching had become widespread in these areas by 2000, putting the stock under critical threat (Godfrey et al., 2005).

In the urban areas surrounding Port Elizabeth in close proximity to the study site, illegal fishers had no traditional or artisanal links to the abalone; rather the illegal fishery was thought to emerge from the recreational fishery. The majority of these abalone fishers had low education levels whom were unemployed or worked in blue-collar occupations

(Britz & Raemaekers, 2009). Following steep increases in overseas prices for this commodity many turned to full time poaching to obtain income. Two types of illegal operations developed: opportunistic shore-based diving with low capital investment, and highly organised and experienced boat-based diving with high capital investment supported by intelligence and marketing networks (Britz & Raemaekers, 2009; Raemaekers, 2009).

1.2.3.2 Fishery Management

Experimental quotas were granted in 1998 but were soon halted due to rising illegal fishing (Raemaekers, 2009). On the basis of the volumes of abalone being removed by illegal harvesting, it was recommended by Britz et al. (2002) in their management plan for the abalone resource in the Eastern Cape that a legal fishery be established. It was recommended that a species-specific TURF be implemented to manage the Eastern Cape abalone fishery. In 2002, a TURF-based programme was implemented briefly in rural areas where subsistence fishers were targeting abalone, but it was later terminated due to declining catch rates (Britz et al., 2002; Raemaekers & Britz, 2009). Illegal fishing quickly became a serious cause for concern as a highly organised network developed from the urban centre of Port Elizabeth (Godfrey, 2003). By 2005, there were 30 purposely built 'super ducks' (high powered semi-rigid inflatable vessels) with an estimated capital investment of four million USD, employing around 300 divers harvesting 1000 - 2000 tons of abalone at an estimated value of 35 - 70 million USD (Raemaekers & Britz, 2009). By 2007, there were almost 50 'super ducks' operating around Port Elizabeth. In addition to the boat-based divers, the number of shore divers was estimated to be around 1500 individuals involved in some way in the illegal fishery (Raemaekers & Britz, 2009). The failure of the state to adequately implement appropriate management interventions meant that illegal fishing has taken its toll on the resource. Research has shown that the mean size of abalone has decreased dramatically with the proportion of abalone below minimum size increasing significantly (Godfrey, 2003; Witte, 2013). As the large abalone were poached out, divers began targeting smaller abalone, which then forced poaching efforts to shift further afield and new reefs began to be targeted (Godfrey, 2003). In 2005, there was a clear shift in effort by the boat-based divers to move away from the nearby fishing grounds of Cape Recife towards the Sardinia Bay MPA (Raemaekers & Britz, 2009). In 2006, the Ndlambe Municipality eastwards of Port Elizabeth experienced an upsurge of illegal fishing activities with around 40 'super ducks' observed per month (Raemaekers

& Britz, 2009). Illegal fishing continued unabated in 2007 and 2008, where the average size of abalone was found to have decreased in all monitored sites, with Cape Recife being hit the hardest (Raemaekers & Britz, 2009).

The consistent large illegal haul of abalone from the Eastern Cape has sparked debate about creating a legal commercial fishery in the province. Fishery authorities in 2012 granted a 31.5-ton experimental catch split across seven areas ranging from the Groot River to Dwesa (DAFF, 2014). Sub-area catch allocations have been put in place using experimental quotas to effectively assess the fishery potential of the resource, area by area. The recent granting of ranching rights to certain entities based on a TURF system can be seen as a dynamic approach to transforming what is currently an illegal fishery towards a legal one. After the ranching policy was adopted in South Africa in 2010, Ulwandle Fishing (Pty) Ltd. in conjunction with Wild Coast Abalone applied for ranching rights under the TURF management system. An 18km section of coastline between Cape Recife and Schoenmakerskop was demarcated as abalone ranching area. At the end of 2013, the Tactical Task Force (TTF), a private security team responsible for enforcing compliance within ranching area EC1, was deployed. This unit has been very effective in combating illegal fishing activities and has reduced effort substantially in recent years.

1.2.4 Stock Enhancement and Marine Ranching

Marine stock enhancement and ranching is a relatively new fishery management tool, which is receiving increasing attention as a means to restore production from marine and coastal fisheries (Bartley, 1999). Stock enhancement is defined as “releasing of stock for the public good without the intention of directly benefiting an exclusive user group” which is usually undertaken by governments in efforts to restore fisheries, whereas marine ranching is defined as “identifiable stock released with the intention of being harvested by the releasing agency” (Bannister, 1991).

The traditional fisheries management tools, categorised as input or output controls have essentially been ineffective in controlling or managing this abalone fishery. These tools include gear and size restrictions, seasonal closures, quotas, bag limits and limitations on entry (Molony et al., 2003). Other tools that have been used to sustain whole fishing ecosystems have been the use of Marine Protected Areas (MPA's) (Hockey & Branch, 1997). Although such approaches have been shown to work in certain countries, stock recovery is often perceived as too slow (Michelson, 1993; Dayton et al., 2000; Beattie,

2002). While traditional management is relatively simple and cheap compared to stock enhancement (Hilborn & Walters, 1992), controlling certain factors can be difficult and expensive (Molony et al., 2003). Advances in marine aquaculture along with a plateau in fisheries landings (New, 1997) have promoted a worldwide interest in marine stock enhancement (Leber, 1999).

Stock enhancement using hatchery juveniles is not a new concept, and dates back to the late 1870's using Atlantic Cod (*Gadus morhua*) in the United States and Norway (Kitada, 1999). After decades of releases, both programmes were halted, as the stocking effectiveness was inconclusive and not clearly evaluated (Solemdal et al., 1984 cited in Kitada, 1999). In Japan stock enhancement began in 1876 using chum salmon (*Onchorhynchus keta*) and has subsequently been supported by the Japanese government (Kitada, 1999). After a century of stocking programs, there is still a poor understanding of the effectiveness of marine stock enhancement. This has been attested to all the focus being applied to aquaculture production and release magnitude, while the critical assessment and impacts of stocking were largely neglected (Leber, 1999). The lack of evidence to support marine ranching eventually halted the advancement of stocking programs. The recent proliferation in modern tagging technology as a means to track released juveniles along with huge expansion in marine aquaculture capabilities and improvements in marine ranching technologies has and created a second wind for marine stock enhancement (Masuda & Katsumi, 1998; Leber, 1999). More than 100 species have been used in stock enhancement programs worldwide to help sustain or increase coastal fisheries (Liao, 1999). There has been much debate among the scientific community regarding the efficiency of stock enhancement as a tool to replenish fisheries, however potential has been shown with salmoids (Coronado & Hilborn, 1998), scallops (Uki, 2006), and Hirame flounder (Kitada et al., 1992; Sproul & Tominaga, 1992). For example, in Japan over the period 1980 – 1995 (15 years) the catch of salmon tripled from 20 to 60 million fish, of which 90% of chum salmon caught originated from released juveniles (Kaeriyama, 1996; Masuda & Katsumi, 1998). The scallop fishery in Japan is possibly one of the biggest ranching success stories with consistent annual harvests of 300,000 tons per annum representing a four-fold increase over the historical maximum catch (Uki, 2006). However in many ranching programs determining the success has been much less clear such as the kuruma prawn (shrimp) (Hamasaki & Kitada, 2006). So the potential exists for restocking hatchery reared juveniles into the wild and achieving

favourable catch returns, with that being said little success has been demonstrated at a commercial level for abalone stock enhancement.

Abalone release programs around the world have been undertaken on experimental scales where seed size, habitat and density have been cited as critical variables determining the success of a project (Schiel, 1993; Rogers-Bennett & Pearse, 1998; Sweijid et al., 1998; Dixon et al., 2006; Roberts et al., 2007; Hart et al., 2013a). The main countries to experiment with stock enhancement besides South Africa are Australia (Heasman et al., 2004; Dixon et al., 2006; James et al., 2007; Chick et al., 2013; Hart et al., 2013a), New Zealand (Tong et al., 1987; Schiel, 1993; Roberts et al., 2007), United States (McCormick et al., 1994; Rogers-Bennett & Pearse, 1998; Burton & Tegner, 2000) and Mexico (Searcy-Bernal et al., 2013). These studies have had varying degrees of success, however potential has been shown for ranching to rebuild depleted stocks. According to Chick et al. (2013), in New South Wales, Australia, depleted wild abalone populations could potentially be rebuilt should the process of restocking be used. Sampling at 108 and 280 days post-release provided estimates between 2 and 31 % and 9 and 18 % of abalone surviving within locations, respectively, declining to an average of 2.9% 777 days post-release, which is a similar survival expected for wild abalone (Chick et al. 2013). Similarly, Roberts (2007) suggested that restocking would be an economically viable operation if sites and habitats were selected carefully but these appropriate habitats have eluded the proponents of re-stocking.

The only country known to implement abalone stock enhancement on a large-scale is Japan, which has done so since the late 1960's (Masuda & Tsukamoto, 1998; Hamasaki & Kitada, 2008). Hatcheries and nursery rearing technologies in Japan were developed with the intention to augment wild fishery production. The stock enhancement program has released an average of 25 – 30 million juvenile abalone (25 – 30mm SL) per annum (Hamasaki & Kitada, 2008). Catches from hatchery releases were 235 tons (5% of total catch) in 1980 increasing linearly and maintained around 500 tons (30% of total catch) after 1989 with increasing hatchery catches and decreasing wild catches (Hamasaki & Kitada, 2008). Despite the release of hatchery seedlings, fishery production has declined from 6,500 tons in 1970 to 2,000 tons in recent years, it has been said that the magnitude of these releases on a national scale has not been sufficiently large enough to sustain total production of Japanese abalone and further the minimum size limit too small in most instances to enable the released abalone to survive long enough to spawn

(Masuda & Tsukamoto, 1998; Hamasaki & Kitada, 2008). However, on a local scale, it has been suggested that hatchery releases could augment total production at some locations depending on carrying capacity of areas (Hamasaki & Kitada, 2008).

In South Africa, abalone farming only developed in the late 1980's after it was demonstrated that *H. midae* could be successfully spawned in captivity (Genade et al., 1988). The abalone industry has subsequently grown rapidly, producing 1,470 tons in 2013 being the third largest producer in the world (Cook, 2014; DAFF, 2014). Farms are now in the process of upgrading infrastructure to double current production by 2019 (Britz et al., 2015). The large capacity for producing cultured juvenile abalone cost effectively has allowed farms to contemplate stock enhancement and explore the potential for marine ranching. Experimental release of juvenile abalone (known commonly as seeding) was first undertaken in 1995 at Port Nolloth on the West Coast, an area beyond its natural distribution range. Sweijd et al. (1998) reported mean minimum survival rates of 30% six months post release and this along with size at release suggested good prospects for commercial scale seeding in that area. A further analysis was performed on this enhancement program by De Waal and Cook (2001a) to quantify the physical and biological attributes to successful seeding accompanied by the use of a basic spreadsheet model to investigate the dynamics and economies of a seeded abalone population (De Waal & Cook, 2001b). Godfrey (2003) undertook experiments off Cape Recife near Port Elizabeth on the East Coast of South Africa and concluded that abalone ranching had the potential to be feasible if operated in conjunction with an existing abalone farm as opposed to a stand-alone operation. Currently, there are three experimental ranching projects that are in operation in South Africa, two along the West Coast and one along the East Coast (DAFF, 2014).

While ranching has been viewed as a potential fisheries tool to restore depleted stocks, concerns exist around the limited rigorous documentation of the impact of marine ranching as well as the cost effectiveness and the danger that programs may pose towards wild resources (Bartley, 1999). The many recurrent failures and inconclusive attempts historically, along with lack of comprehensive analyses of enhancement programs covering ecological, social and economic aspects substantiate the need for appropriate monitoring of enhancement attempts (Lauerc, 1999). Before ranching is formally initiated, there needs to be clear definitions regarding the status of the fishery, reasons for its decline, genetic structure of the ranched species, carrying capacity of the

environment, the expected returns from the ranching program and the expected benefits for beneficiaries (Bartley, 1999). Further careful planning, evaluation of the potential impacts on both biological and human communities, establishing a means to monitor the actual impacts and then adapting a program when certain targets or limits are reached are all necessary prerequisites (Bartley, 1999). Marine ranching has been viewed as an increasingly important fishery management tool, but it has also received its share of controversy and criticism as many programs have failed to produce any measurable impact on stock abundance or yield, or these programs have impacted negatively on wild populations through introduction of diseases and reduced fitness and genetic variability in juveniles (Hilborn & Wanton, 1993; Bartley, 1999; Bell et al., 2006).

The experiments on stock enhancement in South Africa to date have been conducted on very small scales with variable results. In order to adequately assess the full potential of ranching, releases would need to be undertaken on much larger scales with a strong focus on commercial development and scientific monitoring. An 18km section of coastline situated between Cape Recife and Sardinia Bay MPA in the Eastern Cape was selected for this commercial pilot project. For Lidomix Pty Ltd, the ranching rights holder, this was a logical choice of site for a few reasons: (1) Previous experimental ranching work had been conducted here by Godfrey (2003) which showed promising results for large-scale releases; (2) existing baseline data in conjunction with illegal catch data provided compelling evidence for stock decline and the need for stock enhancement; (3) the productive habitat found along this section of coastline. This pilot project set out to build on Godfrey's (2003) seeding experiments, which were done on a small scale with inconclusive results in respect of the economic viability of ranching. Specifically, his experiments did not track the long-term survivorship of seed or calculate a natural mortality rate, which is required to determine the economic viability of ranching. These gaps in knowledge were informed the objectives of the present project.

1.3 Research approach

The first requirement of this research was to establish the state of the stock at Cape Recife to provide the necessary motivation for ranching. This was investigated using fishery dependent and independent data from various unpublished studies and government records which allowed for long-term trends to be modelled. A baseline survey of abalone stock at the designated core seeding area was undertaken by conducting dive surveys to estimate stock abundance, abalone size and recruitment in the fishery, against which the potential success of ranching could be measured. Small-scale replicated experiments were then set up to establish which parameters at the study site influenced survival and growth of seeded abalone. Embedded into an experimental split plot matrix were critical variables such as density, seed size and habitat effects. The purpose of this was to better identify the parameters governing the success of released seed and inform the large-scale releases. Lastly as this research project formed part of a larger commercial seeding venture, long-term monitoring was undertaken on the large-scale releases to track changes in survival over a period of up to 666 days post release. These long-term data then could then be used to project an estimated harvest biomass for seed abalone, which could infer the potential economic viability of ranching.

1.4 Aim and Objectives

The aim of this study was to investigate the potential for abalone ranching to be used as a fishery restoration tool for *H. midae* stocks at Cape Recife in the Eastern Cape Province.

Research Objectives

The research objectives were:

1. A baseline assessment of the state of the abalone stock in the proposed ranching area.
2. Quantification of factors affecting the survival and growth of seeded abalone at Cape Recife.
3. Assessment of the long-term survival of seeded abalone in the commercial seeding experiment.

CHAPTER 2

The illegal exploitation of *Haliotis midae* populations at Cape Recife and a baseline wild stock assessment

2.1 INTRODUCTION

This chapter set out to describe and provide evidence of the illegal exploitation of wild abalone at Cape Recife and the subsequent declines in the stock as a result. The purpose of this analysis was to provide rationale and motivation for using stock enhancement as a fishery restoration tool. Further, before commercial ranching could be implemented a baseline stock assessment was required in the designated ranching zone EC1. This was a permit requirement by the Department of Agriculture, Forestry and Fisheries (DAFF). This baseline assessment was essential in order to gauge the most recent status of wild stocks as well as provide a benchmark from which to measure the success of seeding.

The Eastern Cape Province historically never had an established commercial fishery, and therefore few attempts have been made to monitor changes in abundance of *H. midae* populations. A few studies have nevertheless been conducted at selected sites which have measured abalone abundance and population size structure (Newman, 1969; Tarr, 1986; Tarr, 1993; Wood, 1993; Fielding, 1995; Godfrey, 2003; Godfrey et al., 2005; EFA, 2010). One site that has undergone monitoring over the years, and which is considered to be prime abalone habitat, is Cape Recife. This area once supported abundant natural abalone populations (Newman, 1969; Wood, 1993; Godfrey, 2003). *In situ* research work completed here has allowed changes in the stock to be tracked over time. Studies were first initiated here by Newman (1969), which measured the population size structure and growth for juveniles only. Stock assessment work was completed by Godfrey (2003), which showed significant declines in abalone populations providing the rational basis for the use of ranching. Extensive research was also undertaken in the area to assess impact of poaching and provide management options for then fisheries authority Marine and Coastal Management (MCM) (Britz & Raemaekers, 2009). The information on abalone stocks and illegal fishing resulted in the formation of the abalone management plan for the Eastern Cape with a recommendation for rehabilitation and community TURFs (Britz et al., 2002).

Another fishery stock assessment was commissioned by DAFF in 2012 and took place in close proximity to previous studies at Cape Recife (Hutchings & Biccard, 2012).

Concurrently the fisheries department, then MCM and now DAFF, have documented confiscated illegal catches over the past 17 years. Using these fishery independent data, it has been possible to infer the health of abalone stocks. The rise and development of illegal fishing has been relatively well documented in the vicinity of the study site (Raemaekers & Britz, 2009). Illegal fishing in the Eastern Cape was first recognised as a major source of illicit supply in 1997, the lack of appropriate management interventions by the state allowed poaching to escalate rapidly in this area (Raemaekers & Britz, 2009). Government restrictions on vessel size and launch sites, as well as the continuing decline in abalone abundance, have seen poaching operations reduce within the Port Elizabeth area. Recent development of the Tactical Task Force (TTF), a new private anti-poaching unit, has been a vital step for ensuring the protection of the wild resource at Cape Recife. The implementation of type of unit is a fundamental component of any abalone stock enhancement program in South Africa. They have been effective in reducing illegal fishing effort in the designated ranching zone (Wood, 2016), but still face numerous challenges and have yet to eliminate illegal fishing in the area.

This chapter attempted to collate all information (mostly unpublished work) about emergent shell lengths, emergent densities and recruitment densities for abalone stock assessment work conducted at Cape Recife. In addition, unpublished data on confiscated abalone collected by fisheries authorities for the average mass, confiscated abalone units and number of undersized individuals were analysed to monitor the health of the abalone stocks indirectly. Further *in situ* dive surveys established more recent baseline data from the proposed area for seed releases for abalone ranching.

The aim of this study was to assess the impact from illegal fishing on abalone stock within the ranching zone EC1 at Cape Recife to provide rationale for use of stock enhancement as a fishery restoration tool and establish baseline stock abundance estimates for a portion of the ranching area. The objectives were to (1) establish reliable estimates of the trends in the wild abalone stock at Cape Recife using *in situ* surveys and fishery dependent catch data; and (2) Conduct baseline data for abalone density and size distribution at reefs within the proposed seeding area

2.2 Methods

2.2.1 Research approach

The status of the abalone stock at Cape Recife was assessed using data from various sources and by conducting *in situ* diving surveys. Fishery dependent data was obtained from abalone confiscations for Cape Recife and the Eastern Cape, and was used to provide indices of the health of the abalone population. Recruitment surveys undertaken in the present study were used to update trends in abalone shell length and density from previous studies. On the outside bay of Cape Recife, *in situ* surveys were conducted on SCUBA to provide a baseline abalone stock assessment, which used transects for densities and measured the shell lengths of emergent abalone.

2.2.2 General study area

Cape Recife point, a prominent rocky headland forming the western point of Algoa Bay was selected as the study site due to the existing baseline data from previous studies and because it is a target abalone ranching site (Figure 2.1). The complex geology of the Eastern Cape coastline is reflected at Cape Recife where several geological features are characteristic of the study area (Marker, 1998). The dominant underlying rock is hard quartzite and forms the outcrops in this area to a greater or lesser degree. Overlying this substrate are quartzite boulders and cobbles, aeolian deposits weathered to a lesser or greater degree, and mobile and stable sand deposits (Godfrey, 2003). This geology along with various geomorphological and ecological processes gives rise to a complex sub-tidal habitat (Godfrey, 2003). The distribution of wild abalone is largely dependent on substrate type. The heterogeneous substrate is reflected by the variable distribution of *H. midae* in this area. The algal components at Cape Recife are dominated by *Plocamium corallorhiza*, with other seaweeds such as *Pachymenia carnosa*, *Laurencia flexuosa*, and *Hypnea rosea*; as well as the upright coralline *Aphiroa ephedrea* being prominent (Du Preez & Steyn, 2013). The habitat at Cape Recife changes over small spatial scales and as part of the surveys undertaken, each habitat type was categorised according to wave exposure, substrate type, habitat profile (relief), algal types and depth (Appendix 2.1).

2.2.3 Trends in abalone stock at Cape Recife

Research surveys on wild abalone at Cape Recife have been undertaken periodically since 1998 and provide a valuable timeline of trends in the abalone stock. All data collated for this study were obtained from unpublished work. The survey localities differed slightly between the various studies and are summarised in Figure 2.1. All emergent density counts were recorded in the yellow area for the years 1993 (Elliot), 1999 (Godfrey), 2001 (De Waal), 2004 (Godfrey) and 2006 (Daly). Emergent size measurements were also recorded from the yellow area during 1998 (Scott), 1999 (Godfrey), 2000 (Godfrey), 2001 (Godfrey), 2004 (Godfrey), 2006 (Daly) and 2012 (Godfrey). Emergent density and size measurements were recorded in the white area in 2006 (Daly). Recruitment surveys measuring juvenile abalone density were done in the blue area during 1999 (Godfrey), 2000 (Godfrey), 2001 (Godfrey), 2005 (Godfrey & Raemaekers), 2006 (Godfrey & Raemaekers), 2007 (Godfrey & Raemaekers), 2013 (Witte), 2014 (Witte) and 2016 (Witte) shown in Figure 2.1. The green area in Figure 2.1 shows the area surveyed by Hutchings and Biccard (2012) from which they recorded emergent density. The red area in Figure 2.1 shows density and size measurements for emergent abalone measured in 2013 (Witte). The data collected by Witte (2013) is presented separately from preceding years because these measurements of density and size were conducted in deeper water than the other studies.

2.2.3.1 Emergent density and size at Cape Recife

Previous surveys using similar methods to estimate emergent abalone density at Cape Recife were carried out during 1993 (Elliot), 1999 (Godfrey), 2001 (De Waal), 2004 (Godfrey), 2006 (Daly) and 2012 (Hutchings & Biccard). Godfrey (2009), De Waal (2001) and Daly (2006) used a 10m long weighted line, recording counts 1 m on either side (20 m² transect area); whereas Godfrey (2004) conducted surveys along 30 m transects recording counts 1 m on either side (60 m² transect area). The number of transects conducted varied according to the study (Table 2.3 Appendix A). Hutchings and Biccard (2012) used GPS devices on surface floats attached to float lines to record the start and end positions of each transect line. Surveys were done using breath-hold diving as opposed to SCUBA, which was used for all other surveys. Transects were not conducted using permanent lines so it was important to account for sampling bias. Abalone density is significantly influenced by substrate and habitat type, and the resulting non-uniform (“patchy”) distribution leads to naturally high

variability in abundance between different sites (SFRI, 1986; Fielding, 1995). Abalone density is partially determined by random effects of habitat suitability within an area.

In the present study, measurements of ‘emergent’ abalone were performed *in situ* at Cape Recife using callipers to measure the shell length under water. Individual abalone were categorised as emergent if they were > 80 mm shell length. Godfrey (2003) distinguished between cryptic and emergent abalone based on the observation that abalone are often emergent at smaller sizes. For the purpose of comparison, we only considered abalone if measurements were > 80 mm SL.

2.2.3.2 Recruitment at Cape Recife rock pool

Recruitment refers to the post-settlement stage of organisms that can be first observed (McShane, 1995). Abalone measured for these assessments were all cryptic juveniles found beneath boulders. Juvenile abalone densities and size measurements have been recorded mostly from the berm of the rock pool, which is considered prime juvenile habitat (Britz pers. comm., 2013; Godfrey, 2013). Surveys have been conducted fairly regularly over the years, 1999 (Godfrey), 2000 (Godfrey), 2001 (Godfrey), 2005 (Godfrey & Raemaekers), 2006 (Godfrey & Raemaekers), 2007 (Godfrey & Raemaekers) and 2012 (Godfrey). Witte completed surveys in 2013, 2014 and 2016. Godfrey (2003) as part of his seeding experiments in the ‘lighthouse rock pool’ counted and measured juvenile abalone concurrently. From 2005 onwards, juvenile counts were done on the berm of the ‘lighthouse rock pool’. These surveys used 1 m² quadrats placed along a transect line (see Table 2.4 for total area). Boulders were very carefully picked up and turned over, urchins lifted, and abalone located and measured.

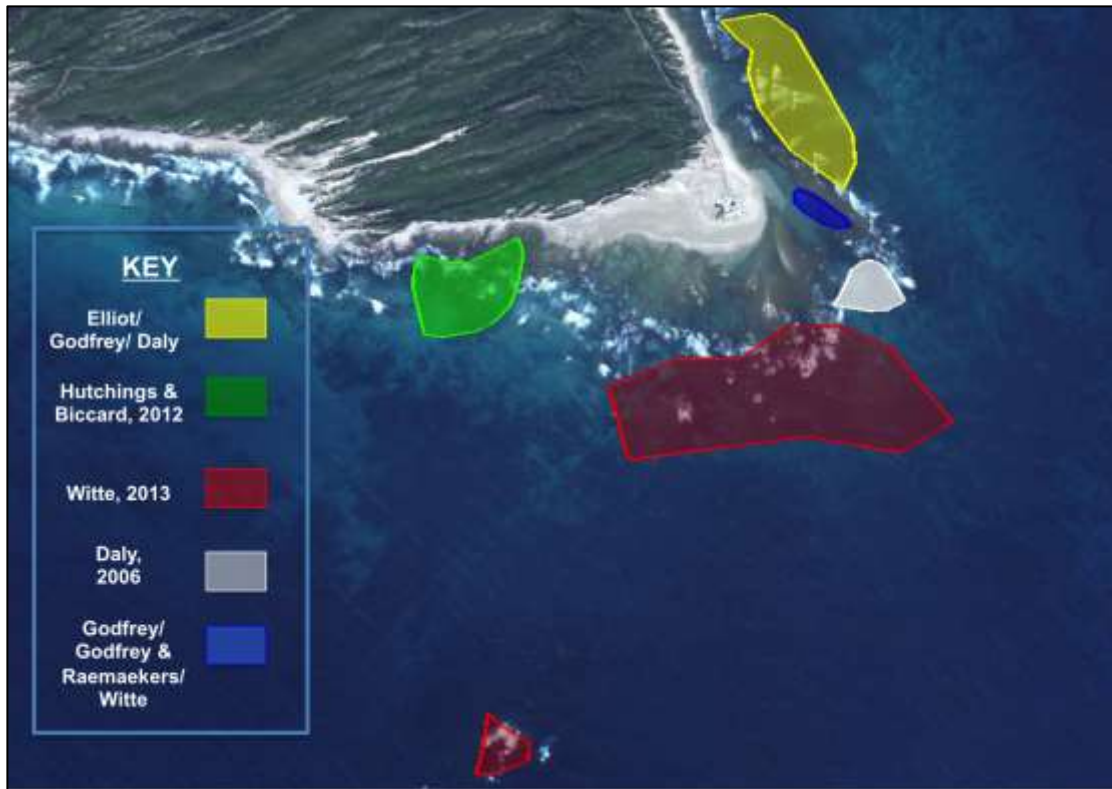


Fig 2.1 The areas where wild abalone surveys were conducted between 1998 and 2013 at Cape Recife. The sites were plotted based on recorded GPS points or were extracted from existing maps indicating the location where the respective studies were undertaken.

2.2.4 Fishery dependent catch data

The data for the mean mass of confiscated and abandoned poached abalone was obtained from the DAFF. Samples existed from a wide range of localities along the Eastern Cape coastline. The samples were derived from bags of abalone that had washed ashore; were found hidden bushes; were abandoned by fleeing poachers; or had been confiscated from apprehended poachers and abalone processing houses during law enforcement operations. Most of the samples consisted of eviscerated/ shucked specimens, which were counted and weighed to the nearest gram. For the purpose of identifying abalone into undersized groups, a mass of 176 g was used as the weight equivalent to animals of the legal minimum size of 114 mm shell breadth (Godfrey, 2003). This mass was established from the extensive previous research conducted on confiscated abalone samples by Marine and Coastal Management (MCM). This size limit for undersized animals may need revision given the new legal-size limit set for the Eastern Cape.

2.2.5 2013 Baseline stock assessment pre seeding

A baseline abalone stock assessment of newly recruited and emergent abalone was conducted prior to seeding in 2013. Sea conditions were relatively calm with good visibility (> 5 m) throughout the survey although strong surge in some areas made counting challenging. The recruitment survey was undertaken at low tide in the protected 'lighthouse rock pool' where previous recruitment surveys were conducted. The rock pool conditions were optimal for the careful and methodical work required for counts and measurements. While baseline data was readily available for the inside bay of Cape Recife or just east of the lighthouse, little survey work has been performed west of Cape Recife or outside the bay area, where the designated ranching boundary starts.

2.2.5.1 Study Site

GPS points were recorded for all the localities where transects were surveyed and measurements made during the baseline survey. The spatial data was imported into a Geographic Information System (GIS) framework created for this study, which stores qualitative information for each data point. This allows a user to click on a point surveyed and obtain categorical information such as depth, habitat type, wild abalone density, and sea conditions when the survey was performed (Figure 2.2).

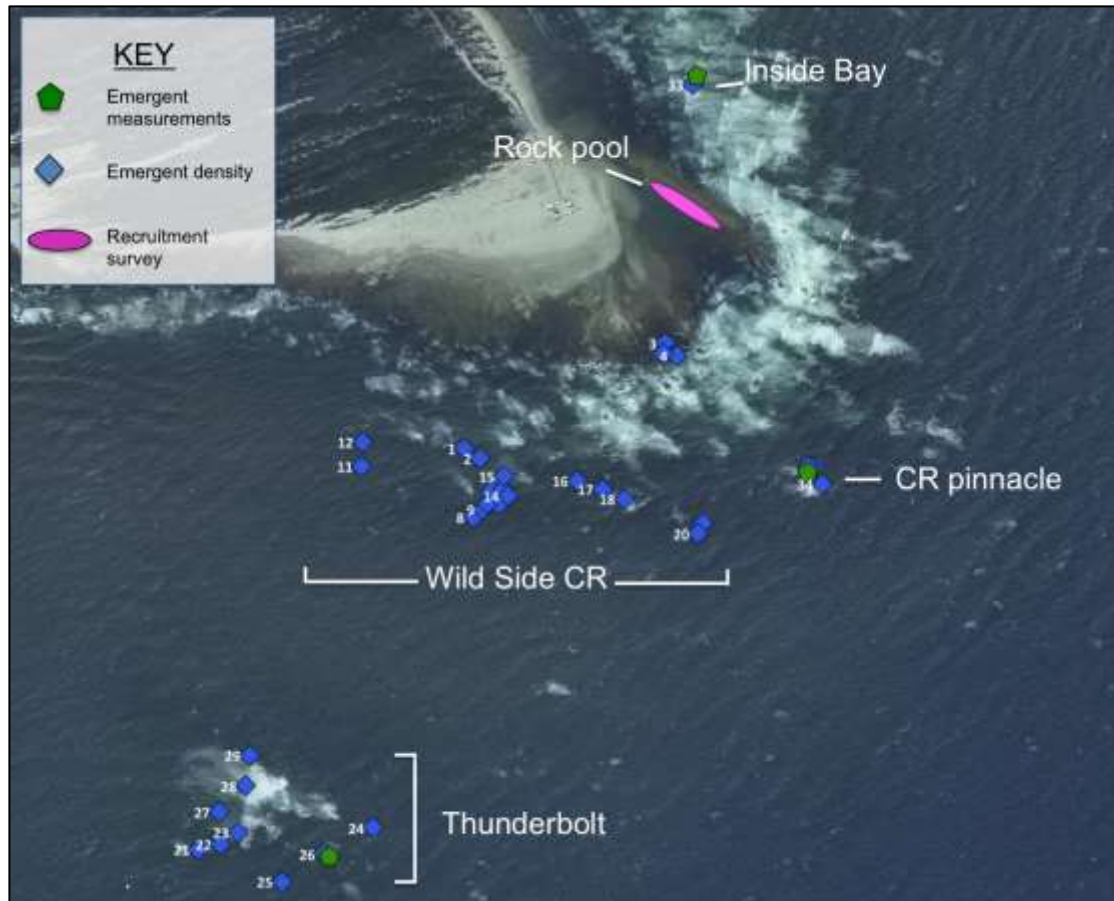


Fig 2.2 GIS map showing the location of emergent density transects, size measurements and recruitment surveys. The map excludes Suicide reef situated 5km to the east of Thunderbolt reef.

A brief habitat description along with photographs is provided in table 2.1 for the different localities in which the baseline survey was conducted. Although most surveyed areas were in relatively close proximity they exhibited different habitat characteristics. This is likely a reflection of the heterogeneous nature of the substrate at Cape Recife and the varying depth profiles of the different areas.

Table 2.1. Descriptions and photographs of areas sampled off of the coast of the designated study site - Cape Recife, Port Elizabeth, South Africa

Study Area	Description	Photographs	
1. Inside Bay	The inside bay area comprises gently shelving substrate consisting of an aeolian deposit base, with an overlying layer of cobbles embedded in a consolidated sand-biota matrix (Godfrey, 2003). A few solid quartzite reef outcrops are dotted within this area. The habitat extends 150 – 200 m offshore in places. The outer boundary consists of shifting sandbanks between 3 – 4 m depths. <i>Plocamium</i> spp. are the dominant seaweed found here along with coralline algae.		
2. Cape Recife Rock Pool	Recruitment studies were conducted in the rock pool, which consists of loose boulders in at a depth of 0.5 m. The rock pool is approximately 150 m x 50 m and is protected at low tide from the open ocean by a boulder berm on its eastern side. There is a narrow opening to the south. This habitat is significantly different in appearance to other surrounding habitats. Encrusting coralline algae covers the underside of rocks while a heavy silt deposit is found on the upper surface due to frequent deposition under regular, relatively calm conditions. A suite of fauna and flora was present underneath the boulders with high abundance of juvenile abalone found under the protection of urchins or just under the cover of the boulders. No large or emergent > 80 mm SL abalone were found in this rock pool.		

3. Wild Side / Pinnacle Reef	Cape Recife wild side and CR pinnacle is an exposed reef bearing the brunt of the prevailing southwesterly swells. This area is characterised by patchy but large, solid quartzite reefs often mushroom shaped, surrounded by deeper gullies with cobbles or sand on the bottom. Cobbles are less stable than other habitats owing to the relatively shallow nature and high exposure of the sites. This habitat was dominated by <i>Plocamium corallorhiza</i> with a strong geniculate coralline component.		
4. Thunderbolt Reef	Situated 1.2 km from the shore, Thunderbolt Reef is a high profile reef with large boulders interspersed between raised segments. Pinnacles completely dominated by redbait (<i>Pyura stolonifera</i>). <i>Plocamium</i> spp. were present in most transects but much less abundant than on the Wild Side Reef. Extremely wave exposed sites, with waves breaking in the smallest of swells (> 1.2 m).		
5. Suicide Reef	Similar to Thunderbolt, being an offshore reef situated about 1 km from the shore with high rising quartzite pinnacles separated by large boulders and deep gullies. Pinnacles dominated with redbait (<i>Pyura stolonifera</i>). <i>Plocamium</i> spp. present but not abundant. High wave exposure with waves capping in the smallest of swells (> 1.2 m).		

2.2.5.2 Abalone Transect Counts

A baseline stock assessment on the outside bay of Cape Recife was required as the bulk of the commercial scale ranching was planned to take place in this area. The survey was undertaken in September/ October 2013 during calm days with good visibility. A 10m-weighted line was laid over reef that was deemed suitable for abalone habitation at varying depths between 2 m – 10 m. Each transect line was marked with a GPS point. Two divers would then count 1 m on each side of the line from opposite ends resulting in a 20 m² area being covered for each transect. Some transects proved difficult to effectively search due to the abundant *Plocamium* spp. cover and a very strong surge.

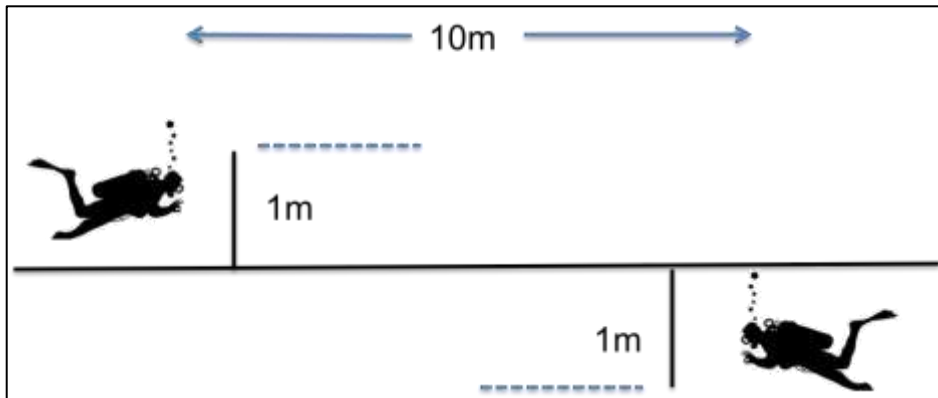


Fig 2.3 Description of 10m-weighted transect line laid over reef area deemed suitable for abalone habitation; with divers counting 1m each side of the line to record the number of abalone within an area of 20 m² per transect.

A total of 36 transects (720 m²) were completed over the four reef areas. 23 transects (460 m²) were performed on the 'Wild Side' from lighthouse extending $\pm$ 800 m eastwards. Nine transects (180 m²) were performed at 'Thunderbolt' reef which was considered prime abalone habitat in many areas. Three transects (60 m²) were done on 'Suicide' reef $\pm$ 1.2 km offshore from Noordhoek ski boat club. Only one transect (20m²) was carried out on the 'Inside bay' of Cape Recife due to poor diving conditions. Transect surveys were selected subjectively in areas that were deemed suitable for abalone habitation.

2.2.5.3 Emergent size measurements

Size measurements of emergent abalone were undertaken on four reefs, visibly, the 'Wild Side pinnacle' (n = 35), 'Thunderbolt' (n = 40), 'Suicide' (n = 10) and 'Inside bay' (n = 3). Only three measurements were taken on the 'Inside bay' due to rough diving conditions. Emergent *H. midae* were chosen at random, pried from the reef surface using a shucking tool and lengths measured underwater using a calliper and recorded on slates.

2.2.5.4 GIS Methodology

All data collected from the baseline survey for emergent density measurements, size measurements and recruitment surveys were imported into a spatial Geographic Information System (GIS) framework, which captured qualitative information with the corresponding co-ordinate points. The purpose was to store abalone stock assessment information and provide easy access for resource managers (Figure 2.2). The open source QGIS 2.2.0 Valmiera platform was used, with geo-referenced aerial photographs.

2.2.5.5 Data Analysis

One-way ANOVA's were conducted to test differences in shell length measurements and density between different sites for the 2013 stock assessment. Due to the unequal sample sizes, Levene's test for homogeneity of variances was run. If the test for homogeneity of variances was satisfied Post-hoc Turkey HSD or Fisher LSD tests were used to test for further significance between individual samples.

Regression trendlines fitted in Figures 2.4, 2.5, 2.7 and 2.8 were plotted using MS Excel.

2.3 Results

2.3.1 Trends in abalone stock

2.3.1.1 Density surveys

Emergent density surveys have periodically been undertaken place at Cape Recife documenting a progressive decline in abalone density, visibly: 1.6 m^{-2} (Elliot, 1993), 1.2 m^{-2} (Godfrey, 1999), 0.8 m^{-2} (De Waal, 2001) 0.5 m^{-2} , (Godfrey, 2004) and 0.3 m^{-2} (Daly, 2006) and 0.1 m^{-2} (Hutchings & Biccard, 2012) (Figure 2.4). The decline in surveyed abalone densities at Cape Recife coincided with high levels of poaching over that period which is reflected in the number of confiscated units (Figure 2.10) and the declining mean mass of abalone (Figure 2.7).

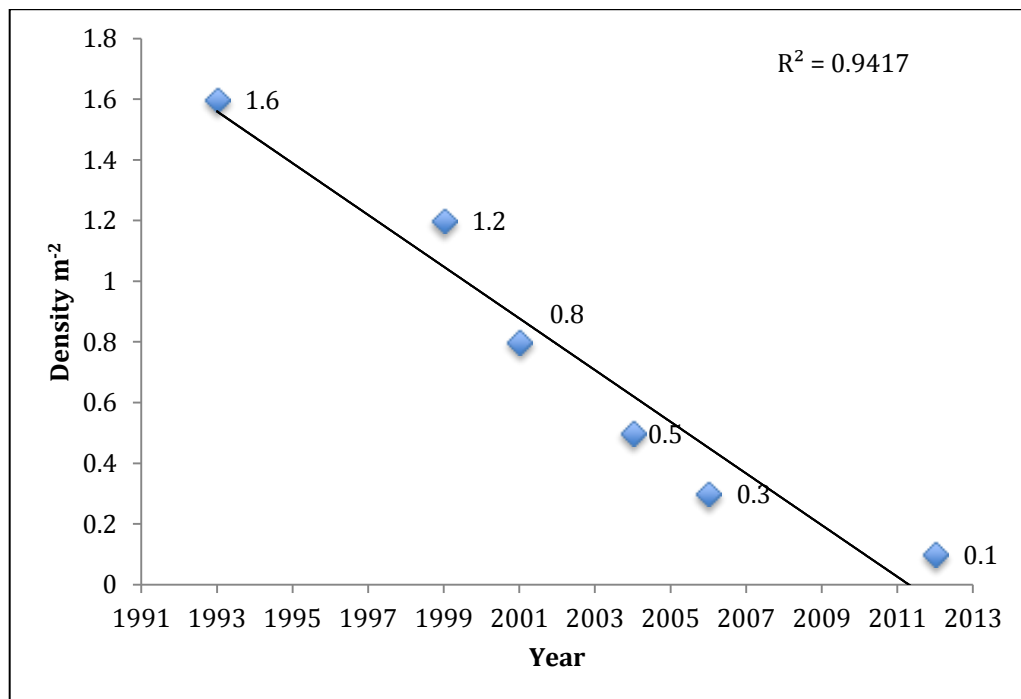


Fig 2.4 Density m^{-2} of emergent abalone at Cape Recife during 1993 – 2012. Blues diamonds and associated labels are mean values derived from past surveys. Solid black trendline fitted by is linear regression.

2.3.1.2 Emergent length measurements

In situ sampling of shell lengths at Cape Recife from 1998 to 2012 did not indicate a significant decline in the size of abalone measured over the sampling period ($\beta = -0.46$, $p = 0.056$, $R^2 = 0.014$). Low sample sizes and the fact that only emergent > 80 mm SL were included and missing years is likely to be responsible for not detecting significant declines in the shell lengths.

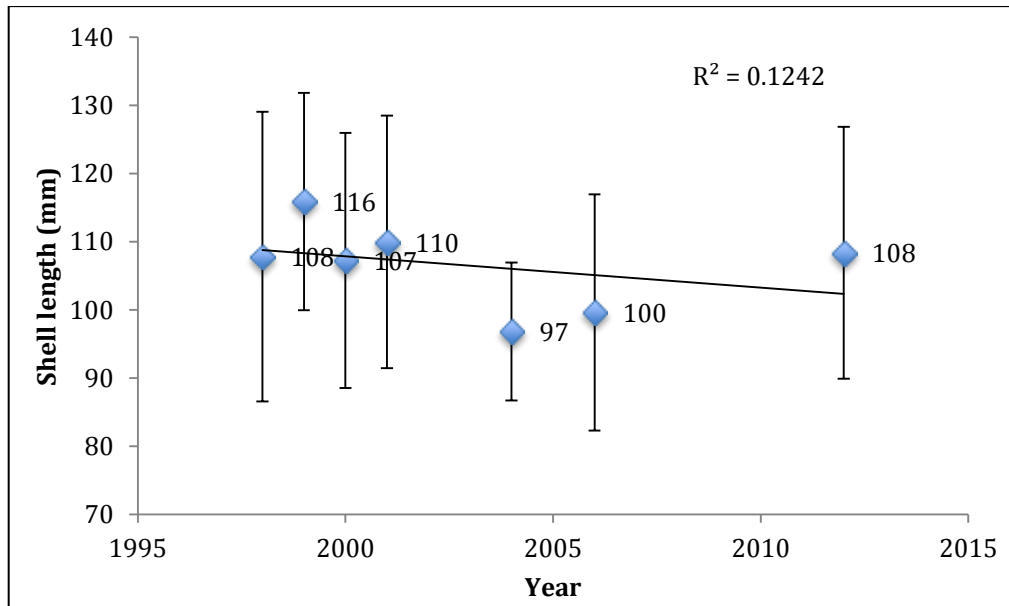


Fig 2.5 Emergent shell lengths (> 80mm SL) for *H. midae* at Cape Recife from 1998 to 2012. Blues diamonds are mean values; error bars show standard deviation, and solid black trendline fitted by is linear regression.

2.3.1.3 Recruitment

The surveys for recruitment were all conducted in the 'Lighthouse Rock Pool' at Cape Recife, which is considered prime juvenile habitat. Recruitment appears to have been variable from 1999 – 2007. During this period Godfrey (2003) collected recruitment data in conjunction with his seeding experiments (1999 – 2001). Godfrey's earlier recruitment surveys were not always located in the same areas as his surveys in the proceeding years, which is likely to impact the consistency of results. From 2001 to 2007 there was a notable decline in recruitment, concurrently intense poaching activities were taking place within Cape Recife. *In situ* surveys show a marked decline in the density of emergent abalone (Figure 2.4) during this period as well as declining mean mass (Figure 2.7) of confiscated abalone (indicating smaller animals being targeted as larger animals became fished out). In addition, the

highest confiscations of poached abalone units at Cape Recife occurred during this period (Figure 2.10).

From 2013-2016 Witte undertook annual recruitment surveys. Recruitment over this period appears to have remained stable and higher than during previous years.

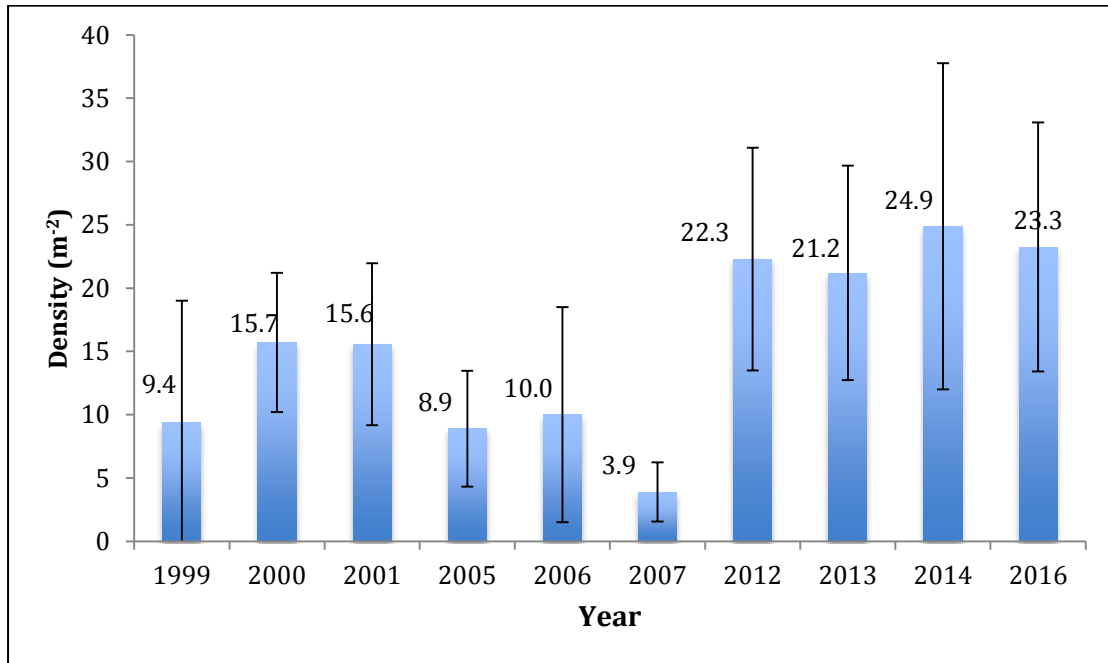


Fig 2.6 Density m⁻² of juvenile abalone as measured at the Cape Recife rock pool. *Graph is a continuation of data collected by Godfrey (1999, 2000, 2001, 2012) and Godfrey & Raemaekers (2005, 2006, 2007).* The labels are the mean values and error bars show the standard deviation.

2.3.2 Fishery dependent catch data

There has been a general decline in the mass of abalone confiscated for the Eastern Cape (Figure 2.9) and Cape Recife (Figure 2.10) from 1998 to 2012. The mean mass for Cape Recife has been consistently lower over the years than the remainder of the Eastern Cape. It is worthy of mention that only one confiscation event took place in 2010 and 2012 at Cape Recife with relatively low number of samples (Table 2.9). It appears that mean mass increased in 2010 and 2012, but this is most likely an artefact of the small sample size. In 2005 there was a spike in the mean mass of abalone with one confiscation event having abnormally large abalone (possibly a result of harvesting a previously unexploited dense abalone bed).

Both the Eastern Cape and Cape Recife poached abalone samples reflected an increase in the percentage of undersized *H. midae* from 1998 - 2012. The higher percentage of undersized animals in confiscations from Cape Recife is likely a reflection of the historically high fishing intensity in this area. In more recent years 2008, 2010 and 2012 all abalone confiscated from Cape Recife have been undersized animals.

A high number of abalone began being confiscated from the Eastern Cape and Cape Recife in particular from 2000 to 2005. In the year 2000, 28399 abalone units (eviscerated and whole abalone) were confiscated; this peaked in 2005 to 48367 units in the Eastern Cape. Confiscated abalone from Cape Recife reflected a similar trend, with 3012 units confiscated in 2000, peaking at 4570 units in 2002 and with 2742 units in 2005. Confiscations for both areas have shown steady declines in confiscations from 2006 through to 2012.

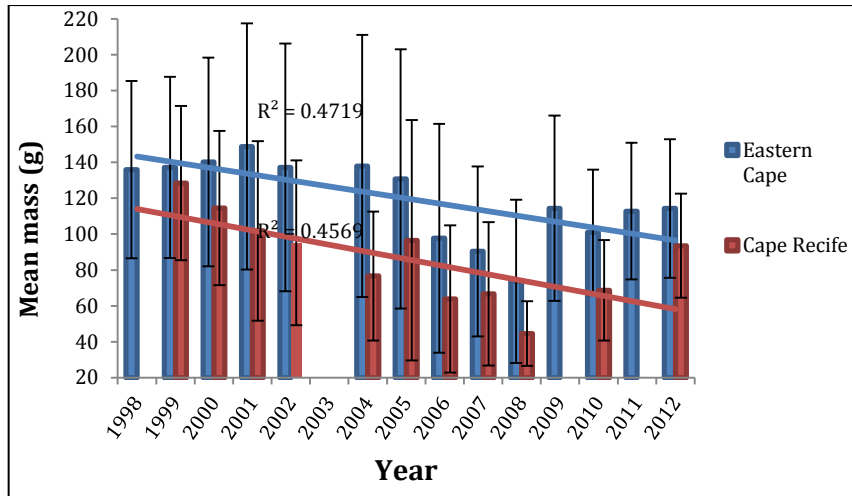


Fig 2.7 Mean mass (as eviscerated mass) of shucked abalone from confiscations in the Eastern Cape province and Cape Recife. The red and blue trendlines are fitted by linear regression.

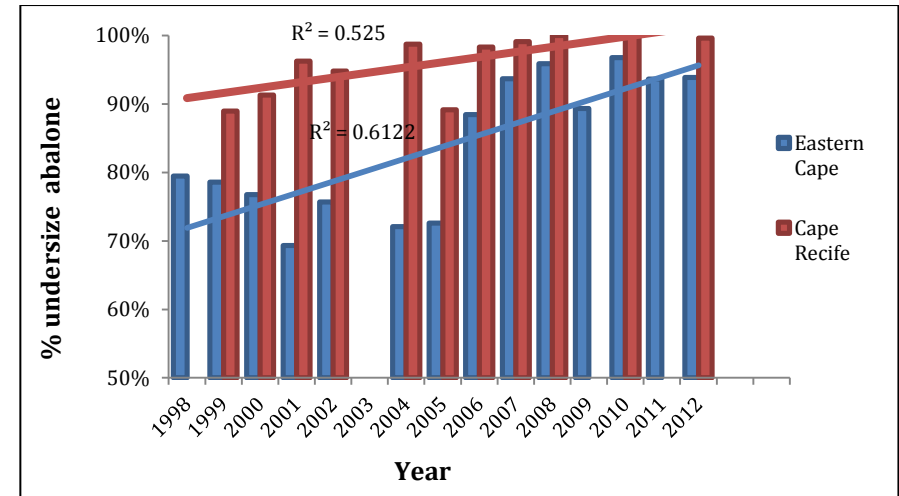


Fig 2.8 Percentage of undersized abalone recorded from confiscated samples for the Eastern Cape province and Cape Recife. The red and blue trendlines are fitted by linear regression. The legal size is 114mm shell breadth in the Western Cape commercial fishery, or 176 g of eviscerated mass.

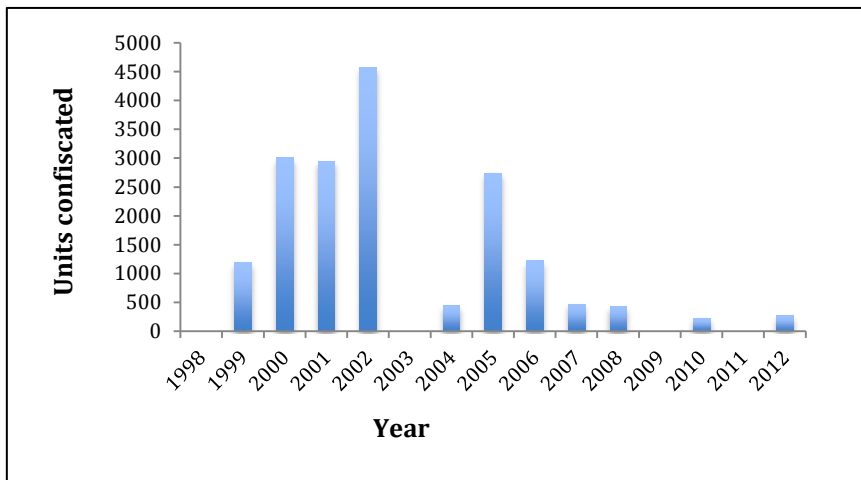


Fig 2.9 Number of abalone units confiscated in the Eastern Cape from 1998 to 2012.

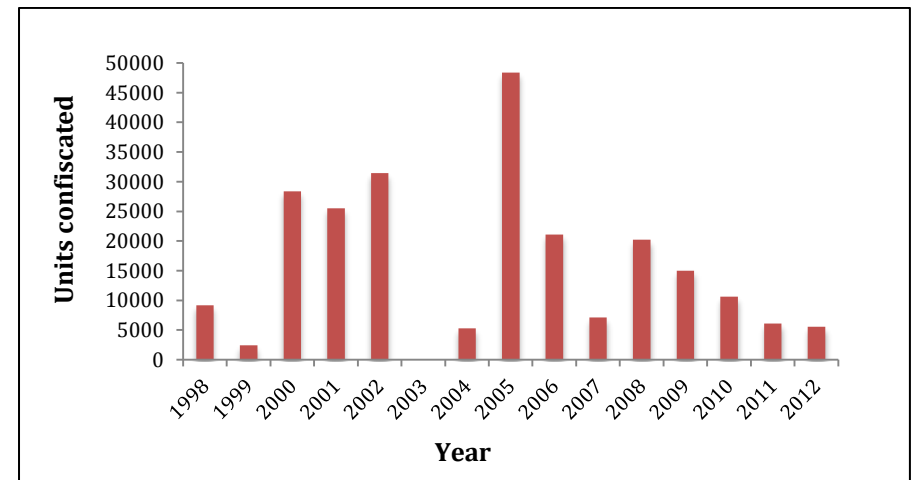


Fig 2.10 Number of abalone units confiscated at Cape Recife in the Eastern Cape from 1998 to 2012.

2.3.3 Baseline transect surveys - Outside Bay (wild side)

Five reef areas were sampled by transect counts during the baseline survey to obtain density estimates. Due to poor diving conditions, the Inside bay which had only one transect line completed, was excluded from further sampling. A one-way ANOVA was conducted to compare the effect of site (Suicide, Thunderbolt, Wild Side CR and Wild Side pinnacle) on density of abalone. There was a significant effect, although marginal, of site on density at the $p < 0.05$ level for the three conditions ($F_{3,31} = 3$, $p = 0.043$). Post Hoc comparisons using the Turkey HSD test however did not reveal significant differences between reefs possibly due to small sample sizes of groups and high variance of density at each site. The more liberal Fisher's LSD test does, however, reveal that Wild Side CR ($M = 0.74$, $SD = 0.53$) is significantly different to Thunderbolt ($M = 0.33$, $SD = 0.24$) and Suicide ($M = 0.16$, $SD = 0.29$) but not significantly different to Wild side pinnacle ($M = 0.3$, $SD = 0.26$). Overall the Wild Side of Cape Recife excluding Suicide Reef had a density of 0.58 -abalone m^{-2} .

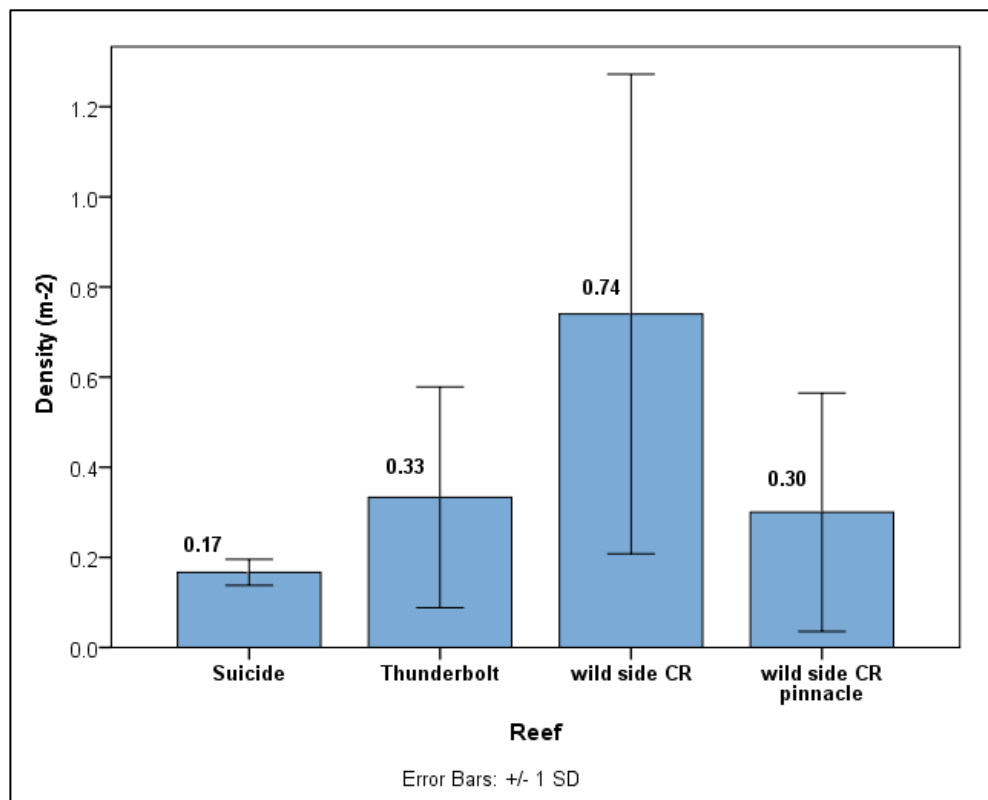


Fig 2.11 Emergent density survey for *H. midae* for four different reefs around Cape Recife. Error bars show the standard deviation.

It appears that the shallower reefs (Wild Side CR) generally had higher densities than the deeper reefs (Suicide and Thunderbolt). To test this assumption transects were plotted on a scatter plot showing density as a function of depth and analysed with a linear regression in SPSS. The most productive areas for abalone are shallow water reefs with high water movement. Figure 2.12 below shows a significant negative relationship between density and depth (decline in density with increasing depth) the low R^2 value of 0.38 is due to the large variability of density between transects at the similar depths, however the result is still significant ($\beta = -0.12$, $p < 0.001$, $R^2 = 0.38$). The large difference in density estimates at similar depths is due to the large variability of habitats, which influence density.

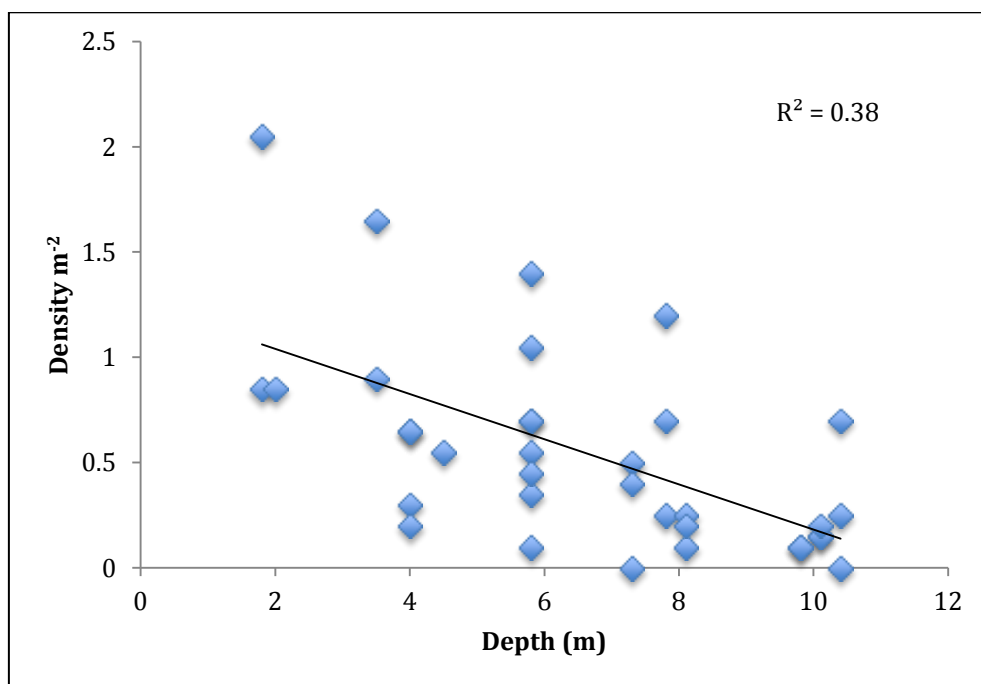


Fig 2.12 Surveys conducted for emergent abalone were done between 2 – 10 m depths; the graph shows a decline in the density of abalone with increasing depth.

All emergent abalone (green bar) shell lengths were measured across three reefs in the ranching area (Figure 2.13). A one-way ANOVA was conducted to compare the effect of site (Suicide, Thunderbolt and Wild Side pinnacle) on size measurements of abalone. There was a significant effect of site on size measurements at the $p < 0.01$ level for the three conditions ($F_{2, 82} = 5.12$, $p = 0.008$). Post hoc comparisons using the Turkey HSD test indicated Thunderbolt ($M = 104.2$, $SD = 21.2$) was significantly different than Wild Side pinnacle ($M = 85.9$, $SD = 26.3$). Mean shell length across all the sites was 94.5 ± 26 mm.

For the sake of comparisons to previous studies, Figure 2.13 also shows emergent > 80 mm SL as this was an earlier distinction made by Godfrey (2003) to separate cryptic from emergent. The mean across all the reefs using this distinction was 108.1 ± 15.7 mm SL, comparable to the 2012 SL estimate at Cape Recife (Figure 2.5).

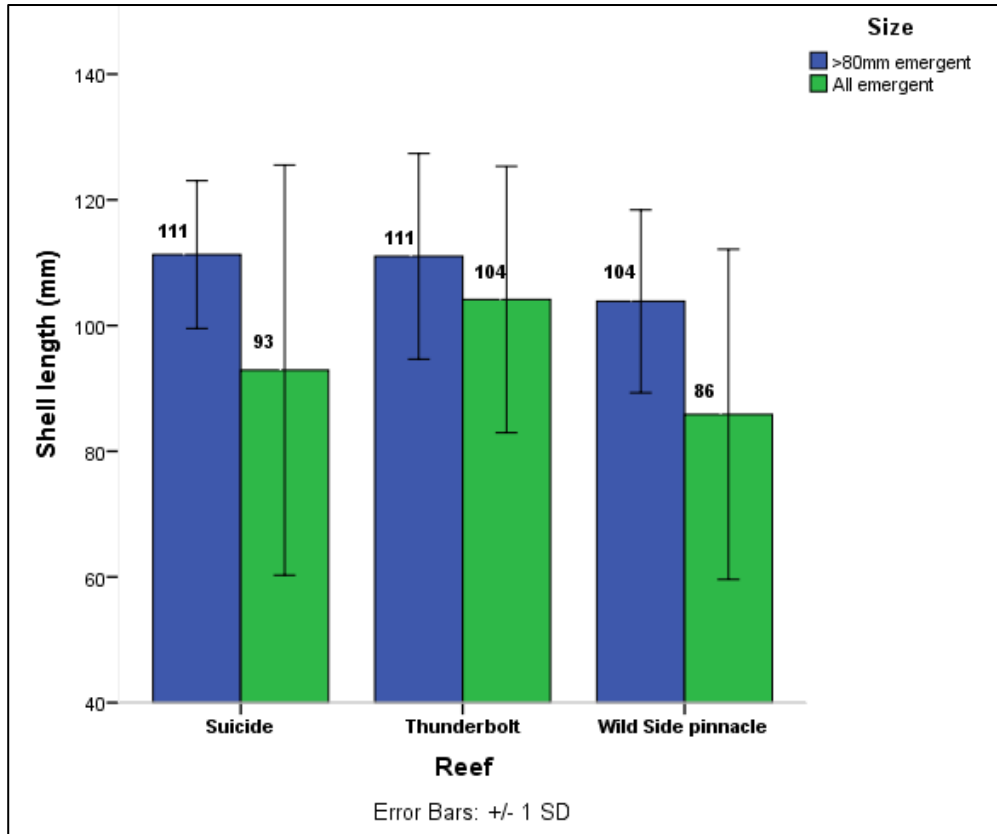


Fig 2.13 Emergent (All & >80mm) shell length measurements for three reef areas on the Wild Side of Cape Recife

2.4 Discussion

2.4.1 Trends in abalone abundance at Cape Recife

Sampling conducted at Cape Recife from 1993 to 2012 (Figure 2.4) indicates a significant reduction in the density of abalone over the years. A caveat to this trend is that the surveys conducted by different researchers have not always employed the same sampling procedures and have employed random transect lines over suitable reef around the Cape Recife point. This conventional method to estimate abundance is influenced by the “patchy” spatial distribution of abalone, an improvement to this method is the distanced based abundance method which has been found approximate the true abundance of the population (Officer et al., 2001). While caution must be exercised in using different density estimates as absolute abundance measures, the decline in density over the years is strong evidence of the effects the uncontrolled illegal fishing of the abalone stock in the Port Elizabeth area (Godfrey, 2003; Raemaekers & Britz, 2009). This hypothesis is supported by the extensive beds of old shucked shells left by poachers that were observed in the habitats surveyed.

The impact of the illegal fishery is further evidenced by the decline in the average mass of abalone from confiscated samples from 1998 – 2012 for both Eastern Cape and Cape Recife (Figure 2.7). There was also an increasing proportion of undersized abalone from the Eastern Cape in more recent years (2008, 2010 & 2012). Cape Recife samples had a distinctly lower mean mass and higher portion of undersize abalone than the remainder of the Eastern Cape for all years from 1998 – 2012 (Figure 2.8). This is a reflection of the historically greater fishing pressure at Cape Recife due to its easy diving conditions and close proximity to the urban centre of Port Elizabeth. Abalone poaching effort was heavily focussed on Cape Recife during these years, before spreading further afield (Godfrey, 2003; Raemaekers & Britz, 2009).

The emergent (> 80 mm SL) abalone (Figure 2.5) showed no significant decline over the years, while all other stock abundance indices have shown declines in mean size and increasing proportion of undersize individuals over the 14-year time period. The reason for the lack of a significant decline in *in situ* shell measurements is likely a result of the small sample sizes and the fact that divers actively select the larger individuals to measure.

Furthermore, the search time to measure the samples was not recorded, but it is likely that divers had to spend longer looking for abalone to measure.

2.4.2 Trends in recruitment of *H. midae*

Recruitment at Cape Recife rock pool over the period 1999 – 2016 does not show a clear trend. There appeared to be a reduction in measured recruits from 2000 – 2007. A clear shift in poaching activity in 2006 was noted away from Cape Recife to other areas, potentially due to resource depletion in the area (Raemaekers, 2009). The high illegal fishing effort in the area may well be responsible for the declines in recruitment from 2000 – 2007. When recruitment was measured again in 2012, a significant increase was recorded. From 2012 – 2016 recruitment density has remained constant. In 2013 – 2016 Witte undertook annual recruitment surveys. Recruitment over this period appears to have remained stable and higher than previous years, a potential indicator for stock recovery. However direct comparisons between data collected by Witte and Godfrey could be inaccurate for the following reasons: Data collection by different field researchers often yields different results as methods and experience may differ; secondly, sites surveyed may have varied somewhat and even the smallest variations in sites has the ability to influence the outcome of a result. It was well noted that placing transects one or two meters from the boulder berm yielded entirely different counts (far lower). A prime narrow band for juvenile abalone existed along the edge of the berm.

It could be expected that the large-scale decline in fecund abalone at Cape Recife would result in a decline in the recruitment of *H. midae*. A notion, which has become somewhat of a dogma in fishery science, is that recruitment depends in some way on abundance of spawners (McShane, 1995). However, empirical evidence in support of this claim is not strong and many studies have found no relationship between stock size and abalone recruitment (Shepherd, 1990; Shepherd *et al.*, 1992; Tegner *et al.*, 1992), which may be a reflection of the inability to monitor recruitment effectively. It was found that a low frequency of adults corresponded with a low abundance of juveniles, but it was also found that in an area where the abundance of adults was high no juveniles were found (McShane, 1995). In light of this evidence it is possible that recruitment is not directly linked to stock abundance adjacent to the Cape Recife rock pool. This is not to say that the large decline in stock does not have an impact on recruitment over a larger scale but rather there are other exogenous factors influencing recruitment density (McShane & Smith, 1991). Godfrey (2003)

demonstrated that there was significant difference in juvenile density between two areas at Cape Recife, separated only by a 20 – 30 m-boulder berm at low tide. The rock pool had higher densities than the exposed site over the three-year period but no significant differences were detected within the same sites. Settlement rates in the rock pool are likely to be enhanced due to an obvious degree of water entrapment at low tide possibly resulting in the concentration of free-swimming larvae in calm water. Further the rock pool is considered prime juvenile habitat possibly resulting in lower rates of post settlement mortality compared to Godfrey's (2003) other study area for recruitment density. Further compounding the uncertainty in the time series of recruitment density at Cape Recife is the use of different field researches to collect data. Sampling bias and experience combined with locality can have a profound impact on the outcome of results and caution must be raised when making direct comparisons between different studies. While all assessments were carried out in the rock pool, the exact locations would have varied as no GPS points or permanent marks were taken. It was noted during the recruitment survey that by placing the quadrat just a few meters from edge of the berm yielded much lower densities. These are important factors to take into consideration when analysing the results from this study and in designing a population or stock survey. Another theory, which has been suggested for the increased recruitment from 2012 – 2016, is the protection of Cape Recife from poaching. Since 2012, controlled access has been implemented at Cape Recife by means of a boom and security officer, further the deployment of a private abalone anti-poaching unit has been situated at the lighthouse at Cape Recife since 2013. This has drastically reduced the fishing pressure in the area, and observations from divers suggest that the stock appears to be in recovery. This potential stock recovery could be a cause of the apparently enhanced recruitment in the rock pool.

2.4.3 Compliance efforts

A high number of abalone confiscations took place in the Eastern Cape (Figure 2.9) and Cape Recife (Figure 2.10) up to 2005, a period cited as being the height of abalone poaching in the Port Elizabeth area. After this period, from 2006 to 2012, confiscations by law enforcement agencies declined. This could be seen as a response to a declining resource as the healthy stocks or dense abalone beds became fished out, which is supported by the declining mass (Figure 2.7) and increased numbers of undersized individuals in confiscated samples (Figure 2.8). There was a distinct shift in boat-based activities from Cape Recife area to Sardinia Bay

MPA, which is reflected in the reduced confiscations from Cape Recife, and is likely a result of a local resource depletion (Raemaekers & Britz, 2009).

While the confiscations of abalone over time provide a proxy for the quantity of abalone being poached, fluctuations in law enforcement effort have also played a large role in the quantity of abalone being confiscated, and therefore the trends need to be viewed with caution. There has been a very uneven effort distribution focused on compliance over the years by law enforcement agencies due to consistently changing management structures (Raemaekers et al., 2009). The recent deployment of TTF, the private anti-poaching unit, by ranching managers at Cape Recife has been an important move to combat poaching and secure the area that has been designated as an abalone ranching area.

2.4.4 Pre-seeding baseline stock assessment 2013

Prior to the commencement of reseeded abalone at Cape Recife the present baseline assessment of the wild stock abundance revealed that the 'Wild Side' reef had significantly higher densities than the deeper sites of 'Thunderbolt' and 'Suicide' reef. Abalone density was found to be significantly negatively correlated with depth on all sites. This is an important consideration when reseeded abalone back into natural areas as the result suggests that the habitat carrying capacity for abalone may decrease with depth.

The recorded abalone densities are not likely to be close to pristine biomass indices as these areas have been previously subjected to heavy fishing pressure since 1998. Rather the estimates provide pre-seeding abundance estimates for the area and are potential benchmarks in which to measure the success of ranching against.

Emergent densities were first recorded in 1993 and found to be 1.6-abalone m^{-2} at Cape Recife dropping in a stepwise manner to just 0.1-abalone m^{-2} in 2012. This contrasts quite substantially to the 2013 density estimates done on the "Wild Side" in the baseline assessment, which found 0.58 abalone m^{-2} which is similar to the 2004 density estimate of 0.5 abalone m^{-2} . The 2013 abundance estimates were mostly conducted on reef areas deeper than previous studies done from 1993 – 2012 and thus were not included in the Figure 2.4.

2.5 Conclusion

This chapter presented compelling evidence from various sources of the decline of the abalone resource in the Eastern Cape and specifically at Cape Recife. The present transect counts in Cape Recife Bay and the “Wild Side” deeper water habitats earmarked for abalone reseeding experiments confirmed that the stock has been severely depleted by illegal fishing. While the limited surveys indicate that recruitment is still occurring, abalone densities and average sizes were severely reduced and all confiscated abalone from Cape Recife were below the minimum legal size. No spawner biomass – recruitment relationship was found. A more detailed population survey is required to obtain clarity over the stock – recruitment relationship, this would require setting up and monitoring multiple sites around Cape Recife to determine if recruitment is linked to larval production, or rather habitat determined recruitment.

CHAPTER 3

Factors influencing the survival and growth of seeded abalone *Haliotis midae*

3.1 INTRODUCTION

This chapter documents a small-scale seeding experiment conducted at Cape Recife, which aimed to determine the influence of key factors affecting the survival and growth of hatchery reared abalone in the wild.

Before ranching can be effectively pursued on a commercial scale, the establishment of an experimental pilot project is essential as it provides important information on potential parameters governing the limitations and successes of a reseeding initiative. Most projects around the world have been conducted as small-scale pilot projects to assess abalone ranching potential (Sweijnd et al., 1998; Heasman et al., 2004; Dixon et al., 2006; James et al., 2007; Roberts et al., 2007; Chick et al., 2013). Although these results are promising, existing protocols and methods need to be improved if ranching is to be commercialized. This pilot project set out to build on work conducted by Godfrey's (2003) experiments at Cape Recife, which were done on a small scale with often inconclusive results. This study aimed to quantify factors influencing the growth and survival rates of ranching abalone. In order to achieve this, replicated seeding experiments were set up at Cape Recife. Seed size, density and habitat have been cited as some of the most important factors governing the success or failure of a ranching program and were chosen as the key factors to investigate in the present study (Schiel, 1993; Mgaya & Mercer, 1995; Sweijnd et al., 1998; De Waal & Cook, 2001; Roberts et al., 2007; Hamasaki & Kitada, 2008). They are reviewed in detail below to provide context and motivation for the present research approach. Other known factors influencing the survival of hatchery-reared juveniles, which require consideration, include the physiological condition of abalone, predators, release method, and food availability (McCormick et al., 1994) but these were not explicitly measured in the experiments.

3.1.1 Density

Understanding the carrying capacity of a habitat is vital - overstocking can have a detrimental effect on growth and survival rates (Goodsell et al., 2006), whereas understocking will not maximize returns (Munroe & Bell, 1997). Stock enhancement experiments have advocated varying densities according to reef suitability, seed size and species of abalone. Hart et al. (2013a) used a mortality model to predict the cumulative survival of *H. laevis* four years' post-release in order to achieve a target enhancement density of 2.5 m⁻². This resulted in release densities between 18 - 35 abalone m⁻² at a release size of 31 mm shell length (SL). Dixon et al. (2006) hand seeded *H. laevis* at six varying densities from 9 - 45 m⁻² at 30 mm SL. Heasman et al. (2004) used two types of seeding devices holding up to 2,000 (< 8 mm SL) juveniles. Schiel (1993) used hand seeding to individually place juveniles with a target density of 50 - 70 m⁻², which was considered comparable to that at which larger juveniles (> 20 mm) occurred in good habitat. On artificial reefs, *H. rubra* of 10 – 30 mm SL were seeded at 20 - 40 m⁻² (James et al., 2007). Heasman et al. (2004) recommended a seeding density for 5 – 15 mm SL of 1 – 10 m⁻² for *H. rubra*. Godfrey (2003) conducted local seeding trials at Cape Recife using seeding densities of 10, 20 and 40 m⁻² (20 – 30 mm SL).

Pristine wild densities provide a good indication for the potential release densities of seeded juveniles. Wild emergent abalone densities recorded by previous studies in the Eastern Cape Province of South Africa ranged from 0.17 to 1.63 m⁻² (Tarr, 1993; Wood, 1993; Fielding 1995; Godfrey, 2003; Raemaekers, 2009). However, areas surveyed had been previously subjected to unknown levels of illegal harvesting. Pristine densities around Betties Bay in the Western Cape has been known to support average adult densities of three abalone m⁻² with some areas up to as much as 11.43 m⁻² (DAFF, 2011). With the identification of suitable habitat in the ranching area as well as a high quantity of food available, it was expected that reefs around Cape Recife would be able to support relatively high densities of abalone (Britz pers. comm., 2013). Three different densities were this selected for this study; low density of 10 m⁻², medium of 20 m⁻² and high 40 m⁻² which fall within the range of densities used in most other studies.

3.1.2 Seed size

Seed size plays an important role in the economic viability of stock enhancement, as the cost of producing smaller seed is considerably less than raising larger individuals (Schiel, 1993). It has been well established that survival increases with increasing seed size in the range of 5 – 40 mm SL (Saito, 1984; Zhao et al., 1991; Masuda & Tsukamoto, 1998; Sweijd et al., 1998; De Waal & Cook, 2001a; Roberts et al., 2007). However, the increased survival needs to offset the increased cost of the larger seed to be an economically viable operation. Most experimental release studies have investigated sizes ranging between 3 – 30 mm SL (Schiel, 1993; McCormick et al., 1994; Sweijd et al., 1998; Heasman et al., 2004; Dixon et al., 2006; James et al., 2007; Roberts et al., 2007; Hart et al., 2013a). Roberts et al. (2007) found increasing survival with increasing seed size of 5 – 25 mm but the increased survival did not offset the increased cost of production for seed > 10 mm SL. Saito (1984) reported greatest survival for seed sizes of 22 – 38 mm (but survival did not significantly improve beyond 38 mm) and the lowest for seed < 18 mm SL. The relatively cheap cost of seed production by Wild Coast Abalone (Pty) Ltd meant that slightly larger seed could be used without compromising the benefits associated with the cost of production. The performance of smaller size class of 31 – 43 mm (average 40 mm) and a larger size class of 48 – 54 mm (average 53 mm) were compared in the present study.

3.1.3 Habitat

The economic viability of abalone ranching is strongly linked to habitat selection (Dixon et al., 2006; Roberts et al., 2007). Kojima (1981) found that survival varied according to the degree of refuge that was provided to juvenile abalone by different organisms and habitats. Many studies abroad have found the availability of shelter beneath boulders or in crevices critical to the survival of juvenile abalone (Shepherd & Turner, 1985; Prince et al., 1988; Schiel, 1993). In the United States small (< 30 mm SL) red, green and pink abalone selected areas between rocks (Tegner & Butler, 1989). In South Africa a positive relationship was found between juvenile *H. midae* and the sea urchin *Parechinus angulosus*, which has been determined as a critical factor influencing juvenile survival (Day & Branch, 2000a; Day & Branch, 2000b; Day & Branch, 2002). However, studies conducted on the Namaqualand coast of South Africa found that the most significant factor determining the survival of juveniles was the habitat type under boulders (De Waal & Cook, 2001a; De Waal, 2005), similarly at Cape Recife it was found that juveniles were

not as strongly linked to urchins, but rather higher proportions were found in crevices and under boulders without the protection of urchin spines (Godfrey, 2003).

The ranching area at Cape Recife is an ideal location for reseeded due to the highly suitable habitat and because the abalone population is severely depleted as a result of intensive poaching (Godfrey, 2003; Raemaekers & Britz, 2009). Locating the best possible release sites within the two identified habitats at Cape Recife was critical as it has been said that abalone survive at a microhabitat scale (De Waal et al., 2003). At this scale, physical refuge and potential biological interactions become increasingly important and therefore seeding sites should be selected on this level (De Waal et al., 2003). Sites selected for this study were chosen if they could provide a reasonable amount of shelter (cracks, crevices and under boulder habitat).

3.1.4 Research approach and objectives

This study thus addressed key questions relating to seed size, density and habitat preferences influencing the survival and growth of hatchery reared abalone post-release into natural habitats. The aim was to determine the fundamental parameters governing the success of reseeded in order to guide the large-scale stock enhancement project in the area. Objectives were to assess (1) optimal seed size; (2) effects of seeding density; (3) habitat requirements and (4) growth and survival of juvenile abalone (seeds). The potential influence of predators, abalone migration and diver bias were not the focus of this study but their effects were considered on the overall outcome of survival estimates.

3.2 METHODS

3.2.1 Study Site

The experimental site was situated at the point of Cape Recife, a prominent rocky headland forming the western point of Algoa Bay which lies in close vicinity to Port Elizabeth. This area once supported abundant natural abalone stocks (Wood, 1993; Godfrey, 2003), which have subsequently been depleted in the last 15 years due to illegal harvesting (Godfrey, 2003; Raemaekers & Britz, 2009). The geology of the site varies greatly and combined with geomorphological and ecological processes has resulted in a very complex heterogeneous sub-tidal habitat leading to the variable distribution of *H. midae* (Godfrey, 2003). The experiment was conducted in two broad habitats at Cape Recife - one inside the bay and another outside the bay (Figure 3.1). The habitat inside the bay comprised of gently shelving aeolianite rock with an overlying layer of cobbles embedded in a consolidated sand-biota matrix between 0.5 – 3 m deep, hereafter referred to as the 'shallow site' (Steyn & Du Preez, 2013; Godfrey 2003). The outer boundary of this habitat comprised shifting sandbanks at a depth of 3 – 4 m, which is influenced by the prevailing swell and current patterns. The shallow sites were dominated by foliose macroalgae, which in turn was dominated by the seaweed *Plocamium corallorhiza*. The outside bay was exposed to the prevailing southwesterly swells, characterized by patchy but large, solid quartzite reefs which were surrounded by deeper gullies with cobbles or sand on the bottom. The cobbles were less stable than those encountered on the inside bay due to the higher wave energies. These sites ranged in depth from 3.5 – 7m, referred to as the 'deep sites'. The reef was predominantly southwest dipping with a northwest: southeast-orientated strike (Steyn & Du Preez, 2013). This habitat was also dominated by *Plocamium corallorhiza* but with a strong geniculate coralline component (Steyn & Du Preez, 2013). Other seaweeds that were prominent in both habitats included *Pachymenia carnosa*, *Laurencia flexuosa*, and *Hypnea rosea*; as well as the upright coralline *Aphiroa ephedrea*.



Fig 3.1. Map showing the location and site number of the shallow ‘inside bay’ and the deeper ‘outside bay’ sites, which were sampled near Cape Recife, South Africa.

3.2.2 Experimental Design

The experiment was set up as a split plot design. Two factors were applied in orthogonal combinations in random plots nested within larger blocks (Underwood, 1997). Release density (three levels) and seed size (two levels) were tested in orthogonal combinations in each of the two habitats (inside the bay and outside the bay). Release densities of 10, 20 and 40 abalone m^{-2} , were tested in combinations with small (40 ± 3.7 mm) and large (53 ± 3.7 mm) seed sizes. Each combination was replicated three times. The two habitats had 18 plots each (three levels of density x two levels of seed size x three replicates = 18), therefore a total of 36 plots were seeded (Table 3.1).

Table 3.1. Table displaying the theoretical experimental split plot design for seed size and density in the two different habitats. (S) Refers to small seed size of 40 mm (range = 31 – 43 mm) and (L) refers to large seed size of 53 mm (range = 48 – 54 mm).

Factor		Outside Bay				
Seed Size	L	S	L	S	L	L
	10	20	40	10	20	40
Density m^{-2}	20	40	10	20	40	10
	40	10	20	40	10	20
		Inside Bay				
Seed Size	L	S	L	S	L	S
	10	20	40	10	20	40
Density m^{-2}	20	40	10	20	40	10
	40	10	20	40	10	20

3.2.2.1 Experimental Plot Specifications

Each plot had a physical marker to denote the centre. This consisted of an anchor rope approximately 1.2 m in length with a red float attached and a 2 mm thick ABS plastic tag with the plot number engraved (Table 3.3d). The anchor rope and floats were painted with micron extra antifouling paint to prevent marine growth. Four different adhesives were tested and Pratley's putty standard was found to be the easiest to handle, had reasonable working period (one-hour gel time). To secure the markers 400 g of putty were

used in each instance. At the base of the rope section, there was a sinker to offset the float tension on the line to allow the putty to set (Table 3.3a).

Plots were set up over a period of three diving days. Plots were selected based on three main conditions: (1) < 8 m deep (2) provided necessary refuge (boulders/ crevices/ urchins) and (3) contained abundant seaweed cover. In addition, the presence of wild abalone was also used as a guide for appropriate release areas. Once an area was identified, the diver would search for a crevice and scrub the area clean of any growth. The putty was then moulded around the rope knots and pushed into a crevice (Table 3.3a). A surface marker buoy was positioned directly over the plot marker, and the diver would record the location on a GPS (Table 3.3b). Each plot was designed to have a 10 m^{-2} circular area with a 1.8 m radius. To ensure that abalone movement did not corrupt the neighbouring plot, plots were spaced at least 15 m apart and usually separated by physical barriers such as sand gullies.

3.2.2.2 Seed

Wild Coast Abalone (Pty) Ltd supplied the seed abalone used in the stocking experiments. The experiment consisted of two seed sizes: a small size of 40 mm (31 - 43 mm) and a large size of 53 mm (48 – 54 mm).

Table 3.2. Table showing the quantity of abalone seed used in the experimental seeding.

Density & Size Class	Plot size m^{-2}	Abalone per plot	Total plots per class	Total abalone
10 (B/S)	10	100	12	1200
20 (B/S)	10	200	12	2400
40 (B/S)	10	400	12	4800
Total			36	8400

3.2.2.3 Abalone Packing and Transportation

Abalone seed were purged (starved to empty the gut contents) on the farm for a period of three days prior to packing and transport. The seed were moved from the holding tanks and sorted into diving mesh bags according to the size and numbers required for each plot. These mesh bags were placed inside sealed oxygenated bags and inserted into polystyrene boxes with two gel ice packs. A control box was also packed and opened at the same time the seed arrived at the destination. Each box and mesh bag was labelled

with the size, number and weight of seed. Seed were packed at 12:00 am prior to the day of seeding and then transported four hours from the farm to the release location. Once the boxes had been transferred to the boat the following morning, they were opened and mesh bags clipped onto a buoy line for acclimation (Table 3.3c). The experimental abalone seed spent approximately 22 hours in transit before being released.

3.2.3 Release Strategies

A few methods have been demonstrated for releasing hatchery-reared abalone back into the wild. Oyster shells in wire baskets have been used to protect seed (Momma, 1972; Tegner & Butler, 1989; Seki & Taniguchi, 2000). Many studies have constructed artificial seeding devices/tubes to release juvenile abalone onto natural reefs; these devices are seen to minimize stress related to handling (McCormick et al., 1994; Sweijid et al., 1998; De Waal, 2002; Dixon et al., 2006; Goodsell et al., 2006; Chick et al., 2013). The release mechanisms also allow for natural diffusion of abalone onto reefs. While individual hand seeding has been seen as labour intensive (Ebert & Ebert 1998), it can allow a more uniform seeding density to be achieved (Godfrey, 2003). A limitation of the seeding devices is targeted predation by *O. vulgaris*, which has been observed congregating around release models and preying upon juveniles, also these release modules were found not to be efficient in releasing large numbers of seed quickly (Godfrey, 2003). Sites targeted by *O. vulgaris* predation would corrupt the current seeding experiment. Another factor observed by De Waal (2002) was that some seed remained in the housing for the duration of experiment, this study sought to ensure conditions experienced by the seed were true to their natural environment. Furthermore, a study conducted by Hansen & Gosselin (2013) found that handling stress did not cause mortality during out planting but rather predation was the cause of the majority of mortality. These factors combined with practical issues advocated the need for releases to be done by hand.

3.2.4 External Conditions for Release

In the days prior to seeding, weather forecasts were checked daily. A three to four-day notice period was allocated to prepare. Conditions needed to indicate a swell less than 1.5 m, little wind, short wave period (< 11 seconds) and appropriate swell direction. The 36 plots in the two habitats were seeded in three days between March and May 2013. Poor diving conditions meant a delay in releases. The Outside Bay was seeded over two days, 28 March 2013 and the 11 April 2013, using a 7.5 m semi-inflatable dive boat. The Inside

Bay habitat was seeded in one day on 23 May 2013 using a large dive crew based from a 12 m vessel assisted by two jet skis to allow access to shallow sites less than 2.5 m deep. Once the sites were located using the GPS, abalone bags were unclipped from the buoy line and handed to the diver (Table 3.3c). Divers used a 1.8 m weighted line to mark the extent of a plot while hand placing the seed into appropriate refuge spaces. Plots were not necessarily seeded evenly but according to the best available habitat within the plot. Seed clumped together were pried apart and placed individually face down during release to limit fish predation (Table 3.3e). Handling in this manner, in some cases, caused stress and the foot muscle to tense, which in turn took longer for the abalone to take hold and find cover. Surge also lifted seed that didn't take hold. These influences were not quantified and considered minor; observations from divers and Go-Pro footage indicated successful release of seed onto plots. A general overview of the experimental abalone releases was captured in the video titled "[Abalone Ranching South Africa](#)", which details experimental plot set up, visuals of habitat and releases of abalone seed.

3.2.5 Abalone dispersal counts

Three months' post release visual counts were conducted on 18 plots on the Outside Bay. Divers used a 1.8 m search line from the centre of the plot to count seed abalone found within the release area (core). The line was moved 360° around the plot. Then an additional 1.8 m was added to the line to count from the fringe of the release site outwards (1.8 m to 3.6 m) using the same method. The seeded shells at this point in time were clean of growth and distinguishable from wild abalone. The distance travelled by seed from the core area outwards was not measured. Rather the purpose was to count seeded abalone within the core area and outside the core area.

3.2.6 Abalone Retrieval to measure Survival and Physical Growth Rate

To effectively measure rates of survival and growth, abalone were retrieved from plots via exhaustive searches. After eight months at liberty on the Outside Bay all plots were located and searched. After nine months on the inside bay 13 out of the 18 markers were located. Sites 19, 20, 22, 23 and 30 were missing their markers. Plot 19 used a proxy marker, while other missing plots were removed from study. Each diver used a 3.6m-weighted search line (double initial radius), which attached to the plot marker. This increased the search area from 10m² to 40m² (Figure 3.2). To motivate the search area in this study, a similar study at Cape Recife found that of the seed released just 13% were

retrieved within 1m from the edge of site boundary while the reminder had not migrated from their release location.

It was impractical to search a wider area due to logistical constraints. Divers worked methodically turning over every boulder and cobble and searching all crevices and cracks for cryptic juveniles. Seaweed, specifically *Plocamium corallorhiza*, was removed to allow for better sightings as it often concealed abalone. The weighted line was moved around the site slowly until the plot was completed. Divers also collected any shells of seeded origin. Each diver used approximately two 10 L tanks per plot roughly equivalent to two-hour dive time per search.

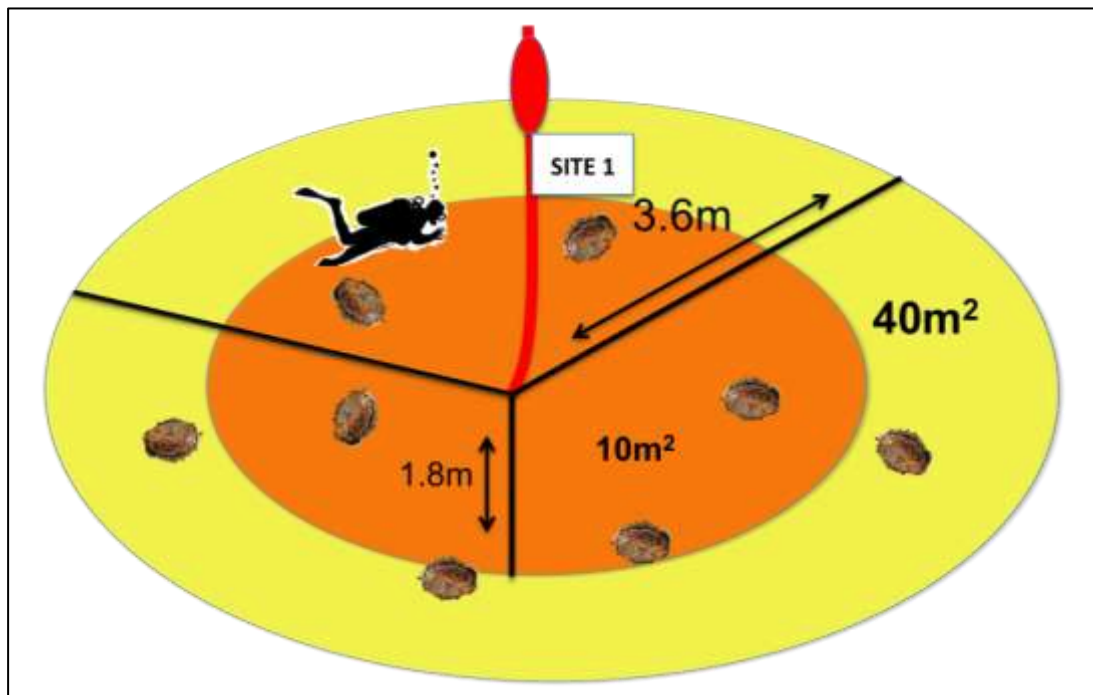


Fig 3.2. Orange circle showing the initial release area of abalone seed on a site, the surrounding yellow circle showing the increased search area on a site for abalone they may have migrated outwards.

The eight to nine-month period at large meant that the clearly distinguishable farm shell had become largely obscured by marine growth. Distinguishing between seeded and wild abalone during collecting was not always possible and often wild abalone were removed as a result. If the origin (wild or seeded) of the abalone was uncertain, divers were instructed to remove them. Large abalone were not collected. The possible influence of diver experience and effort on collections was mitigated by conducting an additional exhaustive search on all the sites by placing divers on different sites than previously

searched (Figure 3.3 & 3.4). On the Outside Bay in the second sample some markers were missing, plots six and 16 used proxy marker points as the diver had extensive knowledge of those sites, while sites 13 and 15 were not searched. In the second sample on the Inside Bay 11 plots were located, while 20, 22, 23, 30, 32 and 33 had missing markers. Plots 32 and 33 used proxy markers for searches. All abalone from the sites were sorted into bags and frozen for identification in the laboratory.

The first sampling round for the Outside Bay was conducted between 227 and 249 days after release over 24 and 25 November and 2 December 2014. The second sampling round for the Outside Bay was conducted between 365 and 381 days post-release over 11, 12 and 13 April 2015. Approximately 135 days or four months had elapsed between the two sampling rounds.

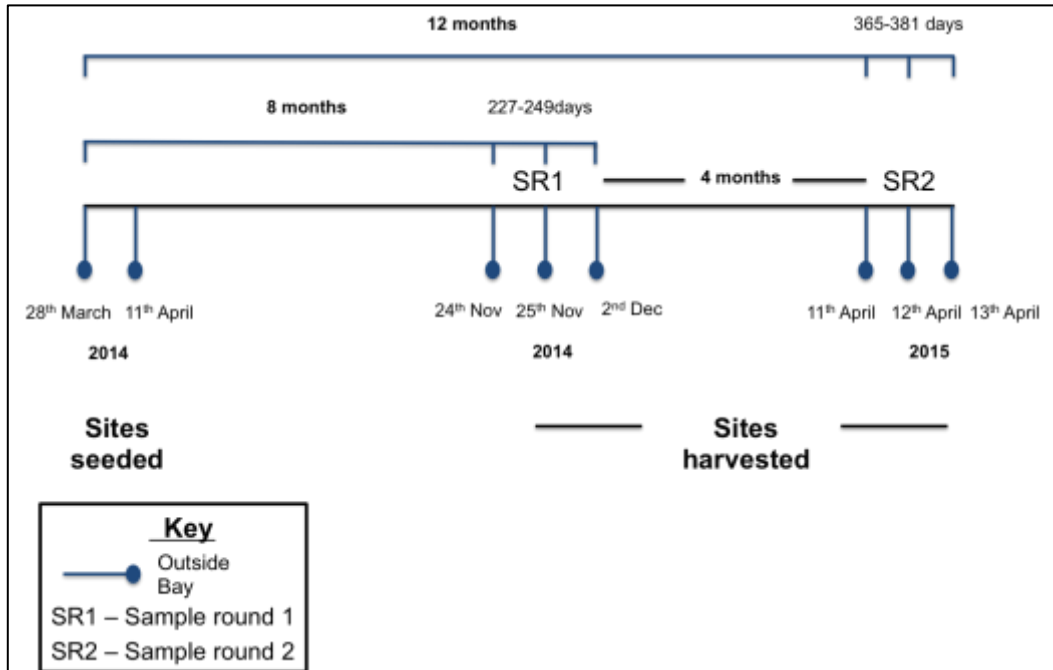


Fig 3.3. Summary showing the timeline of seed release and harvest dates for the Outside Bay habitat sites

The Inside Bay was first sampled between 273 and 282 days after release over 26, 27, and 28 February and 2 March 2015. The second sample for the inside bay was collected between 404 and 405 days after release over the 1 and 2 July 2015. Time between the two samples rounds was approximately 127 days or four months (Figure 3.4).

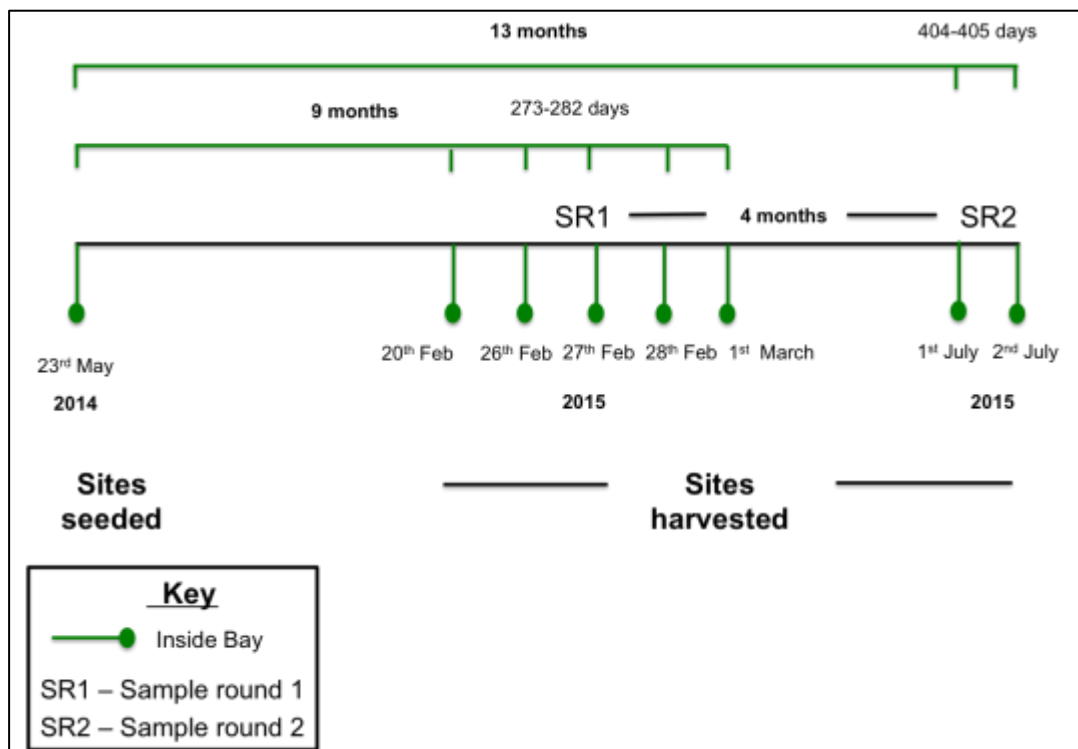


Fig 3.4. Timeline of seed release and harvest dates for sites on the Inside Bay.

3.2.7 Laboratory Analyses

Frozen abalone were carefully shucked and the meat was discarded. Each shell was scrubbed clean using soapy water and a wire brush. Wild abalone shells were separated from the seeded shells. All seeded shells were further cleaned with hydrochloric acid of 30 % strength to remove any growth of crustose coralline, which would otherwise prevent accurate growth measurements. This study did not use tagging to distinguish between wild and seeded abalone due to the potentially high tag loss prior and post seeding (Godfrey, 2003). Instead, the unique shell coloration obtained from the diet on the farm was effective in distinguishing between seeded and wild abalone (Seki & Taniguchi, 2000; Shepherd et al., 2000). This method is supported by studies from other parts of the globe that have used the unique shell colouration from the farm diet as a marker for identification and growth (Kojima, 1995; James et al., 2007; Roberts et al., 2007). It was possible to measure the increment growth rate using the distinct colour band on the hatchery-reared abalone. The colour of the shell changes once introduced into the wild due to the red seaweeds that the abalone consume (Godfrey, 2003). The new shell length is measured and then subtracted from the old shell length and divided by the number of days at liberty to obtain an average daily growth increment.

Table 3.3 Pictures of the different stages of site set up and seeding of the experimental plots

		
(a) Diver moulding the Pratley's putty into a crevice with sinker to offset float tension on the line to allow putty to set	(b) GPS point taken from the surface marker buoy which indicates the centre of a site	(c) Abalone bags clipped onto a line to acclimate before release on a site
		
(d) The central marker with site number engraved into the tag with float to keep tension on line for easy siting upon return	(e) Diver hand releasing abalone seed onto a site into a crevice	(f) Three months post release a seeded abalone clean shell covered by algae growth found on site 16

3.2.8 Data Analyses

All data analyses were conducted using IBM SPSS statistics 23.0. For the analyses involving modelling, the most appropriate model was chosen based on the lowest Akaike information criterion (AIC) value where the predictor variables contributed to explaining the variation in the response variable (Symonds & Moussalli, 2010). Models were reassessed and the non-significant predictor variables were dropped one by one and the least parsimonious model was selected (Bolker et al., 2009; Symonds & Moussalli, 2010).

3.2.8.1 Factors Influencing Survival

Sample Round One

To understand what factors could be influencing survival rate on plots after the first round of sampling, a generalized linear mixed-effects model (GLMM) was used to model survival (response variable) in relation to habitat (Inside Bay/ Outside Bay), density (100/200/400 m⁻²), seed size (small/big), diver search time and diver (diver 1, diver 2, diver 3, Warren and non-core divers). Plot was included as a random effect. The GLMM was specified with a Gaussian distribution with an identity link function. The differences in diver retrievals were further investigated through a one-way ANOVA.

Sample Round Two

Similarly, a GLMM was used to determine if survival (response variable) was influenced by habitat, density, seed size, octopus and diver (Diver 2, Warren and other). Plot was included as a random effect. The GLMM was specified with a Gaussian distribution with an identity link function. The purpose of running this analysis was to monitor the effect of diver on retrieval rate.

Sample Rounds Pooled

After both rounds of sampling, the data were pooled. The effect of diver on the result was largely eliminated this way, however it was established that Warren had higher collections in both sample rounds than other divers and this is something to bear in mind regarding the overall survival estimates. A GLMM was used to model survival (response variable) in relation to habitat (inside bay/ outside bay), density (100/200/400 m⁻²), seed size (small/big), diver search time and predators (octopus present). Plot was included as a

random effect. The GLMM was specified with a Gaussian distribution with an identity link function.

3.2.8.2 Somatic Growth Rate

Every seeded abalone that could be measured accurately was measured unless the shell was damaged or the growth band was unclear. During the first sampling round 594 abalone from the Outside Bay and 296 for the Inside Bay were measured. In the second round of sampling 144 abalone on the Outside Bay and 64 on the Inside Bay were measured. In order to determine the potential influences on the physical growth rate of abalone, a GLMM was used to model growth rate (response variable) in relation to habitat (inside bay/outside bay), density (100/200/400 m⁻²) and seed size (small/big). Additionally, the sampling round (one/two) interaction with habitat was included. Plot was included as a random effect. The GLMM was specified with a Gaussian distribution with an identity link function. A one-way ANOVA was used to investigate the differences in physical growth rates between plots within the same habitat and sample period.

3.3 RESULTS

3.3.1 Abalone Collections

In the first round of sampling, 14.1% (979) of abalone originally¹ seeded were recaptured during searches. This comprised of a mean retrieval of 14.7% (range: 3 – 31%) for the Outside Bay after eight months at liberty and 13.7% (range: 3 – 42%) for the Inside Bay after a minimum of nine months at liberty (Site 35 obtained 42% after 12 months). Searches during the second sampling event resulted in the collection of an additional 3.3% (215) of the abalone that were originally seeded. This accounted for 18% of total seed recaptured. Mean retrieval from the Outside Bay was 4% (range: 0-9%) and the Inside Bay 2.2% (range: 0-5.5%). For the search events combined the Outside Bay had a mean retrieval of 18.25% and Inside Bay 15.04% among the sites seeded and searched (Figure 3.5).

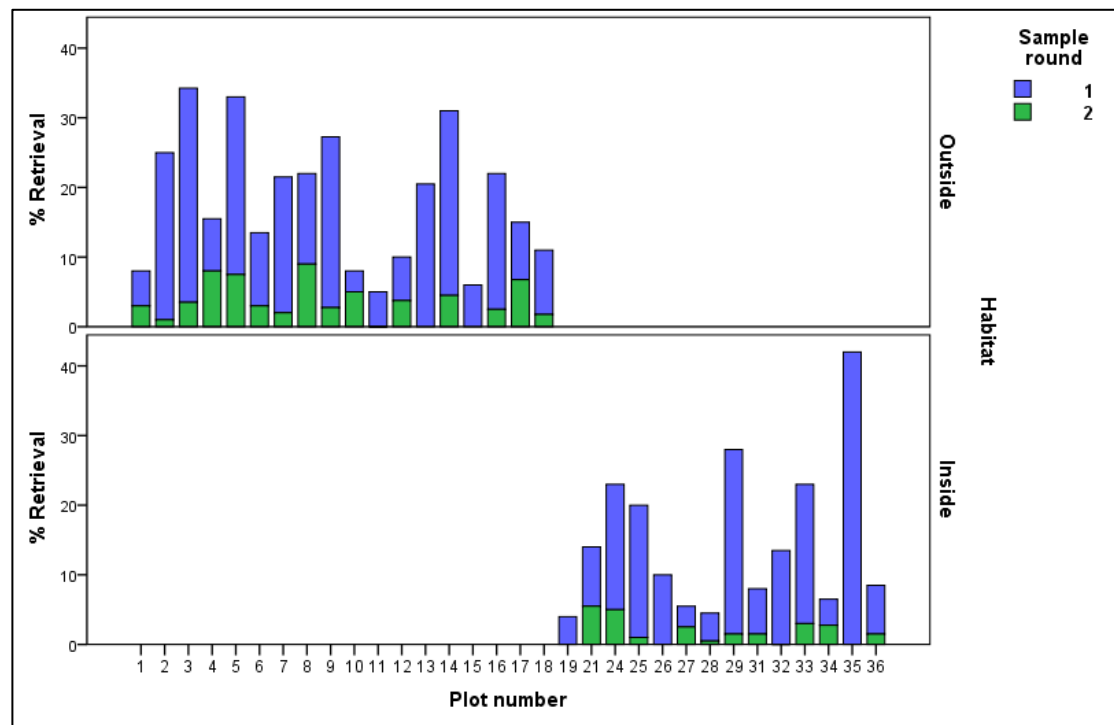


Fig 3.5. Combined retrievals of seeded abalone for sites after a first and second round of sampling.

¹ This value relates to only the plots that were actually harvested for abalone. Originally 8400 abalone were released but four sites were not sampled (1300 abalone) at all, which reduces the original amount to 7100 abalone.

3.3.2 Factors Influencing Survival

3.3.2.1 Sample Round One

The global GLMM model revealed that survival was not related to habitat ($F_{1,22} = 0.003$, $p = 0.96$), search time ($F_{1,22} = 0.15$, $p = 0.7$) or density at seeding ($F_{2,22} = 1.2$, $p = 0.32$), but indicated that survival differed in relation to seed size ($F_{1,22} = 4.64$, $p = 0.042$) and between core-divers ($F_{4,22} = 5.87$, $p = 0.002$). The reduced model two performed best (Table 3.3) and confirmed the difference in survival rates between seed sizes ($t_{1,23} = 4.9$, $p = 0.037$) and core divers ($t_{4,23} = 6.1$, $p = 0.002$). Survival rates were on average $6.1 \pm 2.7\%$ (95% CI: 11.8, 0.4) higher for small (40mm) seed sizes compared to large (53mm) seed sizes ($t_{1,23} = 2.2$, $p = 0.037$). A post-hoc test of survival rates between divers revealed similarities between all divers except Warren, who reported higher survival rates than the other divers.

Table 3.3. Variations of generalized linear mixed effect models with different fixed effects for sample round one

Model/ Parameter	F	P	df	AIC
(1) Habitat	0.003	0.96	1, 22	181
Size	4.64	0.042	1, 22	
Diver	5.87	0.002	4, 22	
Search time	0.15	0.704	1, 22	
Density	1.2	0.32	2, 22	
(2) Habitat	0.18	0.89	1, 23	177
Size	4.9	0.037	1, 23	
Diver	6.1	0.002	4, 23	
Density	1.24	0.31	2, 23	
(3) Habitat	0.029	0.86	1, 25	187
Size	5.25	0.031	1, 25	
Diver	5.55	0.002	4, 25	
(4) Size	5.44	0.028	1, 26	191
Diver	5.76	0.002	4, 26	

3.3.2.2 Sample Round Two

The global GLMM, the first model in Table 3.4, had the lowest AIC value for combinations of fixed factors. Core diver was the only factor that had significant impact on survival estimates ($F_{2,19} = 4.98$, $p = 0.018$). Warren had $2.4 \pm 1.4\%$ (95% CI: -5.4, 0.57) higher survival than diver 2, however this result was not significant ($t_{2,19} = -1.7$, $p = 0.1$). Warren's abalone retrievals were significantly higher $3.1 \pm 0.99\%$ (95% CI: -5.2, -1.05) than the non-core divers ($t_{2,19} = -3.15$, $p = 0.005$).

Table 3.4. Variations of generalized linear mixed effect models with different fixed effects for sampling Round 2.

Model/ Parameter	F	P	df	AIC
(1) Diver	4.98	0.018	2, 19	99
Habitat	2.88	0.16	1, 19	
Size	0.14	0.91	1, 19	
Octopus	0.22	0.64	1, 19	
Density	0.16	0.85	1, 19	
(2) Diver	5.36	0.01	2, 21	103
Habitat	2.91	0.1	1, 21	
Size	0.017	0.9	1, 21	
Octopus	0.36	0.5	1, 21	
(3) Habitat	1.98	0.17	1, 21	111
Size	0.09	0.77	1, 21	
Diver	6.44	0.007	2, 21	
Search time	0.28	0.62	1, 21	
(4) Diver	6.81	0.05	2, 22	107
Size	0.003	0.96	1, 22	
Octopus	0.018	0.9	1, 22	
(5) Diver	7.01	0.004	2, 22	105
Size	0.0003	0.98	1, 22	
Habitat	2.646	0.12	1, 22	
(6) Diver	8.21	0.002	2, 24	110

3.3.2.3 Sample Rounds Pooled

The collections of seeded abalone were combined from both sample rounds. The global model once again revealed that survival was not related to habitat ($t_{1,25} = 0.46$, $p = 0.5$), search time ($t_{1,25} = 0.39$, $p = 0.53$), density at seeding ($t_{2,25} = 0.25$, $p = 0.78$) as well as octopus on site ($t_{1,25} = 1.9$, $p = 0.18$) but indicated that survival potentially differed in

relation to seed size ($t_{1,25} = 3.93$, $p = 0.058$). Core-diver was removed from the models, as there were now two different divers used during both sample rounds. The reduced model 2 performed best (Table 1) and confirmed the difference in survival rates between seed sizes ($t_{1,26} = 43.99$, $p = 0.056$). Survival rates were on average $6.9 \pm 3.4\%$ (95% CI: -13.99, -0.2) higher for small seed sizes (40 mm) compared to large seed sizes (53mm) ($t_{1,26} = 2.0$, $p = 0.056$).

Table 3.5. Variations of models with different fixed effects for both sample rounds.

Model/ Parameter	F	P	df	AIC
(1) Habitat	0.46	0.5	1, 25	212.4
Seed size	3.93	0.058	1, 25	
Octopus	1.9	0.18	1, 25	
Search time	0.39	0.54	1, 25	
Density	0.25	0.78	2, 25	
(2) Habitat	0.75	0.39	1, 26	208
Density	0.13	0.88	2, 26	
Size	3.99	0.056	1, 26	
Octopus	2.1	0.16	1, 26	
(3) Habitat	0.76	0.39	1, 28	217
Size	4.21	0.05	1, 28	
Octopus	2.7	0.11	1, 28	
(4) Habitat	4.78	0.49	1, 27	215
Density	0.34	0.72	2, 17	
Size	5.1	0.03	1, 27	
(5) Size	5.34	0.02	1, 29	224.6
Habitat	0.43	0.51	1, 29	
(6) Size	5.93	0.02	1, 30	229.3

In the GLMM after sampling bias had been removed through a second search, only seed size emerged as being a potential significant predictor of survival with the smaller seed displaying a higher survival rate than the larger seed.

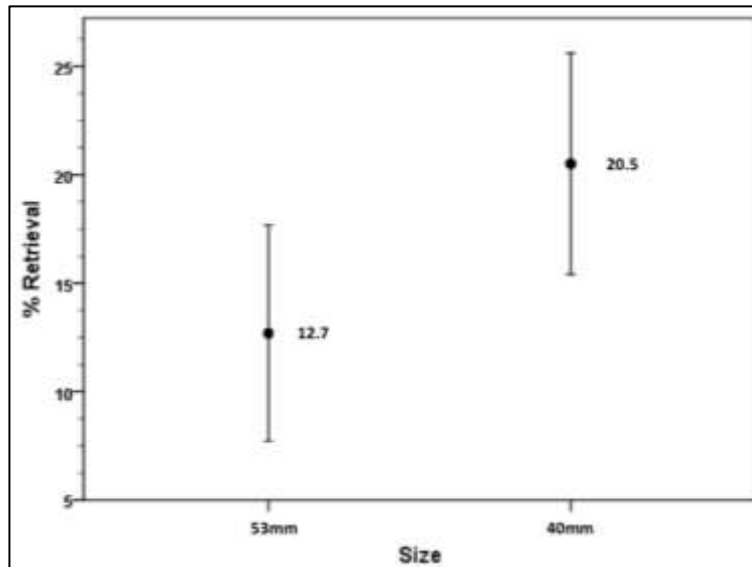


Fig 3.8. Mean retrieval of large size (53 mm) and small (40mm) abalone seed after two collection periods.

During seed retrievals, divers recorded any resident octopuses observed on the plots. Six of the 32 plots sampled had recorded a resident *O. vulgaris*. The retrieval for these plots was 9% compared to 17.8% for plots without any octopuses on. The GLMM however found the result to be insignificant due to a large standard error and small sample size, however likely impact of resident octopus on the long-term survival of seed is worth consideration.

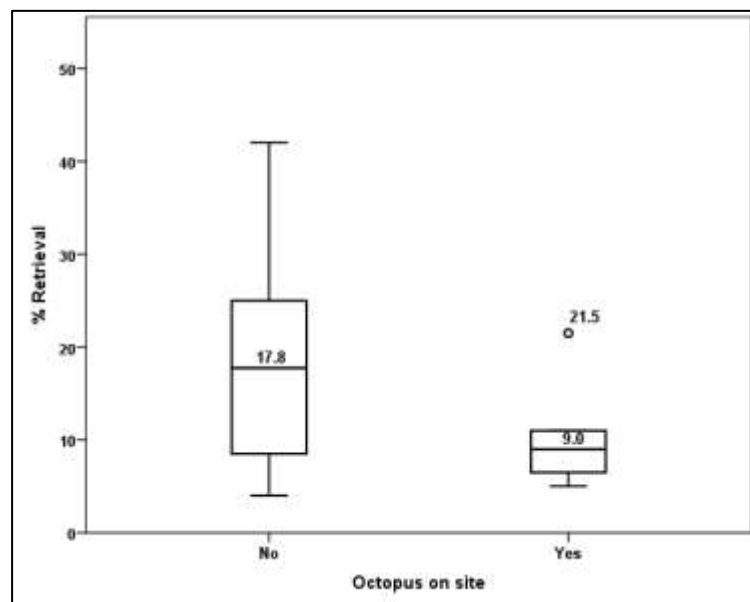


Fig 3.9. Retrievals of seeded abalone on sites with and without resident octopuses.

3.3.3 Diver experience – a factor influencing retrieval of seed

Multiple divers (four core and seven non-core divers) were used in order to sample all sites in the designated timeframe and thus the differential degree of experience and effectiveness among divers is problematic. Although the searches were exhaustive, sea conditions were challenging and habitats were complex making some sites more difficult to sample than others. After the first sample round, it was detected that diver had a significant effect in influencing retrieval rates ($P = 0.002$). However, just one diver, Warren, consistently achieved greater retrievals than the other divers (59% more than other divers combined) who were obtaining similar retrievals to each other. Similarly, in the second sample round, diver had a significant effect ($p = 0.018$), with diver Warren collecting 58% more abalone than other divers. Warren who set up, seeded and harvested the sites had a significant amount of diving experience in the terrain. In addition, being the lead scientist and collecting data for his study, he exerted a greater amount of effort. Warren destructively sampled more plots than any other diver doing a total of 17 out of 59 plots over the two sample rounds (Figure 3.6 – 3.7).

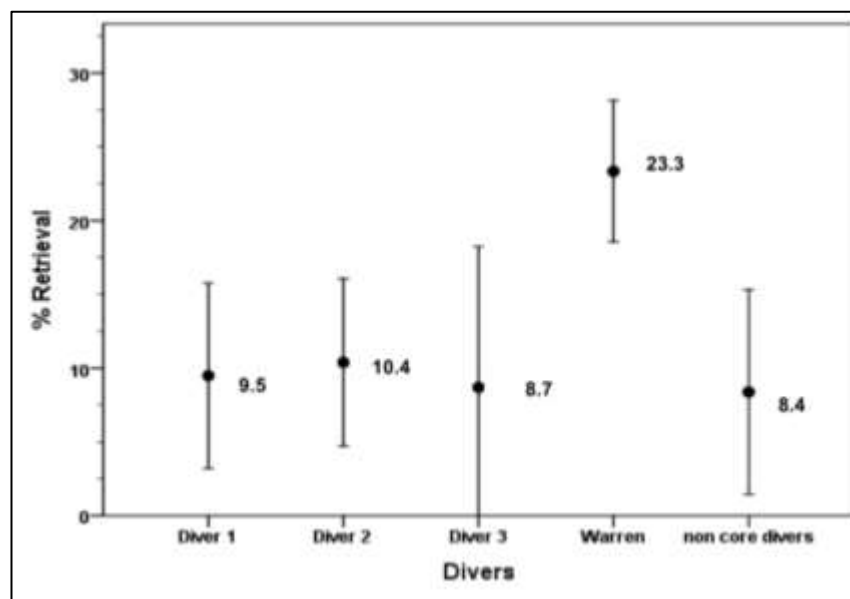


Fig 3.6. Mean abalone retrieval for deployed divers in Sample Round 1 with five divers comprising of the non-core divers.

A one-way ANOVA was conducted to further compare abalone retrieval rates between divers. Diver had a significant effect on the retrievals of abalone [$F(4, 27) = 5.86, p = 0.002$]. A Tukey HSD post hoc test indicated that Warren ($M = 23.72, SD = 9.65$) had significantly higher retrievals to diver 1 ($M = 10.91, SD = 8.8$), diver 2 ($M = 8.93, SD = 5.53$) and non-core

divers ($M = 8.2$, $SD = 3.75$) but this was not significantly different to diver 3 ($M = 11.67$, $SD = 7.32$). Diver 1, diver 2, diver 3 and non-core divers did not significantly differ from each other in the amount of retrievals.

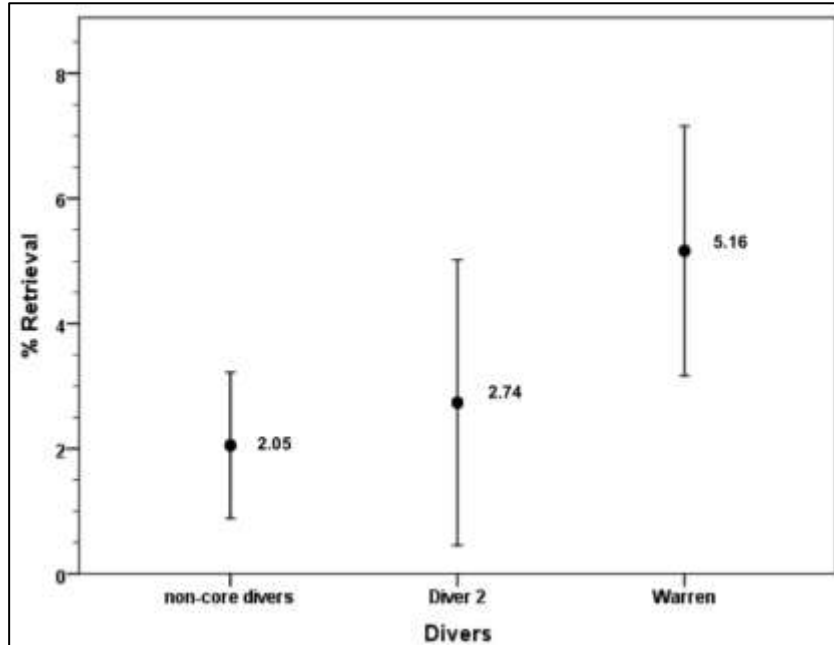


Fig 3.7. Mean abalone retrieval for deployed divers in Sample Round 2 with the non-core divers comprising of four divers.

Again, a one-way ANOVA was conducted in the second sample round to compare diver retrieval rates. Diver had a significant effect on retrieval rate [$F(2, 24) = 8.21$, $p = 0.002$]. A Tukey HSD post hoc test indicated that Warren ($M = 5.78$, $SD = 2.64$) differed significantly from non-core divers ($M = 2.2$, $SD = 1.45$) but not from diver 2 ($M = 3.12$, $SD = 2.4$), likely due to small sample size of diver 2.

Table 3.6. Comparison of diver fishing power. The most effective diver (Warren) achieved significantly higher retrievals of seeded abalone compared to all other divers.

Diver	Sample round	% Retrieval	Sample (n)	Std Dev
Warren	1	23,7	10	9,7
Other divers	1	9,7	22	6,2
Warren	2	5,8	7	2,6
Other divers	2	2,4	20	1,7

Plots 4, 8, 10, and 17 all had relatively similar retrievals on the first and second round of sampling, indicating that much abalone had been missed first time around on these plots. All

first collections on these plots were collected by diver two and three out of the four collections on the second round collected by Warren, statistically the most effective diver.

Table 3.7. Comparing diver retrievals on plots with highest collections after the second round of searching

Plot	Diver 1 st	Diver 2 nd	% Retrieval 1 st	% Retrieval 2 nd	% increase from 1 st sample
4	Diver 2	Warren	7.5	8	107
8	Diver 2	Warren	13	9	69
10	Diver 2	Non-core	3	5	167
17	Diver 2	Warren	8	7	88

The first sample achieved 14% retrieval and second sample an additional 3% of abalone originally released. This meant that at minimum, 21% of live abalone were missed during the first sampling, yet provided confidence that the majority of abalone had been retrieved during the first search. Despite differences in diver effort, the effects of divers on the results was largely removed by ensuring different divers harvested from different sites during the second occasion. This culminated in an average search time of 3.5 hours per plot.

3.3.4 Emigration of abalone outside the release area

Divers counted abalone within the release area on the outside bay plots (1 – 18) after three months post release and found 61% of the released abalone that they encountered remained within the core release area (0 – 1.8m) and that 39% were counted outside the core area in the additional search area (1.8 – 3.6 m). Anecdotal evidence from observation during counting indicated that many of these abalone were counted on the fringe of the core release area

3.3.5 Shell collections

During exhaustive searching, all shells that were observed to be from seeded abalone that had died were collected. Outside Bay shell collections ranged from 0–13% with minimum¹ mortality of 2.14%, while the inside bay ranged from 1 – 12% with minimum mortality of 5%. A total of 3.3% (236) seeded shells were collected across the 32 plots seeded with 7100 abalone.

¹ Minimum mortality is the absolute lowest level of mortality. There is certainly higher mortality than reported in the shell collections, but it provides a potential proxy for good and bad plots. The minimum value reported above is the average across the sites for inside/outside habitat.

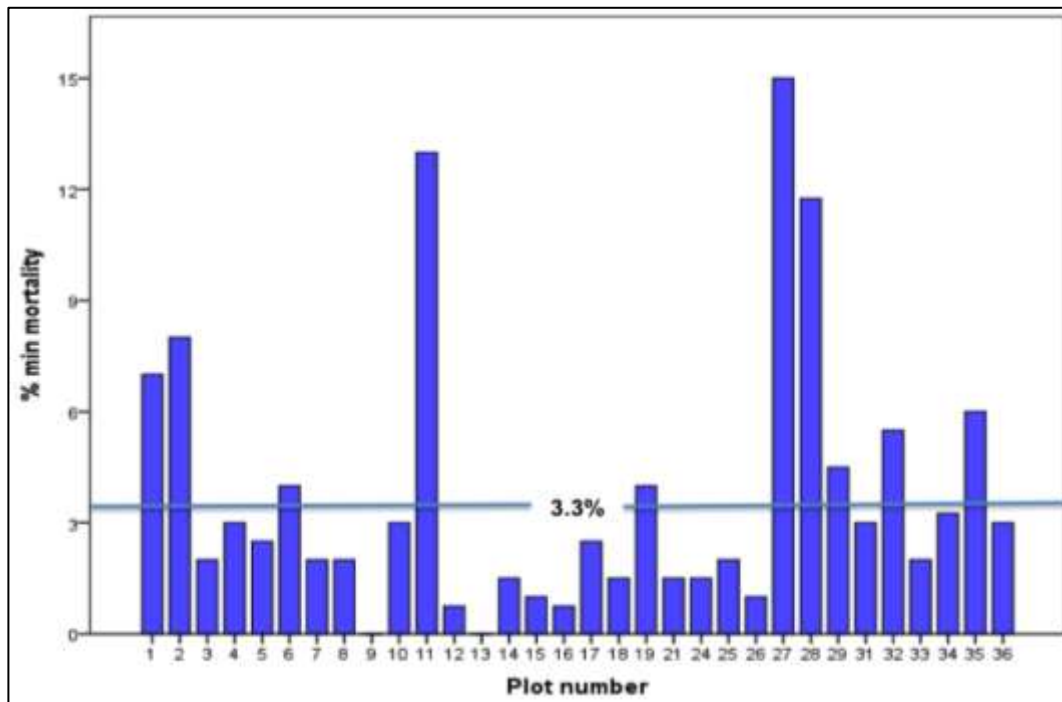


Fig 3.10. Minimum mortality (%) estimated from shells of released abalone that were collected during exhaustive searches of study sites. Most of these shells were located under boulders or wedged into crevices; any exposed shells would have been washed away from the sites.

A small amount of shells, representing minimum mortality were collected across sites. More seed abalone were recaptured alive than dead (shells). Interestingly, plots with some of the lowest retrievals such as plots 11 (5%), 27 (5.5%) and 28 (4.5%) had the highest amount of shell collections at 13%, 15% and 12% respectively. Retrievals accounted for 16.84% of abalone released with shells accounting for 3.2%. Just 20% of the abalone originally released have been accounted for as a shell or live recapture, the remaining 80% is unaccounted for.

3.3.6 Wild Abalone

The Inside Bay habitat had a greater abundance of wild *H. midae* than at Outside Bay, with an average of 60 wild abalone per plot collected compared to Outside Bay of 30 per plot. Nine hundred and sixteen wild *H. midae* were collected across 32 sites in the first sample compared to 453 abalone collected in the second sample from 27 sites, which equated to a 37% drop in collections from first to second collection due to divers removing a significant portion of wild abalone after the first search. With respect to seeded versus wild, Outside Bay had 51% more seeded than wild abalone collected contrasted with Inside Bay with 69% more wild than seeded abalone. When an abalone collected by a diver could be

clearly distinguished to be of wild origin it was not counted and returned to the reef. The wild collections were not precise abundance estimates because they were not removed if they were large individuals or clearly of wild origin. These collections nevertheless provide a relative measure of the abundance of wild abalone on a site or habitat area.

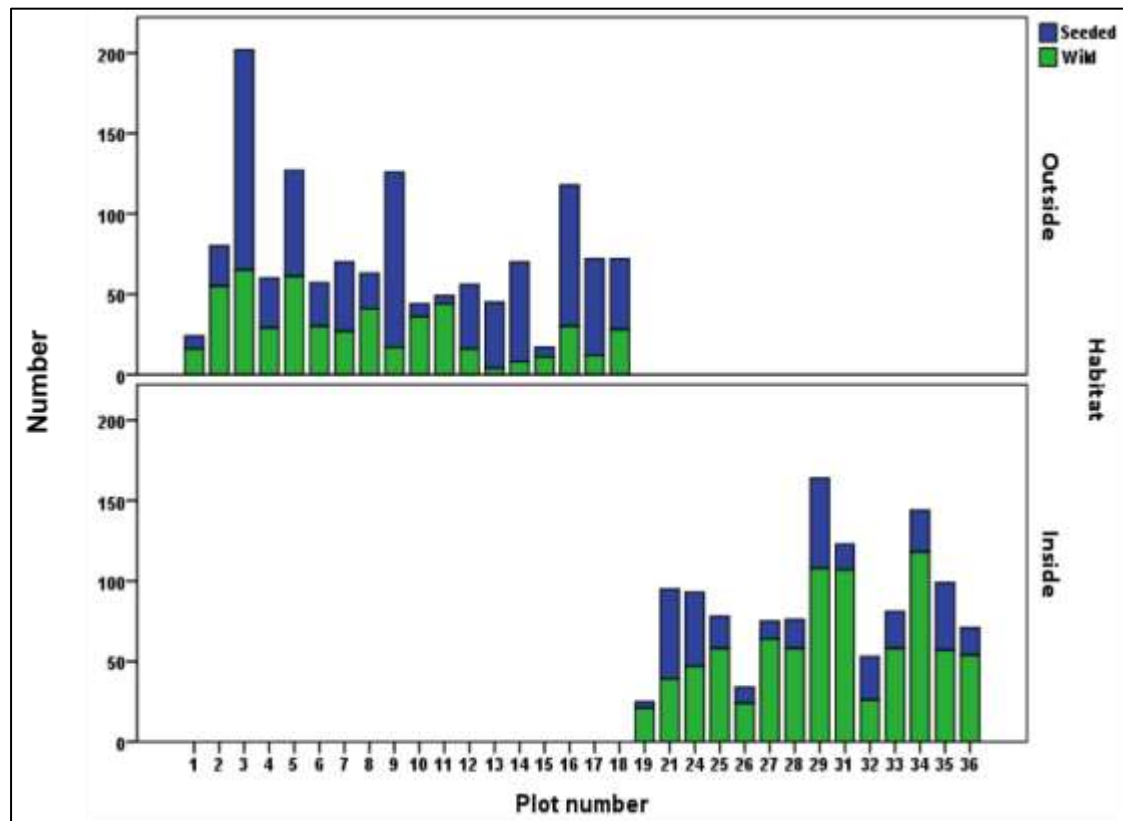


Fig 3.11. Quantity of wild to seeded abalone removed from sites. The Inside Bay sites obtaining much higher wild retrievals than the Outside Bay.

3.3.7 Somatic Growth

The two rounds of sampling events on the Outside and Inside bay meant there were four retrieval periods over seven months. The second sample was done approximately four months following the first sample for both habitats. The lapse in time between retrievals allowed for a seasonal effect on growth to be detected.

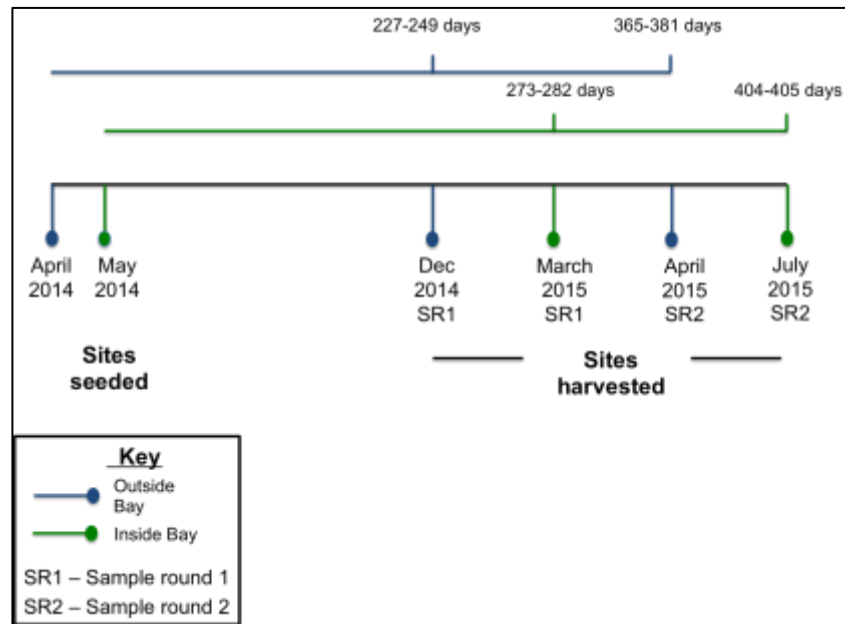


Fig 3.12. Timeline of abalone release and retrieval events for the Outside and Inside Bay habitats

Site-specific Growth

The patchy distribution of abalone at Cape Recife, described as a response to the heterogeneous substrate type and variable food abundance, is known to change over small spatial scales (Godfrey, 2003). One-Way ANOVAs were used to test if growth varied significantly between sites within the same habitat category (Inside and Outside) and within the same sample period.

3.3.7.1 Outside Bay: Sample round One and Two

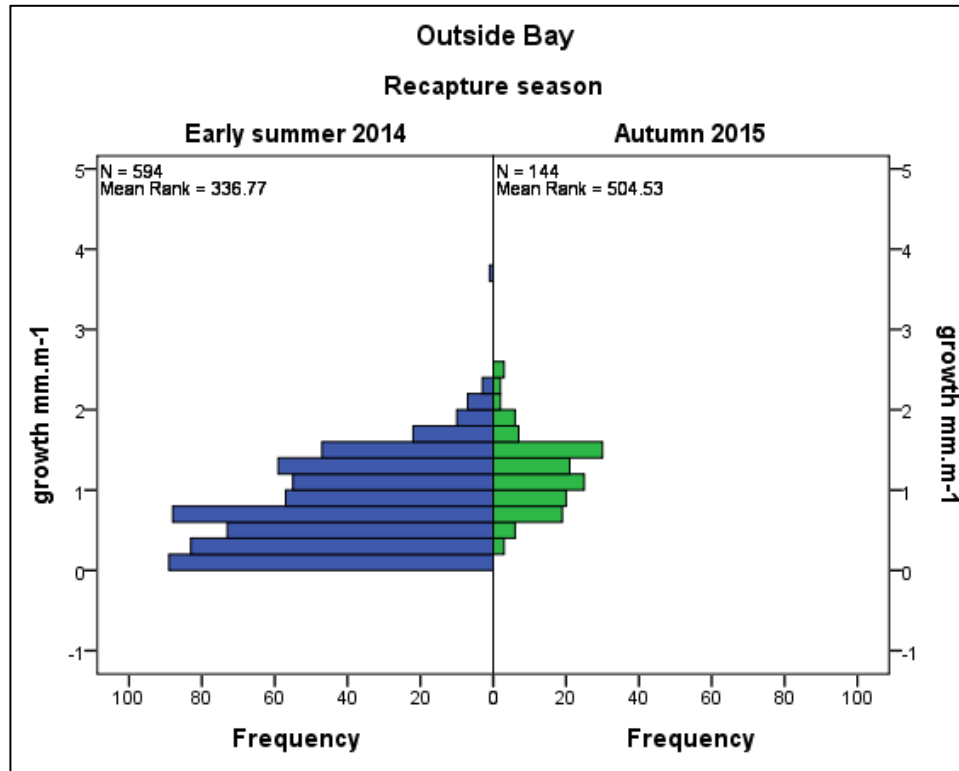


Fig 3.13. The frequency distribution of growth rate per month between the two sample periods extracted during pre and post summer months on the outside bay habitat.

3.3.7.2 Outside Bay SR1 (December, 2014)

A one-way ANOVA was conducted to test if growth rates between plots within Outside Bay and sample round 1 (SR1) were different. There was a significant effect of plot on growth rate at the $p < 0.05$ levels for the three conditions ($F_{16, 577} = 21.57$, $p < 0.001$). Post hoc comparisons using the Games-Howell test (unequal variances) indicated that nearly all plots differed significantly from each other except plots, 1, 8, 10 and 15, which had no significant differences. Plot 13 achieved the highest growth ($M = 1.42$, $SD = 0.29$) with plot 16 with the lowest ($M = 0.32$, $SD = 0.4$), having many zero increments.

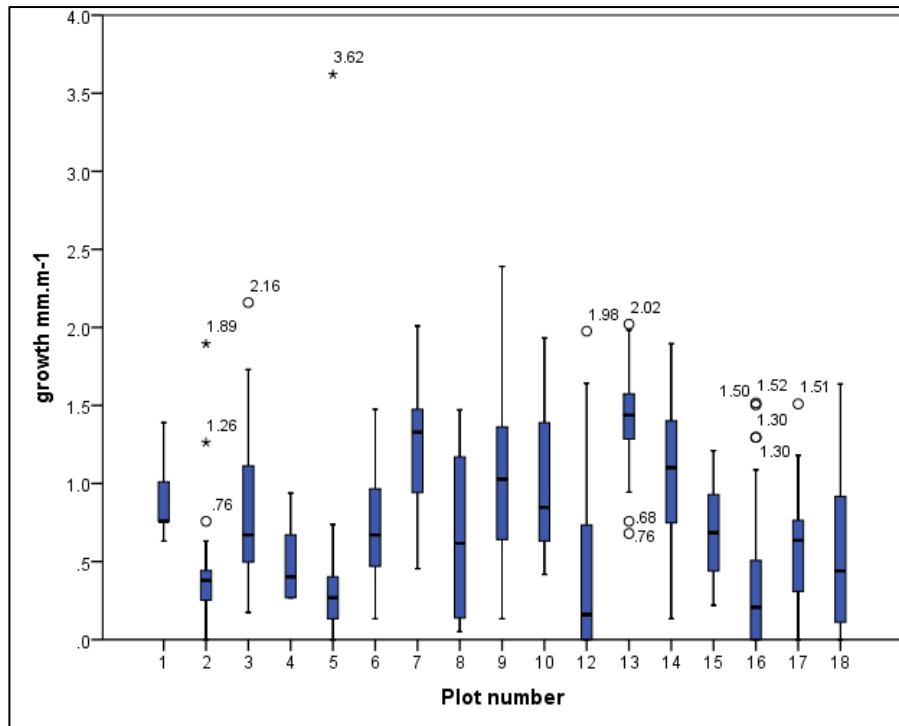


Fig 3.14. Distribution of growth within and between sites for the Outside Bay Sample Round 1

3.3.7.3 Outside Bay SR2 (April, 2015)

A one-way ANOVA was conducted to test if growth rates between plots within the Outside Bay and sample round 2 (SR2) were different. There was a significant effect of plot on growth rate at the $p < .05$ level for the three conditions ($F_{13, 134} = 6.9$, $p < 0.001$). Post hoc comparisons using the Tukey HSD indicated that plot 14 was significantly different to all other plots and plot 9 was significantly different to plots 10, 14 and 17. All other plots growth rates did not differ significantly from each other. Site 13, which achieved highest growth in the SR1, was not searched in SR2 as the plot marker was missing. Plot 14 achieved highest growth ($M = 2.08$, $SD = 0.3$) with 10 having the lowest growth ($M = 0.67$, $SD = 0.57$). Site 16 which had the lowest growth in SR1 had the second lowest growth ($M = 0.93$, $SD = 0.3$) in SR2.

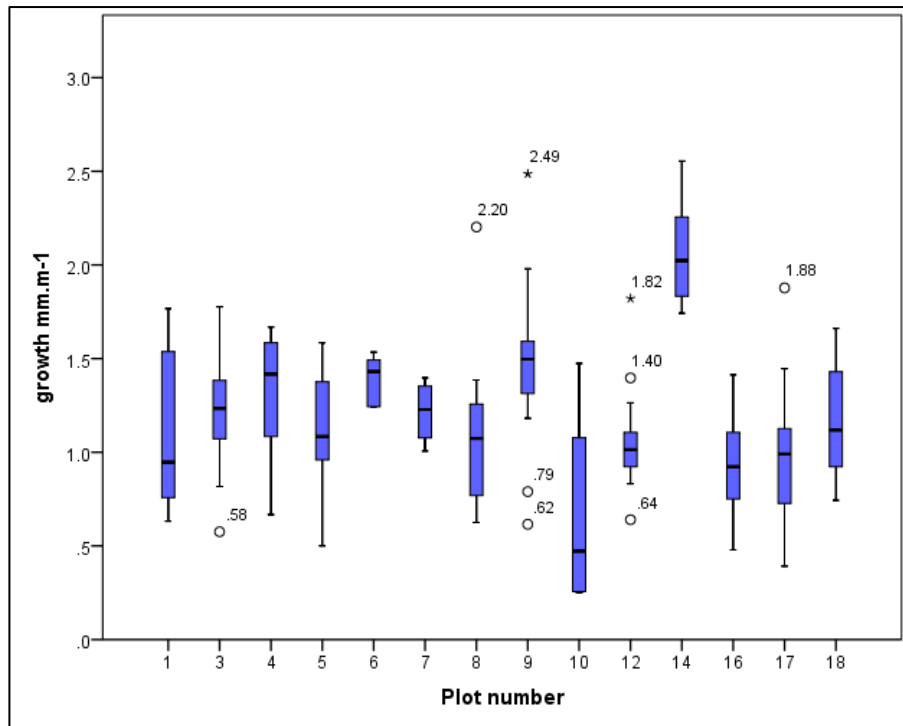


Figure 3.15. Distribution of growth within and between sites for the Outside Bay Sample Round 2

3.3.7.4 Inside Bay: Sample Round One and Two

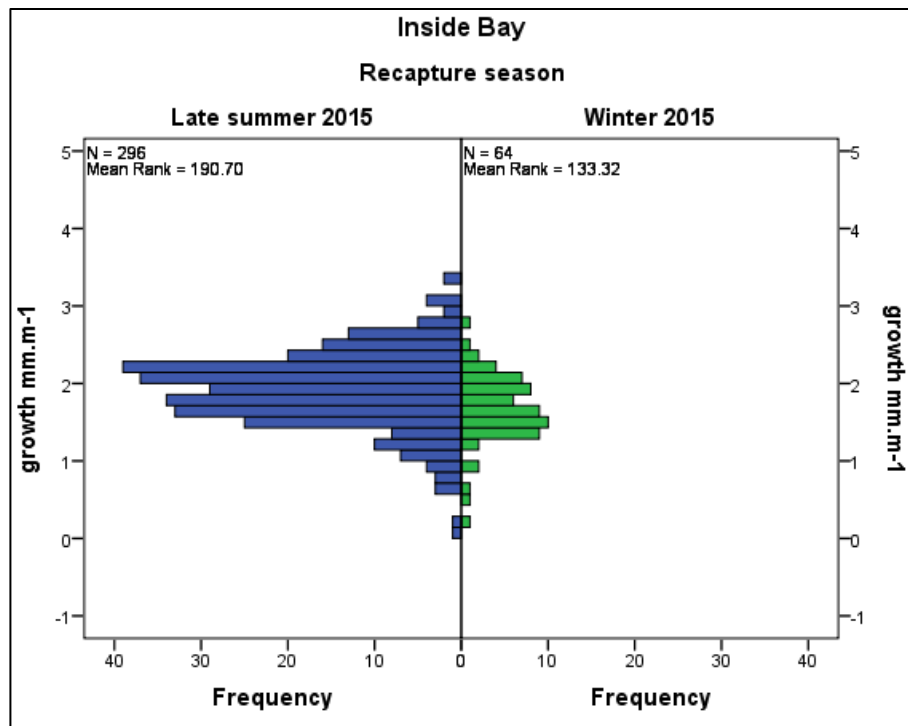


Fig 3.16. Frequency distribution of growth per month between the two sample periods before and during the winter months for the Inside Bay habitat

3.3.7.5 Inside Bay SR1 (March, 2015)

A one-way ANOVA was conducted to test if growth rates between plots within Inside Bay and SR1 were different. There was a significant effect of plot on growth rate at the $p < 0.05$ level for the three conditions ($F_{12, 283} = 4.93$, $p < 0.001$). Post hoc comparisons using the Tukey HSD test indicated that plot 24 was significantly different to plots 21, 25, 28, 32, 33 and 34. All other sites growths did not differ significantly. Plot 24 achieved the highest growth ($M = 2.27$, $SD = 0.42$) with plot 34 with the lowest growth ($M = 1.6$, $SD = 0.58$).

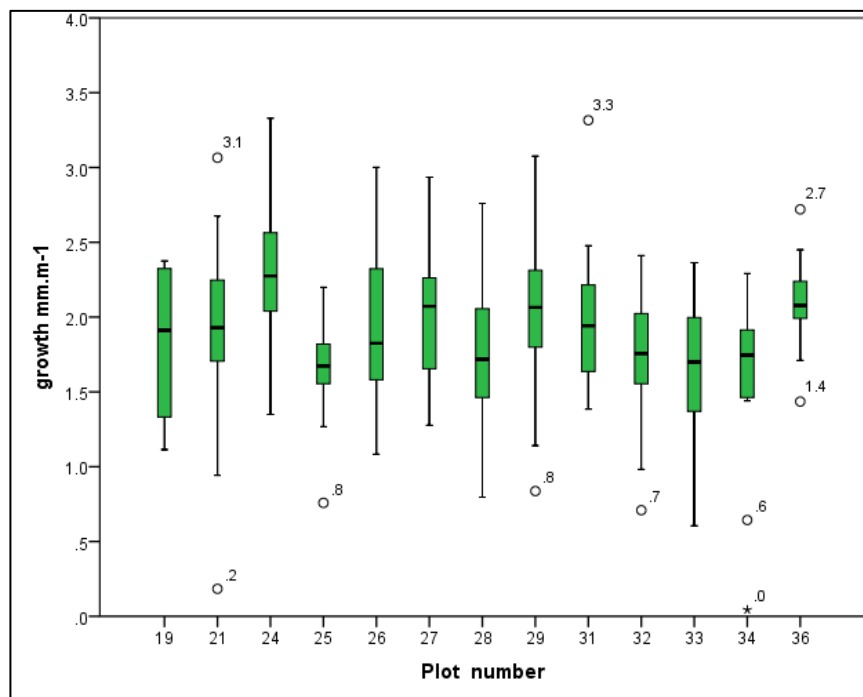


Fig 3.17. Distribution of growth within and between sites for the Inside Bay Sample Round 1

3.3.7.6 Inside bay SR2 (July, 2015)

A one-way ANOVA was conducted to test if growth rates between plots within Inside bay and SR2 were different. There was a significant effect of plot on growth rate at the $p < 0.05$ level for the three conditions ($F_{6, 56} = 3.46$, $p = 0.006$). Post hoc comparisons using the Games-Howell (unequal variances) test indicated that plots 28, 34 and 35 were significantly different from each other. Plot 28 achieved the highest growth ($M = 2.07$, $SD = 0.005$) with plot 34 again with the lowest growth ($M = 1.25$, $SD = 0.6$). Important to note that sample size was small for all plots except 35.

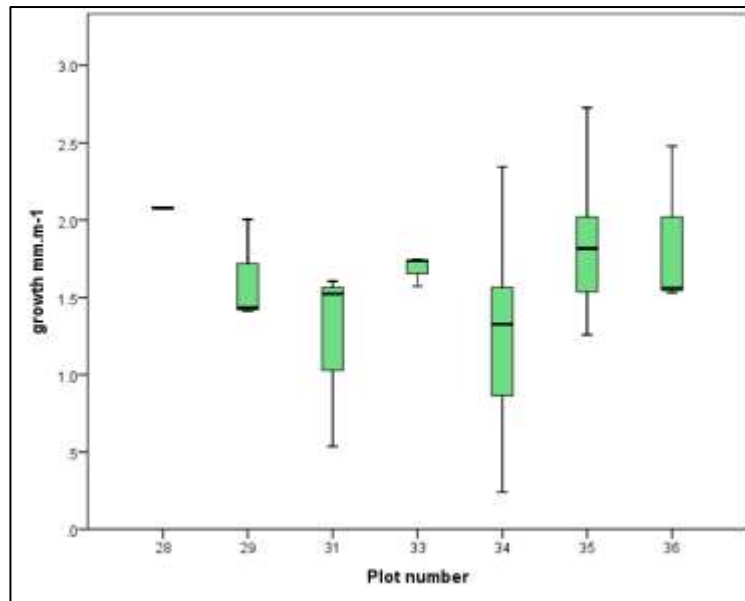


Fig 3.18. Distribution of growth within and between sites for the Inside Bay sampling Round 2

3.3.8 Factors influencing growth

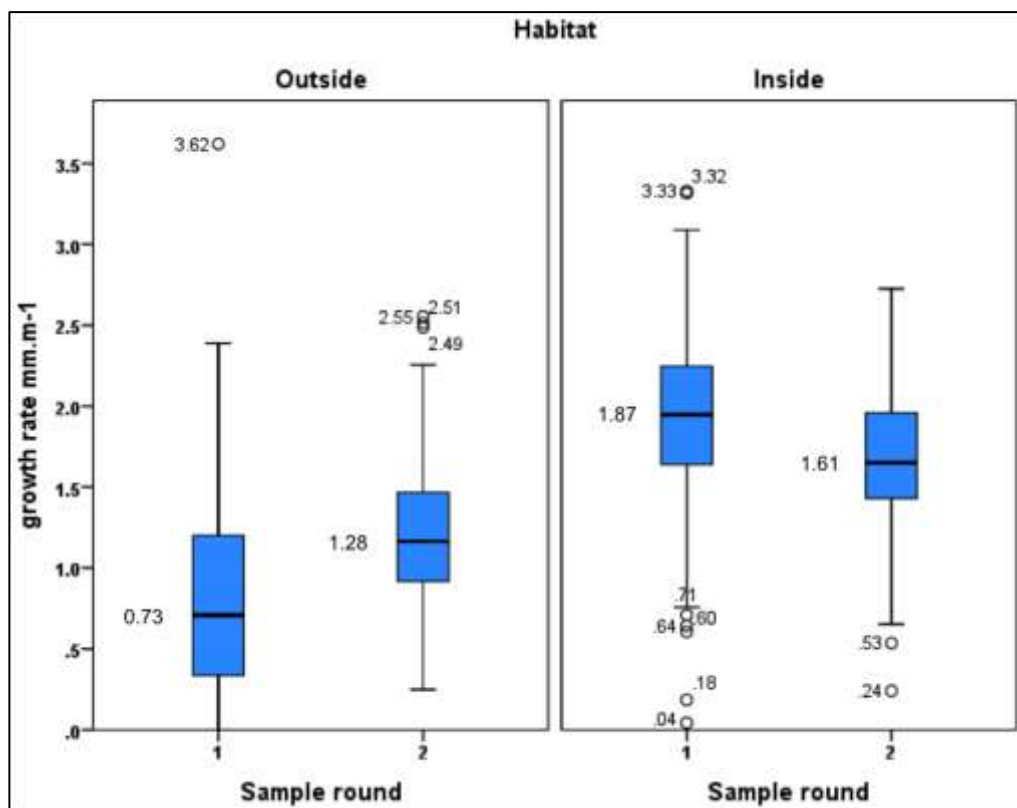


Fig 3.19. Pooled growth for each habitat and sample period. The growth presented is the estimated marginal means from the model output. The Outside Bay displayed higher growth in the second sample period, contrasting to the inside bay which showed a decline in growth rate in the second sample period, a result of seasonally variable growth.

The Outside Bay recorded an estimated mean growth of 0.73 mm.m^{-1} after the first sampling round. The abalone were released into the water during April and retrieved during at the end of November, a duration of eight months spanning autumn, winter and spring months. The second sampling took place in April after a full year had elapsed, and the growth increased to 1.28 mm.m^{-1} . In the four months between samples, during summer, the growth rate appears to have increased exponentially. The Inside Bay had an estimated mean growth rate of 1.87 mm.m^{-1} after the first sample. These animals were released during May and retrieved at the end February, a period of nine months over winter, spring and summer. The second sampling took place during July, 13 months later and growth had declined to 1.61 mm.m^{-1} .

Table 3.8 The estimated marginal mean growth from the GLMM, which found the following parameters to influence monthly growth rate.

Parameter	Description	Growth rate mm.m^{-1}
Habitat ²	Inside Bay	1.21
	Outside Bay	1.68
Density (m^{-2})	10	1.3
	20	1.54
	40	1.27
Seed size	Small (40mm)	1.46
	Large (53mm)	1.29

The global model indicated habitat, density, seed size and sample period each had a significant effect on growth rate. Growth rates were an average of $0.34 \pm 12 \text{ mm.m}^{-1}$ (95% CI: -0.581, - 0.101) higher inside compared to outside the bay ($t_{1, 1091} = -2.79$, $p = 0.005$). Growth rates were $0.03 \pm 0.11 \text{ mm.m}^{-1}$ (95% CI: -0.19, 0.25) higher on plots seeded with a density of 100 abalone ($t_{2, 1091} = 0.25$, $p = 0.8$) although not significant and plots seeded with 200 abalone ($t_{2, 1091} = 2.64$, $p = 0.008$) compared to 400 abalone seeded. The smaller seed size had a $0.17 \pm 0.08 \text{ mm.m}^{-1}$ higher growth rate than the larger seed size ($t_{1, 1091} = -1.98$, $p = 0.047$). Growth rates inside the bay were an average $0.26 \pm 0.09 \text{ mm.m}^{-1}$ (95% CI: 0.08, - 0.45) higher in Sample Round 1 ($t_{2, 1091} = 2.8$, $p = 0.005$) than Sample Round 2. Outside the bay growth rates were $0.55 \pm 0.04 \text{ mm.m}^{-1}$ (95% CI: -0.63, -0.46) higher in sample round 2 ($t_{1, 1091} = -12.45$, $p < 0.001$).

² Growth rates here were calculated using seed collected after a year at sea to account for seasonally variable growth, it varies to the estimated marginal means produced by the model output by a small margin (0.07mm).

In summary, the shallow Inside Bay habitat achieved much higher growth rates than the deeper habitat at Outside Bay. Densities on plots of 100 and 200 abalone had better growth rates than plots with 400 abalone, although by a small margin. Small seed size had higher growth rates than large seed size, but again by a small margin. The time of year when sampling occurred had a significant impact on growth outcome. The winter period slowed growth, while the summer saw increased growth rates.

3.4 DISCUSSION

The results provide insights into the relative importance of key factors governing the survival and growth of *H. midae* at the study site at Cape Recife within the ranching zone. In summary, release density had no significant impact on the growth or survival probably due to the abalones' ability to relocate if cryptic space became limited in the immediate release area. The smaller seed (40mm) exhibited a greater survival and slightly faster growth than larger seed (53mm). Survival between the Inside and Outside Bay was not significantly different, however large variation was evident within habitats, likely a result of microhabitats (De Waal et al., 2003) and/or site-specific predation. Growth was influenced by site, plot and season; with shallow water habitat (Inside Bay) displaying faster average growth rates than the deeper water habitat (Outside Bay). Diver efficiency was shown to influence retrievals, and a second sample round to reduce human bias on the experimental outcome was undertaken.

3.4.1 Survival estimates

Estimates regarding the survival of seeded abalone are notoriously difficult to achieve and very variable (McCormick et al., 1994). The present survival estimates are compared to similar studies from South Africa and abroad. The mean retrieval of 17% (range 4 – 42%) recorded after a minimum eight to nine months post release is within the range of reported seed returns in South Africa (Sweijd et al., 1998; De Waal, 2002; Godfrey, 2003). Other seeding experiments in South Africa have varied geographically and stochastically in time making it difficult to make direct comparisons. On the Namaqualand coast, an area beyond the natural distribution range of *H. midae*, minimum survival rates of approximately 30% six months' post release were obtained for seed of 8 – 15mm (Sweijd et al., 1998), while another study in a similar area achieved lower survival of 0 – 13% between 3.5 – 10.5 months for seed of 8 – 18 mm (De Waal, 2002). The East Coast of South Africa, in the range of the current experimental area, yielded mean returns of 53% for seed of 25mm 1 – 2 months' post release in sheltered sites, larger surface releases in open ocean areas gave mean returns of 32% 3 – 4 months' post release (Godfrey, 2003). Globally the seeding of hatchery-reared abalone onto natural substrates has achieved varying degrees of success. Mean survival rates 1 – 2 years after release for *H. rubra* ranged from 0 – 4%, which compared poorly with rate of 12 – 40% expected of their wild counterparts (Heasman et al.,

2004). *H. rufescens* of 45 and 75 mm shell length showed low survival of only 1% a year (Tegner & Butler, 1985). Survival for *H. laevigata* at age 5 ranged from 6 – 20% with an average of 13% (Hart et al., 2013). *H. d. discus* yielded 12 – 51% survival in 1980 – 1985-year class (Kojima, 1995). Other attempts to determine out planting success have opted for artificial substrates in hope to attain more accurate recapture results (Dixon et al., 2006; James et al., 2007; Roberts et al., 2007).

Survival estimates in this study are presented as retrievals or minimum survival rates, as it is unlikely that every seed released that survived until the time of sampling was retrieved. The second search to collect any potential seed remaining on the sites yielded significantly reduced seed returns, placing confidence that most seed within the area searched had been retrieved. However, obtaining reliable minimum survival estimates after eight and nine months at sea was confounded by the four months between the first and second sampling periods when mortality is unaccounted. Furthermore, disturbance of a habitat during the first sampling round could have caused some abalone to emigrate out of the sample area. Reliable estimates for juvenile mortality rates measured in previous studies could be used as a surrogate for the four months between sample periods, however very limited work has been conducted on mortality rates for juvenile *H. midae* in the wild. A study by Proudfoot (2006), estimated mortality between 0.24 – 3.6 year⁻¹, which at the lowest end is comparable to other abalone species but at its upper limit mortality was found to be three times that for other abalone species (Shepherd & Breen, 1992). The large range in estimated juvenile mortality makes prediction of potential mortality between sample rounds unreliable. Empty shells of hatchery reared seed were also collected in an attempt establish the extent of actual survival but these collections were very low. At best collecting empty shells gives a crude estimate of minimum mortality (McCormick et al., 1994). This method has proved unreliable with some studies retrieving very low to no shells (Sweijdt et al., 1998; Goodsell et al., 2006), which has been attributed to predators crushing and moving shells (Schiel & Weldon, 1987; Emmett & Jamieson, 1988), and swell washing shells away (Dixon et al., 2006). The disintegration rate of empty shells was calculated by Shepherd (1998) to have a half-life of 48 days, which would mean very low returns by the time sites were searched in this study. Other important factors impacting the retrievals were the complexity of the habitat searched, cryptic nature of juvenile abalone, emigration, difficult search conditions in wave exposed sub-tidal habitat, and diver experience. Explored in more detail are density, seed size, habitat, predators and diver on impacting survival or retrievals of seeded *H. midae*.

3.4.2 Factors influencing survival estimates

3.4.2.1 Density and Migration

Contrary to my hypotheses, all three density treatments did not significantly affect the survival of seeded abalone. A similar finding in another study was that survival was not influenced by whether seed was released in a diffuse or concentrated array (Chick et al., 2013). In theory, seeding an area at high densities leads to higher levels of competition as cryptic space and food may become limiting (McAvaney et al., 2004; Dixon & Day, 2004). The higher the levels of competition for these limiting resources, the more likely that juvenile abalone will have to move in order to survive. If they do not move, then they are at risk of being exposed to the elements making them vulnerable to predation or being lifted and displaced or killed by sea swells. In a closed system that is saturated with juvenile seed, density would affect both survival and growth (Huchette et al., 2003). In this study, there was no limiting factor preventing abalone from moving outside the core release area. It is speculated that seeding at high densities results in greater dispersal from the release point as abalone have to travel further to find suitable cover (De Waal et al., 2003). Upon release, it was visually evident that sites seeded with large abalone at the highest density were highly concentrated, with space being a limiting factor when compared with sites harbouring low densities and small abalone.

The follow up count survey took place three months' post release and showed that 630 seeded abalone (61%) were observed within the release site (0m to 1.8m) and 410 seeded abalone (39%) were found just beyond the fringe (1.8m to 3.6m).

During the exhaustive searches, abalone were collected within the initial release site (0m to 1.8m) as well as beyond the site fringe (1.8m to 3.6m), but no distinction was made between the core release area and beyond site fringe in collections. In some cases, abalone were found up to 6 m from the site's centre point but this was uncommon. Anecdotal evidence from observations during searches indicated that most abalone were retrieved within the core release area or just on the site fringe. Selected sites comprised cracks, crevices, boulders and food algae, which in combination provided suitable habitat from which abalone were less likely to move very far (De Waal & Cook, 2001a). In contrast, stress and unsuitable habitat are known to induce movement of abalone (Emmet & Jamieson, 1989; Kojima, 1995; Werner et al., 1995). A study conducted in close proximity to our study site found that 13% of the seed had moved out of the initial release area after 12 days and 25% after 40 days, but these were all recovered within one meter of the release point (Godfrey, 2003).

This experiment sought to establish the most appropriate release densities of abalone at the study site that would provide the most favourable economic returns within natural limits (Hart et al., 2013b). However, the release densities of seed on plots are confounded firstly by changing habitat niches over small spatial scales and secondly the ability of abalone to move when space is limited (De Waal et al., 2003; Prince, 2003). From visual observation it was apparent that plots within close proximity to each other provided varying levels of refuge, which is likely to influence the density of abalone on a site, but the level of refuge was not measured. My findings suggest that there is no release density specific to a habitat area but rather, release densities need to be based on the amount of refuge space offered area-by-area within a specific habitat and this is a factor which requires further investigation.

The results suggest that migration plays an important role in mitigating potentially negative effects from density on abalone competition and survival. Although there is anecdotal evidence that most abalone were collected within the total search area (0 - 3.6m), the extent of the emigration is not well documented in this study and potential existed for abalone to move beyond the 3.6m search radius. This unknown rate of more expansive migration does make it challenging to then accurately measure survival (McCormick et al., 1994).

While many studies have noted varying degrees of migration following release, Shepherd (1986) found that movement was a function of substrate type with little migration and high survival (57%) noted at sites with numerous crevices and high migration and low apparent survival (18%) at sites without crevices. Similarly a study using outplanted northern abalone (*Haliotis kamtschatkana*) found that sites with complex substrate had significantly higher seed retention and lower emigration than the control sites with less complex structure (Read et al., 2013). The lack of food has also been found to significantly induce migration in *H. tuberculata* and *H. discus hannii* (Werner et al., 1995). The level of emigration is therefore likely to be highly dependent on the suitability of the microhabitat with high emigration in areas that have unsuitable microhabitats and low emigration in good microhabitats.

3.4.2.2 Seed size

Smaller seed size of 40 mm achieved greater survival than the larger seed of 53mm; which is contrary to many studies where an increase in seed size is met with an increase in survival (Zhao et al., 1981; Saito, 1984; Inoue, 1976 cited in Masuda & Tsukamoto, 1998; Sweijid et al., 1998; De Waal & Cook, 2001a; Roberts et al., 2007). However, in these studies the large

seed range was between 25 and 40mm and it was found that increasing seed size above 30mm yielded no improved survival (Inoue, 1976 cited in McCormick et al., 1994). The observation that smaller seed performed better than larger seed could possibly be related to the following processes: firstly, small seed have a better chance of seeking shelter and cryptic cover in small spaces, while larger seed are at an awkward stage of becoming emergent (Branch pers. comm., 2016). Secondly, larger seed may undergo habituation during their time in grow-out on an abalone farm making adaptation to a new environment difficult. This is supported by the observations of Hansen et al. (2014) who found that older hatchery-reared abalone were significantly less responsive to shadows, nearby movement and contact with inert objects than younger abalone and therefore more vulnerable to predation. Lastly, the reduced detection by divers of larger seed than smaller seed is likely a result of greater migration/ mobility of the large seed (Shepherd, 1986; Werner et al., 1995).

Size at release plays an important role in the economics of large-scale releases. The larger the seed size, the higher the cost of production due to increased farming costs (Schiel, 1993) and thus increased survival with increasing seed size must offset the increased cost of production. In this study, we showed that seed size larger than 40mm provided no additional benefit because the smaller seed achieved higher retrievals. However, it is possible that larger seed survival is higher than reported as they potentially exhibited higher mobility and thus reduced detection during destructive sampling.

3.4.2.3 Habitat

Habitat type influences the survival of abalone (Kojima, 1981; Shepherd, 1986b; Roberts et al., 2007). Again, contrary to our hypothesis, survival did not differ significantly between the two different habitat types. Similar retrievals were obtained in both the Inside and Outside Bay. We predicted that the shallow Inside Bay plots were more suitable for habitation of juvenile abalone than the deeper Outside Bay sites. Shallow sites had a high degree of food availability (backed up by faster growth rates) as well as higher presence of cryptic cover. Furthermore, the wild abalone densities were more than double that on the Inside Bay than the Outside Bay – an indicator of the appropriateness of the habitat to support abalone (Hart et al., 2013a). During sampling, the conditions differed between the two habitats in that the shallower sites were subjected to small breaking waves, strong surges and greater habitat structural complexity compared to the deeper sites and thus, may have influenced

diver retrieval rate. This is one area to further consider as it is possible that the lower than expected returns for this site was a product of catchability and not suitability of habitat type.

Although the two broad habitat types showed no difference in survival, there was a high degree of variation in survival across plots ranging from 5-34% on the Outside Bay and 4-42% on the Inside Bay. The changing habitat characteristics across sites are known to cause variation in survival (Schiel, 1993; Roberts et al., 2007). Selecting the most appropriate areas is challenged by the highly specific requirements of some species (Munroe & Bell, 1997). Sites in the study, within each habitat, were distanced anywhere from 10 m – 390 m apart. These sites varied in regard to structure, seaweed abundance, crevice space and under boulder refuge. Within a habitat our sites could be categorized into different ‘microhabitats’ where the physical and biological interactions have been suggested to play an important role at scales of cm’s to 10’s of meters (Sweijd et al., 1998; De Waal et al., 2003). The suitability of the substratum is known to influence the distribution of *H. midae* (Newman, 1966; Newman, 1969; Tarr, 1995) and at Cape Recife the heterogeneous nature of the substrate is known to cause patchiness of the abalone stocks (Wood, 1993; Godfrey, 2003). It is likely that this variation of substrate type and microhabitat is responsible for the range in survivals from the different sites in a habitat as some areas are suitable for supporting abalone habitation and other areas/ sites are not. Although microhabitat variability is likely to be a major cause of variation in seed survival, in this study variability of survival was also linked with other factors such as sampling technique (sample rounds, diver, GPS mark and catchability). It was beyond the scope of this study to quantify site-specific microhabitat characteristics, but these should be further investigated to inform which characteristics enhance survival.

3.4.2.4 Predators

Octopus (*Octopus vulgaris*) are a known abalone predator and have the potential to significantly impact seed survival (Okei, 1999). Abalone survival was far less on sites that had resident octopuses than sites with no observed octopuses, however, the result was not statistically significant due to the small sample size of observed octopuses and high variability. Many seeded shells were collected at the entrance of the octopus caves and there was one account during retrievals where a seeded abalone was seen being consumed by an octopus. In False Bay, South Africa, *H. midae* is considered an important prey species in the diet of *O. vulgaris* making up 22% of their diet (Smith, 2003). From shell middens, it

was established that the mean abalone shell lengths consumed by small, median and large octopus were 53 mm, 73 mm and 86 mm respectively, interestingly no middens of abalone shells <30mm length were found (Smith, 2003). This is likely due to small shells washing away or due to cryptic behaviour of abalone < 30 mm. Interestingly targeted predation of octopus on larger seed could be a potential reason for lower survival rates reported for the larger seed in the experiment than the smaller seed. Octopuses are known to bore holes into the shells of abalone (Nixon & Maconnachie, 1988; Kojima, 1992; Okei, 1999). All 236 (3.3%) of shells collected from sites in this study showed no signs of boreholes possibly due to the thicker shells of *H. midae* and ability of the octopus to overpower juvenile *H. midae* (Ambrose et al., 1998; Smith, 2003). The degree of predation by octopuses in the study is unknown, however predation of hatchery-reared seed was observed during release and retrieval. Further anecdotal evidence of low seed returns with resident octopuses on sites suggests that they can potentially influence survival. Other known predators observed during release include fish species, notably, Fransmadam (*Boopsoidea Inornata*) and Black Tail (*Diplodus capensis*). Divers were vigilant in ensuring that all abalone were seeded face down and attached to the substrate to eliminate mortalities from predator fish during the immediate release period. The degree to which abalone were responsive and active was crucial in avoiding being eaten or nipped by fish.

Mortality of hatchery-reared abalone from various predators upon release was observed but not quantified and is a challenge that faces large-scale releases of abalone as the impact of predation on survival over the long term is unknown. What has been established by other studies is that hatchery-reared abalone behave differently to that of wild abalone in important ways that relate to predator avoidance (Schiel & Welden, 1987; Straus & Friedman, 2009; Hansen et al., 2014). The increased vulnerability of hatchery seed to predation (McCormick et al., 1994; Munroe & Bell, 1997) is likely a result of a lack of exposure to predators and/or inadvertent selection for maladaptive phenotypes (Jackson & Brown, 2011 cited in Hansen et al., 2014).

3.4.2.5 Diver experience

Divers are known to exert varying levels of searching efficiency for abalone (Prince & Ford, 1985). The effect of diver experience on searching efficiency was explored and it was found that there was no significant difference between divers with similar diving experience and qualifications. However, the most qualified diver and lead scientist on the project with more

than 150 hours of diving experience achieved significantly higher seed returns. In order to reduce the effect of diver on the outcome of the experiment, different divers were used to search different sites four months after the first sampling occurred. This increased the search effort for seeded abalone and reduced the effect of bias according to experience and effort. Although there were four sites that had high seed returns on the second sample, the majority of sites had significantly reduced returns in the second sample. A study by Dixon et al. (2006) found that the best searching efficiency by divers was 75% after the first search whereas the two follow up searches suggested a maximum searching efficiency of 96%. An important factor to take into account in this study is that diver efficiency is likely to vary between sites according to habitat characteristics, swell and algal cover as found by Shepherd (1985). A possible reason for missing juvenile abalone in the first sample round despite exhaustive searches is the cryptic nature and rapid escape responses of juvenile abalone.

3.4.2.6 Growth rate

The growth rate of abalone can vary greatly, being influenced by local microhabitat differences (McShane & Naylor, 1995), geographic range effects (Tarr, 1993; Wood, 1993; Proudfoot, 2008), seasonal variation in temperature (Poore, 1972; Leighton et al., 1981; Shepherd & Hern, 1983; Naylor et al., 2006), food availability (Shepherd & Hern, 1983; McShane et al., 1988; Tegner et al., 1992; Tarr, 1995) and water movement (Shepherd, 1973; McShane et al., 1988). In the experiment, habitat and season significantly affected growth rate. Abalone grew faster in shallow water sites (1 m – 2.5 m) compared to the deeper water areas (4 m – 7 m). The growth rate increased over the summer and slowed during the winter period. The smaller seed size obtained a faster growth rate than the larger seed. Plots seeded with lower densities of 10 and 20 abalone m⁻² had slightly higher growth rates than sites seeded with 40-abalone m⁻², although this result was not significant and requires further exploration.

The shallow sites yielded a 30 percent faster growth rate after a period of 12 months than the deeper sites. This is likely due to the quantity and quality of food and its spatial patchiness (Day & Fleming, 1992). Furthermore, the bay circulation of the shallow sites regularly results in higher aggregations of drift seaweed than the deeper water sites (Britz pers. comm., 2016). It has been suggested that greater incremental growth found in more exposed habitats compared to sheltered habitats results from food availability (Shepherd

1973; Sainsbury, 1982; Shepherd & Hearn 1983; McShane et al., 1988). The seasonal difference in growth rate was picked up as a product of the four-month time lapse between sample rounds. It found that growth increased over the summer months in the Outside Bay and declined over the winter months for the Inside Bay. A seasonal fluctuation in growth rates for *H. midae* has been observed by Proudfoot (2006) and Sweijd et al. (1998), where growth declined in the winter period between April and September and increased in the summer. Similarly, growth for *H. Iris* in New Zealand was higher in the summer and spring months compared to autumn and winter months (Roberts et al., 2007).

The growth rate varied significantly between sites in the deep habitat after eight months and less so after 12 months. In comparison, growth rates varied less between sites in the shallow habitat with only one site differing significantly from the rest. In our study, the average growth rate after a period of 12 months' post release ranged on average between 11 and 25 mm.yr⁻¹ for all sites. The growth rate for individuals on the deep sites ranged between 2.9 and 30.6 mm yr⁻¹ with a mean of 15 mm yr⁻¹. In comparison, for individuals on shallow sites ranged between 3 and 33 mm yr⁻¹ with a mean of 20 mm.yr⁻¹. To put this in perspective, similar studies in the Eastern Cape obtained growth rates of 25mm yr⁻¹ at Great Fish Point and Mgwalana (Wood, 1993), 19.2 mm yr⁻¹ at Cape Recife (Godfrey, 2003) and 24.25 mm yr⁻¹ at Bird Island (Tarr, 1993). Godfrey (2003) also found high variation in growth rates at Cape Recife over sites in close proximity to one another ranging between 5.4 and 29.2 mm y⁻¹.

Growth was found to be significantly variable between sites small distances apart which is typical of the Haliotids, due largely to variations in food type and availability (Day & Flemming, 1992; McShane & Naylor, 1995; Tarr, 1995). Sites 5, 12, 16, 17 and 18 all had abalone on their sites after eight months at large that displayed zero growth rates. Sites 16, 17 and 18 were grouped short distances apart and displayed very similar habitat characteristics. These sites were all seeded with large (53mm) seed at high density of 40 m⁻². Sites were situated upon raised segments of reef, which were mostly surrounded by sand gullies. They were dominated by finely forked coralline species, mostly *Jania verrucosa*, impregnated with lime to deter grazers (Branch et al., 2008). The similar habitat characteristics, along with the lack of appropriate food possibly is a likely explanation for the poor or absent growth found on these sites.

Shallow water areas with higher wave energy and greater food abundance yielded higher growth rates than deeper water sites, which is an important result affecting the economics of the large-scale releases for commercial scale ranching.

3.5 Conclusion

Our study provides robust evidence for the effects of habitat, seed size, density and season on the growth and survival rates of cultured *H. midae* once released at Cape Recife. The external influence of diver bias was addressed for by conducting additional searches on sites. There are however a number of factors that need further consideration. The effect of predators on survival was not measured but merely observed and it is unknown what the immediate post-release and long-term predation rates on seeded abalone are. Our study assumed that most seed would remain within the released area or in close proximity due to the favourable habitat selected. However, there was nothing inhibiting seeded abalone migrating beyond the 3.6 m search boundary, and the extent or level of this migration remains largely unknown. Future studies directed at measuring rates of movement following release and over time would provide a good estimate as to the quantity of seed that potentially went undetected in this study.

It is recommended that sampling be repeated in the future, at time intervals of 24 hours, one week and one-month post seeding to collect any shells on sites. This would allow better understanding about the amount of abalone that perished within the initial settling period when most mortality is assumed to take place. Practical limitations of surveying 36 sites in a short time frame with minimal days conducive to diving inhibited doing these follow up surveys. Lastly, the catchability of seed was influenced by the complex habitat and difficult surf conditions during collections – this is likely to influence the minimum survival estimates presented. This experiment is one of the most comprehensive to date in South Africa, it has demonstrated the potential for stock enhancement on a small-scale and the parameters that are likely to influence the success of a ranching program.

CHAPTER 4

Large-scale seed releases and harvesting model

4.1 Introduction

This chapter describes the development of commercial seeding at Cape Recife and the long-term monitoring of these large-scale releases. Lidomix (Pty) Ltd. have undertaken the largest known commercial seeding operation in South Africa to date, having released 1.4 million hatchery-reared abalone. This equates to 30 tons, ranging in size from 27 – 84 mm shell length, which were seeded at over 160 natural reef sites at Cape Recife in the ranching zone EC1. The seed releases took place over 2.5 years between June 2014 and December 2016 as part of a pilot commercial abalone ranching project. From a logistical and financial point of view, this has been an enormous undertaking for a private entity.

Historically, attempts at large-scale stock enhancement have failed or been inconclusive, partly due to the lack of comprehensive analyses of seeding success, which is why appropriate monitoring procedures are vital during implementation (Laurec, 1999). A fundamental component of this research was to critically evaluate the effectiveness of the large-scale abalone releases, identifying those factors which were influencing its success, and determining if ranching could be an economically viable operation. An innovative approach was required to assess, in a robust manner, the survivorship of abalone. This was done by ensuring a standard seeding strategy was adopted across all release sites. A variety of sampling methods were used to understand post-seeding behaviour of hatchery-reared abalone as well as to gauge the level of mortality/ and or survivorship occurring over a long period of time. Not all commercial sites could be monitored due to the scale of the operation, rather a representative selection of sites were chosen based on seed size groups and habitat areas seeded in similar swell conditions.

The main aim of this study was to develop a methodology applicable to large-scale releases and implement an accurate monitoring program to determine the long-term survival of abalone seeded *en masse*. This would be used to create an economic harvesting model for abalone ranching. The objectives of this study sought to (1) investigate mortality rate over the long-term in relation to size and density of seeded abalone as well as densities of wild abalone; (2) investigate the presence, behaviour and potential effect of predators on mass

releases through video evidence and shell collections immediately after release; (3) determine the behaviour and migration of abalone post release using time-lapse analyses; and lastly, (4) determine the wild abalone densities at each of the monitoring sites.

4.2 Methods

4.2.1 Study Site

The designated abalone ranching zone EC1 is located in close proximity to the city of Port Elizabeth in the Eastern Cape province, South Africa. It extends to seaward in a southeast direction from the Cape Recife lighthouse ($34^{\circ} 2' 0,33''$ S; $25^{\circ} 42' 18,43''$ E) eastwards towards the Skoenmakerskop Marine Protected Area (MPA) ($34^{\circ} 2' 46,05''$ S; $25^{\circ} 32' 33,39''$ E) covering approximately an 18 km section of coastline (Gov. gazette 33470) (See Figure 4.1). Despite the extensive habitat area found throughout the ranching zone, seeding has been centered almost exclusively at Cape Recife in the depth range of 4 – 10 m (Figure 4.1). Sites were selected between Cape Recife and the offshore Thunderbolt reef. Areas were chosen if they could offer high abundance of seaweed cover, ample crevice space, presence of wild abalone and presence of urchins (Appendix 3.2). These were habitat attributes deemed necessary for the survival of abalone.



Fig 4.1 The yellow boundary showing the extent of the abalone ranching area EC1 situated on the outskirts of Port Elizabeth in the Eastern Cape province of South Africa.

4.2.2 Commercial Seeding Protocols

A careful and methodical sampling approach for the large-scale releases was adopted to ensure that a reliable monitoring program could be established. The process for preparation of abalone for transport and the methods applied for release onto the reef areas is described below in detail.

4.2.2.1 Seed

Wild Coast Abalone (Pty) Ltd supplied abalone seed used in the large-scale releases. Hatchery seed ranged from 27 – 84 mm in length and 5 – 155 g in weight (Table 4.1). The initial seeding phase released larger animals and gradually reduced sizes to a more current and standard 37 mm (12.5 g) animals. A conversion formula of $y = 0.0002x^{3.0617}$ was used to convert weight in grams to shell length.

Table 4.1 Summary data for large-scale abalone releases on 24 sites sampled using quadrats and shell collections.

Site	Quadrat count	Shell collection	Tot seed	Tot weight (kg)	Ave size (g)	Size range (g)	Ave size (mm)	Size range (mm)
5	Yes	No	12323	152	12	6 – 15	37	29 – 39
6	Yes	No	12536	152	12	6 – 15	36	29 – 39
7	Yes	No	12099	152	13	6 – 20	37	29 – 43
9	No	Yes	2689	333	124	100 – 155	78	73 – 84
10	Yes	Yes	2931	333	114	85 – 133	76	69 – 80
13	Yes	Yes	2481	242	98	85 – 140	72	69 – 81
14	No	Yes	1764	243	138	115 – 155	81	76 – 84
15	Yes	Yes	1719	243	141	115 – 155	81	76 – 84
16	Yes	Yes	1875	243	130	100 – 155	79	73 – 84
17	No	Yes	4237	293	69	50 – 60	64	58 – 62
18	Yes	Yes	5699	313	55	50 – 60	60	58 – 62
19	Yes	No	8280	162	20	5 – 25	43	27 – 46
20	Yes	No	8441	162	19	5 – 25	42	27 – 46
21	Yes	No	8410	162	19	5 – 25	42	27 – 46
26	Yes	No	13019	162	12	5 – 15	37	27 – 39
27	Yes	No	12409	163	13	5 – 15	37	27 – 39
37	Yes	No	13897	163	12	5 – 15	36	27 – 39
38	Yes	No	12996	162	12	5 – 15	37	27 – 39
39	Yes	No	12183	162	13	5 – 25	38	27 – 46
40	Yes	No	14248	163	11	5 – 15	36	27 – 39
124	No	Yes	6828	162	24	20 – 35	46	43 – 52
126	No	Yes	6479	162	25	20 – 35	46	43 – 52
140	No	Yes	5448	162	30	20 – 35	49	43 – 52
141	No	Yes	5796	162	29	20 – 35	49	43 – 52

4.2.2.2 Seed Packing and Transportation

Specific size classes of abalone were moved from the holding tanks on the farm and purged for a set period of time to empty any food contents from the gut. Abalone were then packed into mesh bags, placed inside oxygenated plastic bags, and sealed inside polystyrene boxes with two gel ice packs. The seed was then transported from the Wild Coast Abalone farm at Haga Haga to the release grounds at Cape Recife (Table 4.2b-d). On average, abalone spent 22 hours in transit from packing until release. Seed were removed from polystyrene boxes and placed in the live wells on the deck of the vessel for approximately 40 minutes. The live wells consisted of two holding tanks that continuously pumped seawater (Figure 4.2f). This allowed acclimation of the seed to the water temperature and oxygenated the gills prior to release. The abalone seed were visibly more active after this process and had a better chance of attaching to the reef once released.

4.2.2.3 Density and Seed Size

The density that abalone were seeded was determined by the different seed size classes. Abalone were grouped into discrete predetermined size categories. Habitats were graded to serve as an indicator for determining densities: a habitat rating of 'A' suggested prime habitat while 'D' indicated the absolute minimum requirements for seeding (Appendix 3.2). The higher rankings were assigned with higher densities than the lower rankings. The ranking was defined by a set of criteria based on requirements of abalone and indicators of suitable habitat. Different indicators were assigned a numerical value, which was totalled over the different requirements to give an overall score. Score ranges were assigned different habitat categories. This method provided some distinction between what may be good, acceptable and poor habitat, however it was subject to the diver's discretion. The purpose of the exercise and simplicity of the habitat assessment was for rapid determination of appropriate sites. The outcome of habitat identification has repercussions for seeding density and number of sites that need to be selected. Sites were usually selected prior to the day of seeding so that hatchery seed could be batched according to the site selected based on the habitat ranking.

4.2.2.4 Release Methods

Two types of strategies were used for the release of hatchery-reared seed: surface scattering and hand seeding. After a successful trial of surface scatter seeding at Cape Recife, this method was applied from 2014 to 2015 to all long-term monitoring sites (Figure 4.2). It involved scattering abalone from the surface onto known abalone reef areas below.

This was a simple and quick way of releasing large sums of seed. A detailed description of the manner in which sites were seeded is provided below:

- On the vessel, abalone were removed from polystyrene boxes. Oxygenated plastic bags were cut open and mesh bags containing abalone were then placed into the live well (Table 4.2f).
- A diver identified appropriate abalone habitat according to the habitat-ranking table (Appendix 3.2). This is an area that should provide refuge (crevices), abundant food and no sand. Ideally, the site would be preselected before the seed release but due to time and labour constraints, sites were often selected on the day and as a result less optimum sites were often seeded.
- A surface marker buoy was deployed (SMB) in the identified area. The diver then ensured a 15 m radius from this centre point fell within the definition of appropriate habitat. The SMB was made taut to ensure that it did not drift at an angle in the current, which would cause the seeding to be off centre. The deployment of a counter weight system has largely eliminated previous problems of SMB being off centre from the bottom. The central point was recorded by a GPS and an orange concrete marker was placed in the centre so the site could be located during follow up sampling.
- After approximately 40 minutes of soaking in the wells, abalone were placed onto the tray and pushed through the chute. In deeper water, abalone were pushed through a 6 m long perforated plastic pipe (Table 4.3e) which limited fish predation as abalone fell unhindered through the water column and in shallower water, they were scattered from the surface (Table 4.3a). However, the use of the pipe was not ideal as it was cumbersome for a diver to handle in anything but the calmest of seas.
- When abalone were released, the exact start and end times were recorded. The boat GPS tracker recorded a point every ten seconds so that an accurate estimate of the area seeded could be calculated by drawing a polygon around the points at a later stage using GIS. The boat was required to remain within approximately 10 m from the SMB so that any important variables were recorded by the diver as well as video footage of sites.

Table 4.2. Pictures showing some of the key stages in the process of the large-scale releases of seeded abalone

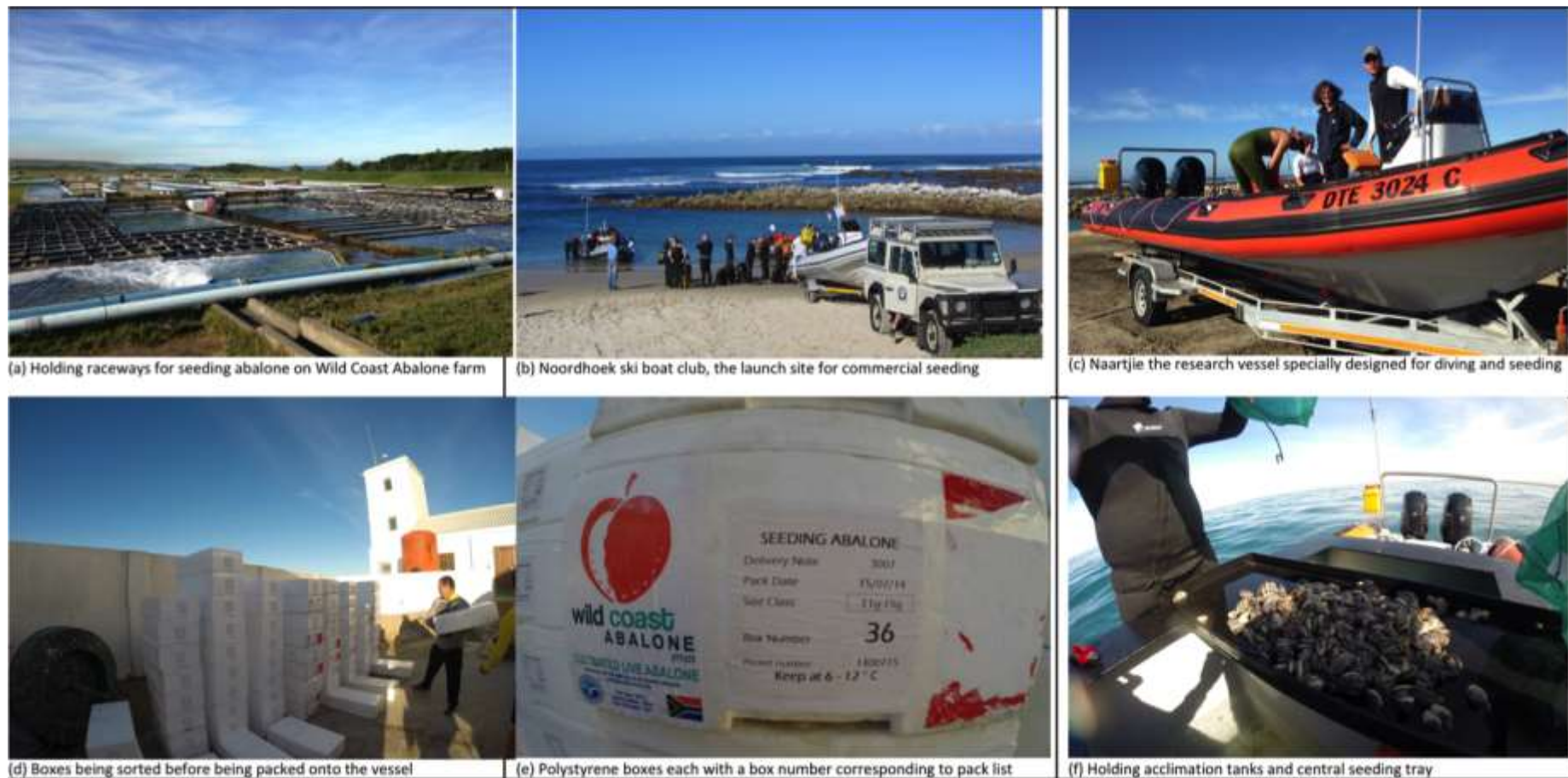


Table 4.3. Pictures showing the large-scale releases beneath the surface using a pipe from the boat and by hand from a mesh bag.



4.2.3 Experimental Design and Sampling

In order to estimate the changing density of seeded abalone on sites and ultimately calculate the mortality rate, quadrat sampling was completed for 17 sites out 160 seeded for a period of up to 666 days post release (Table 4.1). Seeded and wild abalone on release plots were counted using the quadrat sampling method multiple times post release and their densities were determined. Minimum mortality rates were calculated by collecting shells from 12 release sites over a set period of time or through exhaustive searches. Behaviours, such as migration and interaction with predators of seed post-release was filmed using time-lapse videos.

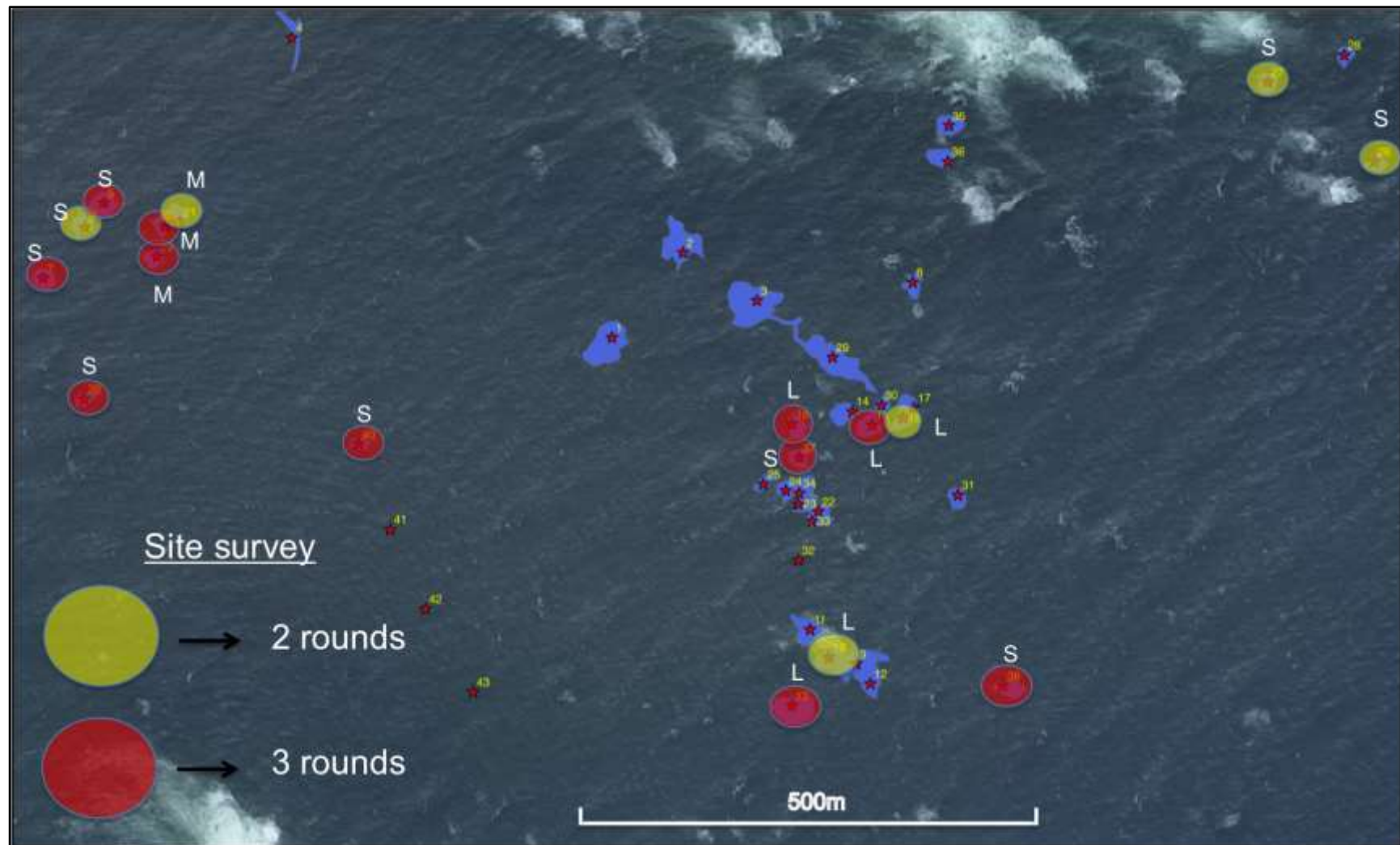


Fig 4.2. Distribution of the large-scale seeding sites undergoing long-term monitoring for three size classes of abalone (S) Small ± 37 mm, (M) Medium ± 43 mm and (L) Large ± 76 mm. Yellow areas refer to sites that were seeded and then re-sampled once more and red areas refer to sites that were seeded and re-sampled twice over varying time scales since release.

4.2.3.1 Quadrat Sampling

Quadrat sampling involved the use of two different sized quadrats depending on seeded abalone size. Smaller abalone (26 – 60 mm) were counted in 30 x 30 cm quadrats (0.09 m^2), with approximately 170 quadrats being sampled per site per sampling event. Larger abalone (69 – 84 mm) were counted in 1 x 1 m quadrats (1 m^2), with approximately 77 quadrats sampled per site per sampling event. In total the dive time spent conducting quadrat counts was approximately 150 hours, culminating in almost 7000 quadrat counts. The smaller quadrats (30 x 30 cm) were used for the smaller abalone due to the higher seed density and the cryptic nature of juvenile abalone, which required finer scale searching in cracks, beneath small boulders, under sponges and in-between redbait (*Pyura stolonifera*). The larger abalone, released at much lower densities, were emergent and easier to find, and therefore larger quadrats were appropriate to conduct counts. Numbers of seeded and wild abalone within quadrats were recorded, and their densities were determined by dividing the number of abalone counted per quadrat by the number of quadrats sampled.

Quadrat positioning on the seeded plots was determined by means of a stratified random sampling strategy, which is considered a standard approach for estimating the biomass of a biological population in a defined geographical area (Manly et al., 2002; Booth pers. comm., 2013). A 10m-weighted line was reeled out from the centre of each plot (marked by an orange concrete block) to the edge of the site. Two divers placed the quadrat along the transect line counting from opposite ends of the line until they met (Figure 4.3). Quadrats that landed on sand patches were discounted and placed again. All counts were recorded onto dive slates. After each line was completed it was picked up and pivoted 5 – 8 m at the edge of the site. 8 – 12 transect lines were done on a site covering most of the habitat type represented on a site. These counts gave a mean density m^{-2} of seeded abalone for the survey area. This could be compared to the initial seed density, which was determined by using the GPS track area divided by the seed released.

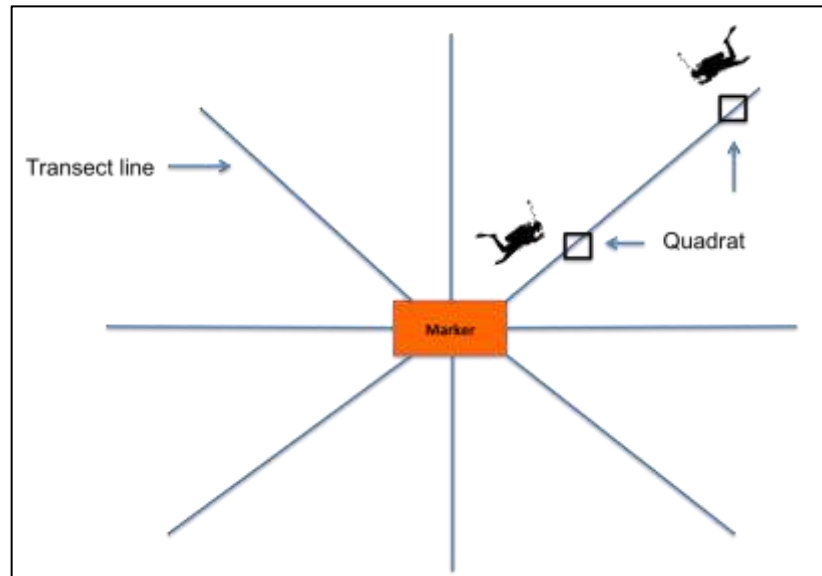


Fig 4.3 Layout of the stratified sampling strategy applied to the commercial seeding sites using two divers working from opposite ends of a 10 m-long transect line until they meet in the centre. The line was typically pivoted between 8 – 12 times on a site.

4.2.3.2 Shell collections

Shell collections were completed initially for only the large seed releases. Shell collections for smaller seed sizes were not attempted at first due to the high numbers seeded (10000 – 14000 abalone per site) and difficulty involved in collecting small shells (Tegner & Butler, 1989). However, the harvesting model described above indicated that high initial losses were occurring on sites. This was then investigated through a more exhaustive and intensive search effort on sites seeded with large numbers of smaller shells.

After 24 hours, post release shell collections took place on seven sites (9, 10, 13, 15, 16, 17, 18) seeded with 23400 large abalone (60 – 81 mm). Repeated sampling at varying time intervals up to 600 days post release were undertaken on sites 10, 13, 15 and 16, which had 8880 of the seeded abalone. This repeated sampling collected additional shells from subsequent mortalities as well as those shells missed during previous searches. The large shells were robust, easy to locate (visible) and less prone to being dispersed far from the sites. Crevices and cracks where shells would often collect were searched thoroughly. The 24-hour post release shell collections were conducted as timed-searches of 75 minutes per site. Most searches were timed, but some repeated follow-ups on sites were not time-limited, and instead shells were collected while divers conducted quadrat counts. Effort was evenly distributed across sites except for site 16 which had fewer repeated surveys but

all searches were dedicated to collecting shells. Shells that were collected during follow up dives were either missed shells from the previous searches or abalone that had perished since the last collection. The growth bands on shells indicated that many seeded abalone had survived substantial periods before perishing.

The large initial losses detected in the harvesting model prompted an exhaustive, and intensive search effort on four sites (124, 126, 140, 141) seeded with 24550 smaller abalone (38 – 51 mm), which was completed in an ad hoc time series between three hours to 40 days post release when weather conditions permitted. Searching for smaller shells compared to larger ones was extremely labour intensive and time consuming. Although the majority of shells on a site were likely to be collected it was impossible to effectively search the entire area and shells were left behind. This meant that estimates must be taken as minimum mortality with a known component of error. Limitations of using the shell collecting method as a measure of mortality are:

- a) Swell (unless calm seas prevailed before collections) and mobile predators have the ability to move shells off sites, however in long-term collections this is indeed a limiting factor.
- b) Complex search habitat, large area and difficulty of locating shells, further the cryptic nature of small abalone meant shells were usually hidden under boulders which cannot all be lifted during searching.
- c) Time was a large limiting factor in being able to adequately exhaustively search the area.

4.2.3.3 Wild Abalone Densities on Seeded Sites

Wild abalone density as well as seeded density was recorded from the quadrats used to sample each site. All sites except 7, 13 and 26 had two wild density sampling events over an 18-month period. Differentiation between seeded and wild was based on differences in shell colouration and abalone size. The average quadrat density was multiplied by the survey area of 314 m² to give the total number of wild abalone per site.

4.2.3.4 Video/ Time-lapse - Behaviour and Movement

To monitor post seeding behaviour GoPro cameras were used to photograph abalone placed in high-density patches at seed size categories ranging from 27 – 84 mm on different sites. A special stand was built to which the GoPro could be attached to for the duration of the time-lapse. The camera shot a frame every five seconds over a period of 1.5 – 2.5 hours. Increased to 29 frames per second (fps) abalone movement and behaviour was observed. Multiple movement time lapses were completed for different seed sizes, sites and varying sea conditions. GoPro cameras were also placed on fixed stands to film fish predation following out-planting to give an indication of the scale and nature of predation taking place in the initial release period.



Fig 4.4 Go-Pro steel frame with weighted base standing 1m off the sea bottom.

4.2.3.5 Growth

No growth data were collected on the commercial sites because representative growth rates for the various habitats were measured during the controlled seeding experiments described in Chapter 3.

4.2.4 GIS data management

The large-scale releases required a data base system capable of representing the seeded area sample data in both a spatial and temporal dimension, with capacity for ancillary data such as habitat notes, photographs and videos. Four datasets were included into the GIS

database (1) Pre-release abalone Seed Packlists, (2) GPS Waypoints and Tracks, (3) Diving Reports and (4) Seeding Footage. Abalone Seed Packlists were recorded for each seeding event, which included the quantity and size grade of abalone packed for each box. Boxes were assigned a site number and release density (number of boxes) according to the habitat-ranking table (Appendix 3.2). The GPS co-ordinates corresponded to the box numbers seeded onto a site. The divers recorded a separate set of data from underwater such as habitat description, depth, and sea conditions as well as video of the site and abalone releases. These datasets were all uploaded online into an organized system which could be accessed by managers and ranching personal. All essential information from each dataset was collated into a central spreadsheet, which was then imported into a GIS framework. Information such as site area, abalone released, seed size, habitat, and video all corresponded to the geographic location of that site. This was seen as the most appropriate way to synthesize and present an array of data in a centralized intuitive manner. The open source QGIS 2.2.0 Valmiera platform was used so that information could easily shared with the various stakeholders involved in the project.

4.2.5 Data Analysis

All data analysis was conducted using IBM SPSS statistics 23.0. For the analysis involving modelling, the most appropriate model was chosen based on the lowest Akaike Information Criterion (AIC) value where the predictor variables and/or their interaction contributed to explaining the variation in the response variable (Symonds & Moussalli, 2010). Due to the complex data set with missing cases for some factors and different scales of measurements it was decided to model certain predictor variables in separate models to see if they influenced the response variable. Site 18 was excluded from all the models due to inaccurate seed deployment, which caused a majority of seed to fall outside the sampled area.

4.2.5.1 Seed size versus seeded survivorship

The slope of a regression of the natural logarithm of abalone counts from each site survey versus time, calculated using generalized linear mixed-effects models (GLMM), was used as an estimate of the instantaneous rate of natural mortality (decay rate) for seed size class. Seeded abalone counts were included as the response variable. The fixed factors of 'days since release' and 'size' were interacted to obtain size differential mortality between the small, medium and large abalone. Commercial site was included as a random effect. The GLMM was specified with a negative binomial distribution with a log link function.

4.2.5.2 Density versus seeded survivorship

The effect of initial seed density on survivorship of seed was investigated using a generalized linear mixed-effects model. The size class differences of seed and different measurement scales (0.09m^2 or 1m^2) made density comparisons problematic. Thus the large seed size was excluded from this analysis. Seeded abalone counts were included as the response variable. The fixed factors of 'days since release' and 'initial number per quadrat' (density) were included. Commercial site was included as a random effect. The GLMM was specified with a negative binomial distribution with a log link function.

4.2.5.3 Wild abalone versus seeded survivorship

As an indicator for appropriate abalone habitat, the influence of wild abalone density on survivorship was explored using a generalized linear mixed-effects model. Seeded abalone counts were included as the response variable. The fixed factors of 'days since release' and 'wild abalone' (density) were included. Commercial site was included as a random effect. The GLMM was specified with a negative binomial distribution with a log link function.

4.2.5.4 Harvesting model approach

A 'harvesting model' which estimated the potential yield of ranched abalone was based upon the repeated quadrat counts of live seeded abalone for 16 different sites for three size classes of abalone over a period of up to 666 days post release. An instantaneous apparent mortality rate (GLMM curve mortality - termed H) for each size class was calculated and then weighted according to the number of seed abalone released for those size classes up until September 2016 (Table 4.5). It was possible using the apparent mortality rate and the known time since release t , to back calculate a predicted initial density of abalone at time of release. This was compared to the actual initial calculated density on a site, which was obtained by dividing the GPS track area (seeded area) by the number of abalone released on a site. The predicted initial density was considerably lower than the actual initial density that was calculated. This disparity was termed the 'initial loss', which is unaccounted for by the apparent mortality rate measured (Figure 4.4). From the evidence provided by time-lapse video a known component of emigration was identified, and thus the apparent mortality rate (H) included abalone which had dispersed out of the seeded area. This was not explicitly measured in experiments and thus movement rates for *H. midae* from other studies (Newman, 1966; Plagányi & Butterworth, 2010) were used to obtain an estimate of emigration and to estimate the natural mortality rate. In conjunction with the somatic

growth rates obtained in chapter 3 for deeper water sites (Outside Bay sites), it was possible to provide a range of harvesting biomass estimates, $\sum_c B_c$, based on the seed releases up to September 2016.

The estimation of the available biomass $\sum_c B_c$ at legal minimum size from quadrat counts of the density of seeded abalone were subject to a number of known errors and assumptions, visibly:

1. High initial loss from a site took place as a result of high levels of **predation** and **migration** (initial emigration) of abalone out of the study area within the first few hours following release which was observed through visual observation and time-lapse video analysis. These two parameters were not accounted for in the instantaneous apparent mortality rate measured using quadrats and it is unknown what proportion succumbed to mortality by predators and what moved outside sampled area.
2. The unknown level of ongoing emigration out of a site in the months and years after release.
3. Some of the sites that were seeded had abalone drift outside the sampled area when seeded due to the prevailing currents which caused abalone to settle beyond the release track area recorded by the vessel GPS. Thus a component of error may exist in the initial starting densities of abalone on a site.
4. It was assumed that illegal fishing was not a factor contributing to mortality as a private security unit was based opposite the study site with 24hour surveillance over the seeded area.

4.3 Results

4.3.1 Survivorship at sample time

Based on the quadrat counts of the 17 seeded sites with repeated sampling, it was possible to establish survivorship of seeded *H. midae* within a site until the time measured which is summarised in Figure 4.3 as a logarithmic decay function. The survivorship of seed abalone ranged between 4 – 27% for all seed sizes up to a period of 666 days post release (Table 4.4). It must be noted that the survivorship values presented in Table 4.4 are what has been explicitly measured on a site and does not account for seed abalone that may have emigrated from the core release area.

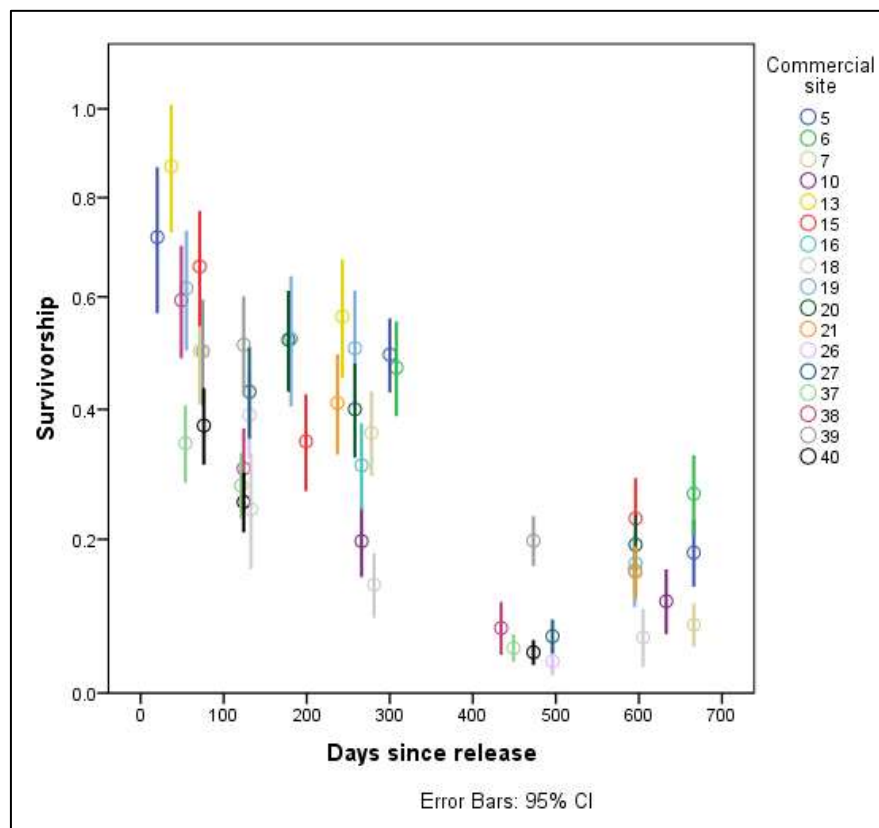


Fig 4.3 Mean survivorship of all abalone size classes for 17 sites monitored at varying intervals for a period of up to 666 days post release. All size class measurements represent shell length (mm). Size classes: 37mm (range 29 – 39 mm: sites 5, 6, 7, 26, 27, 37, 38, 39, 40), 43 mm (range 27 – 46 mm: sites 19, 20, 21), 60 mm (range 58 – 62 mm: site 18), 72 mm (range 69 – 81 mm: site 13), 76 mm (range 69 – 80 mm: site 10), 79 mm (range 73 – 84 mm: site 16), 81 mm (range 76 – 84 mm: site 15).

Table 4.4 Number and size of seeded abalone surviving on a site from release to time when sampled.

Commercial site	SL (mm)	# seeded	Seeded area m ²	Starting density m ⁻²	Days since release	N	Quad size m ²	Observed density m ⁻²	# seed left on site	Mean survival & std error %
5	37	12323	500	24.6	20	120	0.09	17.7	8843	72 ± 7
					300	219	0.09	12.2	6088	49 ± 3
					666	204	0.09	4.5	2233	18 ± 2
6	36	12536	500	25.1	308	196	0.09	11.8	5909	47 ± 4
					666	146	0.09	6.7	3346	27 ± 3
					666	146	0.09	6.7	3346	27 ± 3
7	37	12099	495	24.4	71	221	0.09	12.2	6058	50 ± 5
					278	179	0.09	8.8	4376	36 ± 3
					666	289	0.09	2.1	1019	8 ± 1
10	76	2931	571	5.1	266	75	1	1.0	579	20 ± 2
					633	66	1	0.6	337	12 ± 2
13	72	2481	500	5.0	37	65	1	4.3	2154	87 ± 7
					243	73	1	2.8	1397	56 ± 6
15	81	1719	492	3.5	71	83	1	2.3	1132	66 ± 6
					199	88	1	1.2	598	35 ± 4
					596	92	1	0.8	396	23 ± 3
16	79	1875	316	5.9	266	81	1	1.8	581	31 ± 3
					596	67	1	1.0	311	17 ± 2
18	60	5699	355	16.1	133	142	0.09	3.9	1389	24 ± 4
					281	212	0.09	2.2	781	14 ± 2
					605	142	0.09	1.1	389	7 ± 2
19	43	8280	329	25.2	55	169	0.09	15.5	5105	62 ± 6
					181	136	0.09	13.2	4328	52 ± 6
					258	131	0.09	12.7	4186	51 ± 5
					595	124	0.09	3.9	1297	16 ± 2

20	43	8441	278	30.4	178	97	0.09	15.8	4395	52 ± 5
					258	117	0.09	12.2	3379	40 ± 4
					596	194	0.09	5.8	1624	19 ± 2
21	43	8410	291	28.9	237	205	0.09	11.9	3454	41 ± 4
					596	222	0.09	4.5	1296	15 ± 2
26	37	13019	321	40.6	131	150	0.09	15.9	5088	39 ± 4
					496	185	0.09	1.6	501	4 ± 1
27	37	12409	262	47.4	131	137	0.09	20.4	5333	43 ± 4
					496	182	0.09	3.3	864	7 ± 1
37	36	13897	353	39.4	54	198	0.09	13.6	4794	34 ± 3
					121	207	0.09	11.0	3884	28 ± 3
					449	267	0.09	2.2	764	5 ± 1
38	37	12996	462	28.1	49	139	0.09	16.7	7718	59 ± 5
					124	132	0.09	8.6	3967	31 ± 3
					434	133	0.09	2.3	1042	8 ± 2
39	38	12183	231	52.7	75	107	0.09	26.4	6093	50 ± 5
					124	168	0.09	27.0	6233	51 ± 5
					473	216	0.09	10.4	2412	20 ± 2
40	36	14248	200	71.2	76	152	0.09	26.6	5322	37 ± 3
					124	160	0.09	18.1	3625	25 ± 2
					473	142	0.09	3.5	704	5 ± 1

4.3.2 Mortality rate and harvesting model

The GLMM revealed that ‘seed size’ (small, medium & large) interaction with ‘days since release’ of seeded *H. midae* counts was significant ($F_{4,6329} = 304.3$, $P < 0.001$), meaning that instantaneous natural mortality rate was significantly different between the seed sizes. After one-year post release survival rate for small seed was 21%, medium 28% and the large seed 36%.

Table 4.5 The significant interaction of ‘days since release’ with ‘seed size’ giving the instantaneous apparent mortality rate per day and per year for each seed size class.

Size	Quantity seed per size	t	P	$M (d^{-1})$	$M (y^{-1})$
L (78 mm)	31719	- 8.86	<0.001	-0.00183	-0.67
M (43 mm)	813957	- 13.64	<0.001	-0.00246	-0.9
S (37mm)	550057	- 31.34	<0.001	-0.00326	-1.19

For the harvesting model the apparent mortality rate was weighted according to the quantity of small, medium and large abalone released until September 2016 (Table 4.5). This weighted average mortality was calculated to be -0.0027673 per day or 1 per year. The apparent mortality rate did not distinguish between dead abalone and abalone that had emigrated out of the core seed area, meaning that the apparent mortality and emigration parameters were confounded in the estimation process. For example, although it is possible to use GLMM analyses, in which time to release is a covariate and the target variable are quadrat counts over time, to estimate the average exponential decay rate coefficient of abalone post release, termed H , uncontaminated by initial losses due to initial predation and emigration, this exponential decay rate must be treated as the sum of natural mortality M and emigration coefficients E

$$H = M + E$$

It is possible to use the estimate of H , and the known time since release t , to back calculate a predicted initial density of abalone N_i “at release”, where for each quadrat measured,

$$\hat{N}_{init} = N_q(t)e^{Ht}$$

Each quadrat measurement therefore provides an estimate of the combined effects of initial predation + emigration, $M_{i\%} + E_{i\%}$:

$$\left(1 - \frac{M_{i\%}}{100}\right)\left(1 - \frac{E_{i\%}}{100}\right) = \frac{\hat{N}_{init}}{N_{init}}$$

Where

- $M_{i\%}$ Is the percentage of abalone that suffer mortality in the first few hours after release
- $E_{i\%}$ Is the percentage of abalone that survive initial mortality and that emigrate from the study site in the first few hours after release.

If one assumes, as is done here, that the scale of the initial emigration and natural mortality are the same, then an estimate of $M_{i\%}$ is

$$M_{i\%} = 100 \times \left[1 - \sqrt{\frac{\hat{N}_{init}}{N_{init}}}\right]$$

Where the mean in this formula is across all quadrat samples.

If we let w_{init} and l_{init} be the initial mean mass and length of released abalone, g the growth rate in length per unit time, and l_{min} the legal minimum size, w_{min} the associated body mass, then the mean time to harvest at minimum size, Δt , is:

$$\Delta t = \frac{l_{min} - l_{init}}{g},$$

And the available biomass present in the sea for a given release cohort B_c is:

$$B_c = w_{init} \times N_{init} \times \left(1 - \frac{M_{i\%}}{100}\right) \times e^{-M\Delta t},$$

Where

- w_{init} Is a known initial mean mass,
- $\Delta t = \frac{l_{min} - l_{init}}{g}$,
- $M = H - E$, Where H is derived from the GLMM analysis and E is a credible estimate based on other considerations elaborated below,
- $M_{i\%} = 100 \left(1 - \frac{\hat{N}_{init}}{N_{init}}\right) - E_{i\%}$, Based on a credible estimate of $E_{i\%}$.

The harvestable biomass of surviving abalone $\sum_c B_c$ provides an estimate of the total cohort biomass that will become available at the new minimum legal size for abalone in the Eastern Cape which has been adjusted from 114 mm SB down to 90 mm SB. Godfrey (2003) calculated shell length (SL) to breadth regression using live animals and shells collected at Cape Recife. The non-isometric relationship is described as a power function $y = 0.3714x^{1.1585}$. As all measurements were taken of the SL in the seeding experiments we convert the minimum legal size of 90mm SB to SL using the inverse of the equation. The new minimum SL for the Eastern Cape is equal to 114 mm.

The minimum harvest size in SL was converted into whole wet mass (in grams); this was done using the revised mass-length relationship for *H.midae* (Plagányi & Butterworth, 2002).

$$w_{y,a} = w(y, t = a) = 0.000098 \cdot (l)^{3.1549}$$

114 mm SL equates to a harvest size of 302 grams.

Some insight into the possible values of E and $E_{i\%}$ are provided by the following:

1. **Abalone movement studies:** Estimates of abalone movement following tag and release, as reported in Newman (1966) and De Waal et al. (2003).
2. **Wild versus seeded abalone densities:** The projected density of seeded abalone at the minimum size compared to wild densities measured on sites.
3. **Inshore to offshore abalone migration:** The logic and quantification of the inshore to offshore migration of abalone as estimated in a stock assessment model for abalone reported in Plagányi and Butterworth (2010).

In order to produce estimates of $\sum_c B_c$, each of the seeded / released cohorts was projected to the legal minimum size based on the recorded average growth rate of $14.4 \text{ mm} \cdot \text{yr}^{-1}$, with the following additional nuances:

- The value of M is $H-E$ where H is a weighted average of the time to release covariate parameter for each of the small, medium and large abalone release size categories.
- An additional calculation was run to compare the results produced in this way with a run of the model using values of M from the abalone stock assessment model presented in Plagányi and Butterworth (2010).

Estimates of $\sum_c B_c$ are very sensitive to the value of E . The following estimates are obtained, where E is based on emigration of $X\%$ of seeded abalone from a circular study site with a radius of 10 meters **per year**:

$X\% = 0\%$, $\sum_c B_c = 2.4$ tons

$X\% = 20\%$, $\sum_c B_c = 8$ tons

$X\% = 30\%$, $\sum_c B_c = 14.9$ tons

$X\% = 40\%$, $\sum_c B_c = 31$ tons

$X\% = 50\%$, $\sum_c B_c = 74.4$ tons

$X\% = 60\%$, $\sum_c B_c = 220.4$ tons.

Other parameters associated with these estimates are:

1. A conservative deep-water site growth rate of 1.2 mm per year as calculated in the experimental sites in Chapter 3,
2. An estimate of $(1 - M_{i\%}/100)(1 - \frac{E_{i\%}}{100}) \sim 0.7$,
3. An estimate of $M + E$ of -0.0027673 per day based on a GLMM analysis of quadrat counts using a log-link function, a negative binomial distribution, where site is a random effect, and time since release is a covariate (with an interaction with the size of seeded abalone, being either small, medium or large).

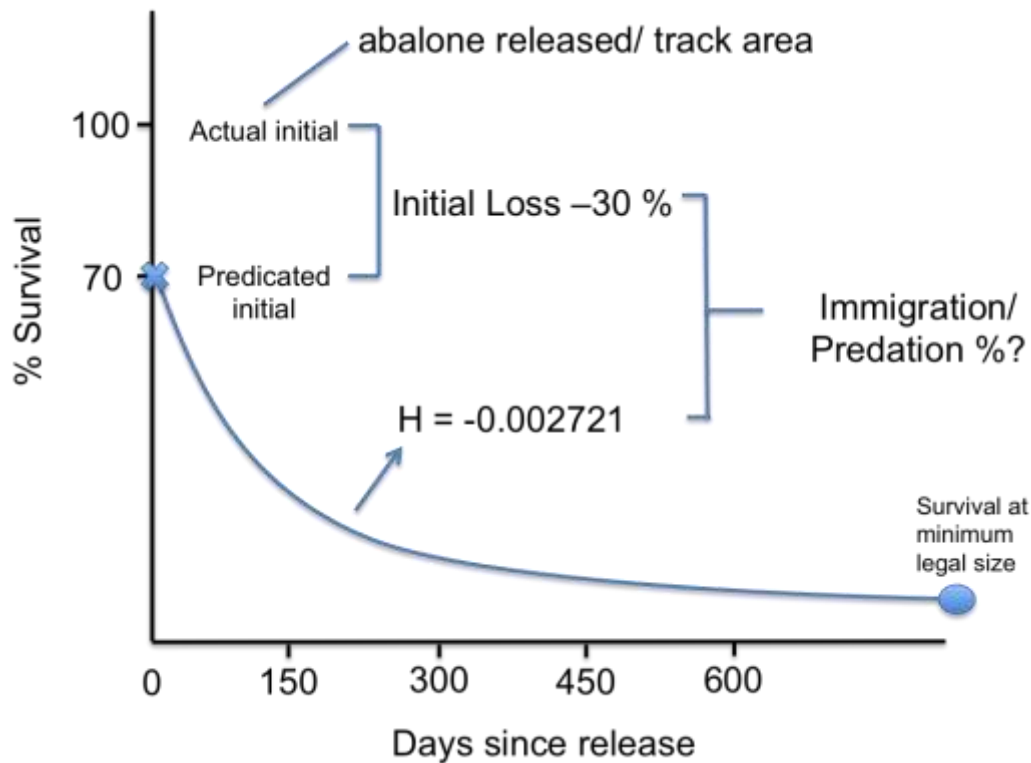


Fig 4.4 Large-scale release model showing the instantaneous apparent mortality rate (decay rate – termed H) back calculated to time at release t to the predicted initial density of abalone. The model also displays a theoretical survival % until minimum harvest size is reached dependent on variable growth and emigration values. The apparent mortality curve includes abalone, which may have migrated off the seeded site.

4.3.3 Density

Some sites were seeded at much higher densities than other sites using abalone in the size class of 27 – 46 mm. The GLMM analysis showed that there was no effect of release density on survival of seeded abalone ($F_{1,5641} = 0.45$, $P = 0.52$), contrary to what was expected where higher density sites obtained lower survival than more sparsely seeded sites.

4.3.4 Mortality – Shell Collections

Seven sites seeded with large abalone were searched 24 hours post release where divers collected 2.7% (632 shells) as empty shells. Repeated sampling on four of these sites yielded average minimum mortalities of 17.5% (1554 shells) up to a 600-day post release period (Figure 4.5). Site 16 was the only site with large abalone that was subject to dedicated shell-collecting efforts throughout the duration of the study, and as a result obtained the highest shell retrievals among the large abalone seeded sites (26%). In general, the rate of shell returns was noted to diminish towards the end of timed searches. The more intensive and

exhaustive searches for small abalone (43 – 51 mm) seeded on four sites found that at an absolute minimum, 20.5% (5032 shells) of abalone perished within 40 days post release (Figure 4.6). The majority of this mortality occurred within the first few hours following release. On site 140, within three hours post release 13% of seed released were collected as empty shells with many shells left on the site due to limitations on the amount of time that divers could remain underwater.

Through observation at three hours post release, hundreds of Black Tail (*Diplodus capensis*) and Big Eyes (*Boopsoidea Inornata*) could be seen predating upon the seeded abalone floating through the water column or any abalone that didn't turn over fast enough. Furthermore, fish could be seen physically bumping off those abalone which were loosely attached to the substrate. Fish predation was considered to be the most significant cause of mortality post release. Other predators likely to be of significance were five Eagle Rays sighted (*Myliobatis aquila*) and two octopus (*O. vulgaris*) among other less significant and less abundant predators on site 140. After three days exhaustive searches were repeated on site 140 with an additional 17.7% collected (total 30.6%) and for the first time on site 141 where 14.7% was collected. Sites 124 and 126 had shells collected five days post seeding where sea conditions had remained relatively calm following release with 13.5% and 12.4% collected respectively. After 40 days at large on these sites, 5.4% and 4% were collected as empty shells. The average minimum mortality of 20.5% for these sites must be interpreted with caution as site 141 was subjected to only one search and the second searches on sites 124 and 126 were not exhaustive, but rather shells were collected during the completion of quadrat counts. Not all the shells could be collected on sites due to the large search area and the fact that many juvenile abalone die under the concealment boulders among other limitations previously described in the methods.

The main cause of mortality was concluded to be post release predation, which was either captured on video, time-lapse footage or through direct visual observation. A list of predators, in addition to the ones mentioned above, was compiled through visual observation or video and time-lapse photographs which included the Cape Rock Crab (*Plagusia chabrus*), anemone, Pajama Catsharks (*Paroderma africanum*), Musselcracker (*Sparodon durbanensis*), Yellowbelly Rockcod (*Epinephelus marginatus*), Malabar Rockcod (*Epinephelus malabaricus*), Twotone Fingerfin (*Chirodactylus brachydactylus*), Roman (*Chrysoblephus laticeps*), Janbruin (*Gymnocrotaphus curvidens*) and Poenskop (*Cymatoceps nasutus*).

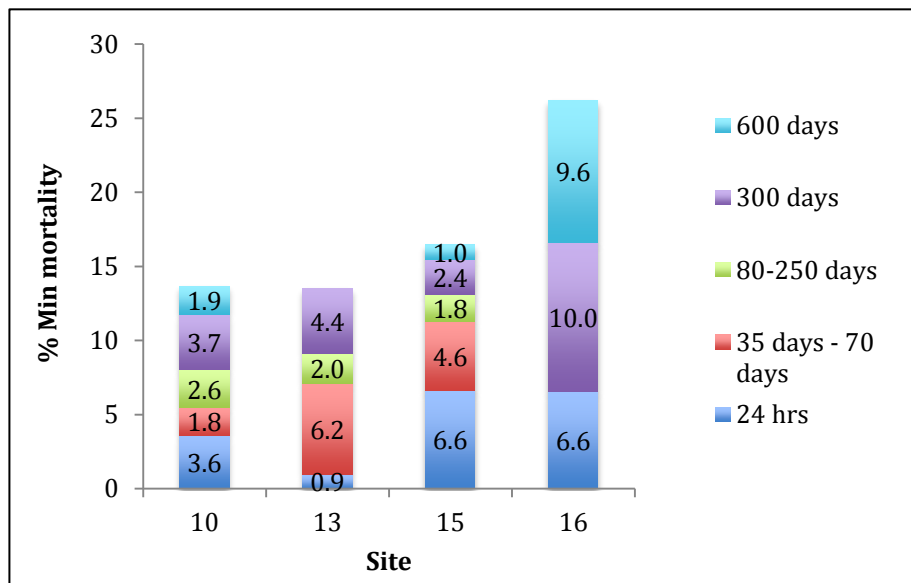


Fig 4.5 Long-term shell collections for large abalone sizes from 70 – 84 mm SL.

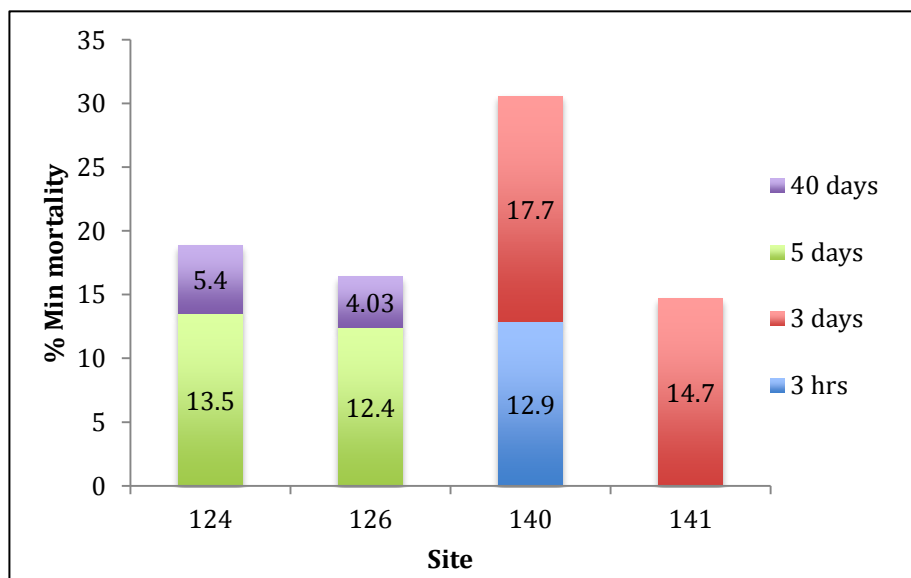


Fig 4.6 Short-term shell collections for the smaller abalone sizes of 43 – 51 mm SL.

4.3.5 Video/Time-lapse – Behaviour and Movement

Many abalone followed similar or same paths as other abalone seeking out the small grooves or gullies in which to travel along. Other abalone could be seen moving directly over whatever substrate lay in their path, traversing steep rock faces, moving over seaweeds and in some cases directly over the spines of sea urchins. These abalone moved in a very directive manner looking for cryptic cover in crevices or beneath boulders. In most time lapses conducted, very few hatchery abalone could be seen in the frame at the completion of the time-lapse ([movement clip 1](#)). This indicated that most abalone had become cryptic within the frame or continued to move outside the field of view in search of appropriate habitat. Movement always appeared relatively substantial in time-lapses, however these were mainly conducted in calm release conditions. A time-lapse conducted on the 16 September 2014 on site 17 was done in very strong surge conditions. Some of the abalone seed displayed considerable movement, however many did not move far at all possibly due to the strong water movement. Another very apparent observation made from the time-lapse video was the vulnerability of exposed hatchery seed to predators if they did not find refuge quickly where they would be picked off by masses of fish and other predators as mentioned above ([movement clip 2](#)). An observation was made in a densely seeded patch where abalone moved to the nearest crevice for protection. This crevice was soon saturated which caused seed to move off elsewhere for refuge, increasing the time exposed to predators, and fish could be observed in the time-lapse imagery picking off these individuals.

4.3.6 Wild densities on seeded sites

Two wild abalone density surveys were conducted for nearly all long-term monitored sites over a year and a half period where little difference in density was noted between the different sampling periods. Densities ranged between 0 – 1 abalone m⁻² with an average of 0.31 ± 0.09 abalone m⁻² for all the sites (Table 4.5). Sites with higher densities of wild abalone were correlated with an increased number of seeded abalone at the end of the approximately one-and-a-half-year period ($\beta = 0.19$, SE = 0.078, t-value = 2.44, $p < 0.05$).

Table 4.5 Mean wild abalone densities on commercial seeded sites with the total wild abalone population for the commercial site with a standard size of 314m² (10m radius).

Commercial site	Quad size m ²	N	Mean m ⁻²	Std Error	Total quad area m ²	Total abalone per site (314m ²)
5	0.09	423	0.16	0.07	38	49
6	0.09	342	1.04	0.19	31	326
7	0.09	289	0.19	0.09	26	60
10	1	141	0.09	0.02	141	29
13	1	20	0.40	0.18	20	126
15	1	159	0.26	0.05	159	81
16	1	148	0.44	0.06	148	138
18	0.09	354	0.19	0.08	32	59
19	0.09	391	0.51	0.12	35	161
20	0.09	408	0.35	0.1	37	111
21	0.09	427	0.26	0.08	38	82
26	0.09	185	0.12	0.08	17	38
27	0.09	319	0.31	0.1	29	98
37	0.09	474	0.16	0.06	43	52
38	0.09	345	0.61	0.15	31	192
39	0.09	384	0.14	0.06	35	45
40	0.09	302	0.00	0	27	0
			0.31	0.09	886	1648

4.4 Discussion

The research presented here provided a robust quantitative assessment of long-term seed survival and the potential factors influencing the survivorship success on natural reef areas at Cape Recife. The apparent mortality estimates generated by the GLMM curve for all size classes were relatively high which is likely as a result of the high predation on seed, unsuitable habitat and the unknown emigration rate off the seeded sites.

4.4.1 Abalone survival

The survivorship on sampled sites (Table 4.4) was variable (4 – 27%) up to 666 days post release. The estimated apparent mortality of larger seed (77 mm) was 0.67 y⁻¹, which is considerably lower than smaller seed (38 mm) of 1.19 y⁻¹. Mortality rates are thought to decline with age, with high survival rates observed in adult populations and low survival rates in juveniles (Prince et al., 1988). These apparent mortality rates included the unknown rate of emigration of seeded abalone out of the circular plots and abalone not found by

divers. Therefore the actual natural mortality rate (M) may be lower. Very little information exists for juvenile mortality rates for *H. midae* in South Africa. One study found that mortality for recruits and juveniles ranged between $0.24 - 3.6 \text{ y}^{-1}$, these highly variable results were attributed to the harsh and dynamic conditions along the coastline in conjunction with potentially high predation densities at sites (Proudfoot, 2006). In other studies from across the globe mortality rates for small (15 – 21 mm SL) transplants were $0.67 - 1.5 \text{ y}^{-1}$ (Kojima, 1981), $1.1 - 1.8 \text{ y}^{-1}$ (Momma et al., 1980), $0.7 - 1.0 \text{ y}^{-1}$ (Saito, 1984), $1.1 - 1.5$ (Shepherd & Godoy, 1989) which are within range of the mortality rate of 1.12 y^{-1} for small abalone presented in this study. The mortality rates for both small and large abalone in this study were considerably higher than what has been reported in the wild for adult *H. midae*, where mortality used in stock assessment models was 0.2 y^{-1} (Plagányi & Butterworth, 2010). Similar mortality estimates of adult abalone obtained in other studies for different species ranged from $0.15 - 0.36$ (Beinssen & Powell, 1979; Shepherd et al., 1982; Sloan & Breen, 1988).

The seeded site apparent mortality (H) estimates included the possible movement of seed out of the sampled area (beyond the 10 m plot radius). Thus the ongoing natural mortality and emigration from the study site are confounded parameters in the GLMM curve. The estimate of cohort biomass at minimum size is particularly sensitive to the estimate of the ongoing emigration coefficient (E), since when this value is large, the estimate of natural mortality is low and vice versa. In the experimental design it was assumed that once abalone settled on a site there would be little displacement over time (Tarr, 1995). However, from the video and time-lapse analysis it was clear that a high level of movement was taking place immediately post release which may have resulted in a significant ‘initial emigration’ as the dispersing abalone actively searched for crevice space. Following the initial post-release release settlement and emigration, it is a plausible assumption that there was a slow diffusion of abalone off the site which was termed ‘ongoing emigration’. Many studies using a tag-recapture method to estimate mortality have not accounted for tag disappearance by dispersal or emigration of tagged abalone beyond the survey area (Nash, 1995; Catchpole et al., 2001). Not accounting for emigration out of the seeding area results in an overestimate of mortality. A study using tagged abalone found that not accounting for dispersal into their mortality model would have resulted in an over estimation of the natural mortality by more than 200% (Dixon et al., 1998). A factor possibly influencing the rate of movement is the high density in which many sites have been seeded, exceeding the natural

carrying capacity of available juvenile abalone habitat in those areas (Goodsell et al., 2006), however no evidence of density dependent mortality was found. Another factor to consider is that the juvenile abalone were seeded in deeper water (5 – 10 m), which is known to support larger emergent abalone but very low densities of juveniles. It may be that these deeper areas were unsuitable habitat for high concentrations of juvenile abalone, due to limited refuge space and lower abundance of food, as algal biomass is known to decline with depth, which would impact on food availability (Steyn & Du Preez, 2013). For these reasons an unknown proportion of the seeded abalone may have emigrated from the core seed area in search of better cover or habitat. As no measurements were taken of the distance covered by abalone post release, the literature on natural abalone movement was used to include an estimate of emigration out of the seeded sites and separate it from natural mortality.

4.4.2 Abalone movement

There are various published studies on the movement of abalone species in the wild (Newman, 1966; Shepherd, 1986; Ault & DeMartini, 1989; Shepherd & Godoy, 1989; Tarr, 1995; Werner et al., 1995). South African abalone (*H. midae*) recruit mainly in the inshore sub-tidal zone and move offshore as they grow. The integrated fishery model by Plagányi and Butterworth (2010) assumed that 4.2% of abalone in the inshore zone (defined as a 185m offshore from the high-water mark to the 5 m depth contour) move offshore per year. If one views the inshore region as a carpet of abalone that moves offshore at a certain speed per year to achieve this movement, the carpet must move 4.2% of 185 m per year, or 7.77 m per annum. To put the rate of movement used by Plagányi and Butterworth (2010) into perspective, a study by Shepherd & Godoy (1989) found the mean rate of movement for juvenile *H. laevis* and *H. scalaris* to be 0.5 m and 0.8 m per month respectively which equates to movement between 6 m and 9.6 m per year, which is within the range of movement for *H. midae*. Other movement studies have been undertaken with tagged and released adult *H. midae* and other species (Newman, 1966; Ault & DeMartini, 1987; Tarr, 1995), however this is believed to induce abnormal movement (Poore, 1972; Ault & DeMartini, 1987) which is not usually observed for in the wild (Tarr, 1995). Newman (1966) observed tagged adult *H. midae* movements of as much as 43 metres after two months. For the purposes of the harvest model in present study, it was decided to use the movement estimate of Plagányi and Butterworth (2010) for the emigration parameter. The release areas in this study were circular with a radius of 10 m. If the seeded abalone moved 7.77 m

in any direction approximately 48% of seeded abalone moved out of the study site in the first year. This provides supporting evidence for potential substantial movement taking place outside of the study area.

To provide additional supporting evidence of potential movement a check was conducted using the wild abalone density for sites and making a comparison with the projected density of seeded abalone at harvest size. The average wild abalone density on a site was 0.32 abalone m^{-2} while the projected seeded density, using the apparent mortality rate (H), at minimum size was 0.16 abalone m^{-2} . This is half the typical wild density measured on sites, considering the typical ratio of seeded to wild abalone at release time was 96%: 3%, it is suggested that something significant such as substantial emigration has occurred.

Lastly, as an additional check on the results, estimates of $\sum_c B_c$ were produced using a value of M of 0.18 yr^{-1} , roughly consistent with the values of natural mortality reported in Plagányi and Butterworth (2010) for the abalone stock assessment model, relevant to the sizes of abalone between release and minimum size. The resultant estimate $\sum_c B_c = 130.2$ tons. This is starkly contrasted when using the weighted apparent mortality (H) calculated from the GLMM in this study of 1 yr^{-1} which the resultant estimate $\sum_c B_c = 2.4$ tons. It is possible that there is an unusually high natural mortality rate over time for seeded abalone once released but these very large differences in biomass estimates do suggest that emigration could a significant factor in H and that the M provided by Plagányi and Butterworth (2010) could be more realistic figure of actual mortality. The uncertainty associated with the value of E means that there is a large uncertainty in the estimate of seeded abalone that will have contributed to the wild stock biomass, measured as the seeded abalone cohort biomass at the legal minimum size. It is known that at minimum 20% are lost immediately following release from predation and 25% survive the first year after release. Among the remaining 55%, it is uncertain what proportion emigrated from the release area and what quantity succumbed to natural mortality.

Cohorts of seeded abalone will reach the minimum size in a staggered manner over the next five years. It should be feasible to carry out further work to estimate the extent of emigration out of study sites during this five-year period, perhaps improving estimates of E . Such work could estimate the density and numbers of abalone that now lie outside the release area, since seeded abalone are identifiable by their shell colour from the farm.

Another factor that to which the harvesting model was sensitive was the adjustment in the growth rate, this study used a very conservative and low growth rate of 1.2 mm.m^{-1} for sites in deeper water (6 – 10 m). It was shown in chapter 3 that seed obtained a 30% faster growth in the shallower water areas. By accurately estimating movement rates and by shifting seeding into shallow habitats more accurate and improved harvesting biomass estimates could be obtained.

4.4.3 Density

Density dependent mortality has been well documented for fish stocks but it is not well known among abalone (Shepherd & Breen, 1992). Contrary to what was hypothesized density appeared to show no significant effects on apparent survival, similar to the density results reported for in chapter three and in Godfrey's (2003) experiments where no significant effects were found. Obtaining exact release densities is difficult due to the heterogeneous nature of abalone reef habitat (Wood, 1993; Godfrey, 2003). Abalone are also known to relocate in accordance to the abundance of available crevice space where sites that have limited available crevice space experience high rates of movement in comparison to sites with high crevice space which had negligible movement (Shepherd, 1990). These factors confound density effects that could influence survival rates. The amount of shelter offered by a site is variable and densely seeding one area could be acceptable depending on crevice space, however if crevice space were limited a densely seeded site would likely mean greater movement. Although no density effect was detected in the GLMM analysis, caution must be raised in seeding areas at a very high density as there is likely to lead to increased exposure by abalone to predators as crevice space becomes limited.

4.4.4 Empty shells and predation

Insights were gained into minimum confirmed mortality for large and small abalone through shells collections. Sites that had large abalone released onto them had lower shell returns than sites which were seeded with smaller abalone. There are a number of factors to consider here when making a comparison. Seed releases for large abalone were done at the start of the ranching project and smaller seed releases which had shell collections completed were done 1.5 years later. From video evidence there appears to be an increase in the predation activities at release sites from the start of the ranching project to present which may account for the greater quantity of shells that were collected for the smaller abalone.

The methods of collection for large and small shells were different in that time-limited searches were used to find large shells, whereas more intensive search effort was necessary to find the smaller shells. This factor is likely to have an impact on the shell returns and minimum mortality presented. Interestingly, site 16 was the only large abalone seeded site to undergo dedicated shell collections and obtained the highest amount of shells (Figure 4.5). This likely indicates that more intensive search effort results in higher returns and that minimum estimates reported for other large abalone are underestimates. A factor further influencing the shell returns for large abalone in the long-term was the shell loss between sampling events which is considered to be relatively substantial given that the shell breakdown rate calculated by Shepherd (1998) had a half-life of 48 days.

However, even with an exhaustive approach for smaller shells it was still not possible to collect all shells that remained on a site during the available collection time because smaller shells were more difficult to collect and were much more likely to wash away from a site or be shifted by predators. Many juvenile seed were observed to die whilst concealed beneath boulders, many of which could not all be lifted during searches. Other studies have noted that recovery rate for small shells was low (Sweijd, 1998; Goodsell et al., 2006; James et al., 2007) as they are hard to find (Tegner & Butler, 1989) and predators may crush them (Mower & Shepherd, 1988; Griffiths, 2006). In this study it was realized that shells on sites were missed due to the large and complex search habitat, time limited search, and the ability of mobile predators and swell to move shells away from the search area. Although the level of mortality is underestimated by the shell collections they nevertheless provide evidence that mortality is taking place in the short and long-term on sites. To estimate the amount of shells missed from collections, future work could look at conducting a series of successive searches over a short time period on a couple of sites (within and outside the site boundary). From this it would be possible to plot a curve of the number of shells collected versus the searches and extrapolate the number of shells missed in the first search. This could then be applied to estimates for other shell samples.

4.4.5 Wild Abalone

The average wild density of 0.32 abalone m^{-2} recorded on seeded sites was found to be lower than the 0.58 abalone m^{-2} recorded during the baseline survey in the vicinity to the commercial sites described in chapter 2. It was decided to model wild density recorded on sites in relation to the survivorship success of seeded abalone, and it was found that higher survivorship was achieved on sites with higher densities of wild abalone. This suggests that wild abalone presence and density are potential indicators for selecting sites that are suitable for ensuring survival of seeded hatchery-reared abalone.

4.5 Conclusion

A large-scale commercial abalone seeding project was successfully conducted by a partnership between the abalone aquaculture industry and marine scientists along the Eastern Cape of South Africa. This study was undertaken on a large scale yielding one of the largest datasets for the monitoring a commercial seeding project. The apparent mortality rate (H) of 0.002767 per day was calculated for the harvesting model based on a weighted average across the different seed size classes. Accounting for the initial loss of abalone on a site in conjunction with the apparent mortality rate (H) meant that 25% of the seeded abalone survived one-year post release. Although estimates of mortality could be attained which projected potential harvesting biomass estimates, these were confounded by the problem of unknown levels of emigration (E). Furthermore, the poor growth rates in the deeper areas impacted negatively on the biomass harvest estimates. Despite these limitations, this model gave a range of potential harvesting estimates based on plausible emigration parameters chosen from other studies. If the level of emigration is negligible then the yields from ranching will be low. It is imperative that future studies adequately address the level of emigration from the study site.

CHAPTER 5

General discussion

This study evaluated those factors influencing the survival and growth of hatchery seed on natural reef sites and quantified commercial-scale seeding performance. In particular, the mortality and growth data provided a basis for evaluating the economic viability of ranching. Insights were also gained into the cause of post release mortality and the behaviour exhibited by seed in the hours following release. Through the various experiments, new insights into the science of marine ranching were provided.

Chapter 2 focused on the state of the wild stock at Cape Recife to provide a rationale for stock enhancement and a method for conducting a baseline stock assessment to benchmark the success of seeding. It was established through the collation and analysis of fishery dependent data (*in situ* surveys) and fishery independent data (confiscated catches) that the wild stock in the study area had declined significantly. This was attributed to the uncontrolled but well documented illegal fishing taking place within the vicinity of Port Elizabeth (Raemaekers & Britz, 2009). Despite the declines in emergent abalone, recruitment at the Cape Recife rock pool was still taking place. No stock recruitment relationship was found, wider recruitment sampling would be required to investigate this relationship further. The analysis provided sufficient evidence that reef areas were well below natural carrying capacities and the use of stock enhancement could be an appropriate tool in which to rebuild stocks. The continued decline of the abalone resource at Cape Recife and in the Eastern Cape more generally highlights the failure by the state to curb illegal fishing. This has been attributed to a failure of the fisheries management structures and anti-crime responses deployed by the South African government (Raemaekers et al., 2011). While abalone farming technology has opened up the possibility of rehabilitating overfished areas with hatchery-reared seed, this cannot be done in isolation of the root causes, which have led to the decline. The implementation of a private anti-poaching unit for this ranching project was seen as a crucial component in reducing the illegal fishing pressure on the wild stock and secondly ensuring the protection of the reseeded abalone. Although

illegal fishing has not been eradicated in its entirety in the ranching zone, it has been significantly reduced (Swartz pers. comm., 2016; Wood, 2016), and it is hoped that the natural stock will be given the opportunity to recover.

The critical assessment of factors influencing the survival and growth of seeded abalone in the small-scale experiments in Chapter 3 revealed important trends which need to be considered when undertaking commercial scale releases as they have a profound influence on the sustainability of a ranching operation. One of the most significant findings was the much higher growth rates observed in shallow water compared to the deep-water sites. This means that a greater quantity of abalone will reach minimum legal harvest size in these shallower areas compared to deeper areas, having significant economic implications for mass releases. The current large-scale releases have targeted deeper reef areas as these have proved to be easier locations in which to conduct releases in than shallow water areas. However, this means that abalone are growing at a much slower rate.

An unusual finding was that smaller seed yielded a higher retrieval rate than larger seed and by inference had a higher survival rate. This is contrary to what most other studies have found where an increase in seed size is associated with higher survival rates, however this study used seed sizes much larger than what has been reported for studies conducted elsewhere. This result is, however, juxtaposed with the large-scale release results in Chapter 4 which showed that an increased seed size led to increased survival. This increased survival is unlikely, however, to offset the additional cost of producing those animals and it is recommended that smaller rather than larger seed be released.

The long-term survival of large-scale releases was monitored for a range of sites and seed sizes. Based on the 30 tons of abalone released, a range of harvesting biomass estimates were produced using the instantaneous apparent mortality rate (H), somatic growth and a range of plausible emigration rates. The instantaneous apparent mortality rates presented for all seed sizes were high, which included an unknown rate of emigration out of the seed plots which was not measured in this study. If it is assumed that no emigration is taking place then the biomass yield is low, with a greater tonnage being released than what actually survives until minimum legal size. A novel tool used to gain insights into the post release behaviour of hatchery seed was the use of GoPro

cameras on fixed stands. These cameras recorded predator interactions and the movement following release. This established that the most significant cause of post release mortality was a result of predation. It also affirmed that abalone can move considerably following disturbance and when searching for cryptic cover.

Based on the evidence provided above, it is recommended that in order to obtain a robust harvesting estimate, future research work needs to be focused on the level of abalone dispersal out of seeded sites. It is recommended that future large-scale releases adjust the current seeding approach and target shallower areas, which are known to support greater quantities of juveniles with faster growth rates. The immediate post release mortality of 30%, attributed mainly to fish predation, is high and innovative ways of reducing this outplanting mortality need to be implemented. Lastly, the results from this study indicate that careful site selection is fundamental because growth rates and survival rates were noted to vary quite significantly between different sites that were small distances apart. A greater focus on site selection is essential to ensure that the best possible areas are selected for release. It was found that sites with higher wild densities (possibly indicators of good habitat) had higher seed survivorship. The economic potential of this ranching project remains undetermined, this will require detailed work, as discussed, on abalone movement, site selection, innovative ways to reduce mortality immediately following release and a better understanding of the long-term causes of mortality in order to establish reliable biomass harvesting estimate.

This thesis has addressed factors influencing the survival and growth of hatchery reared abalone and estimated long-term survival trends for commercial-scale releases. Based upon these results, abalone ranching or stock enhancement could be potentially used as a fishery restoration tool in areas that have suffered stock collapse through illegal fishing. This thesis has contributed substantially to our understanding of ranching and factors impacting on its success.

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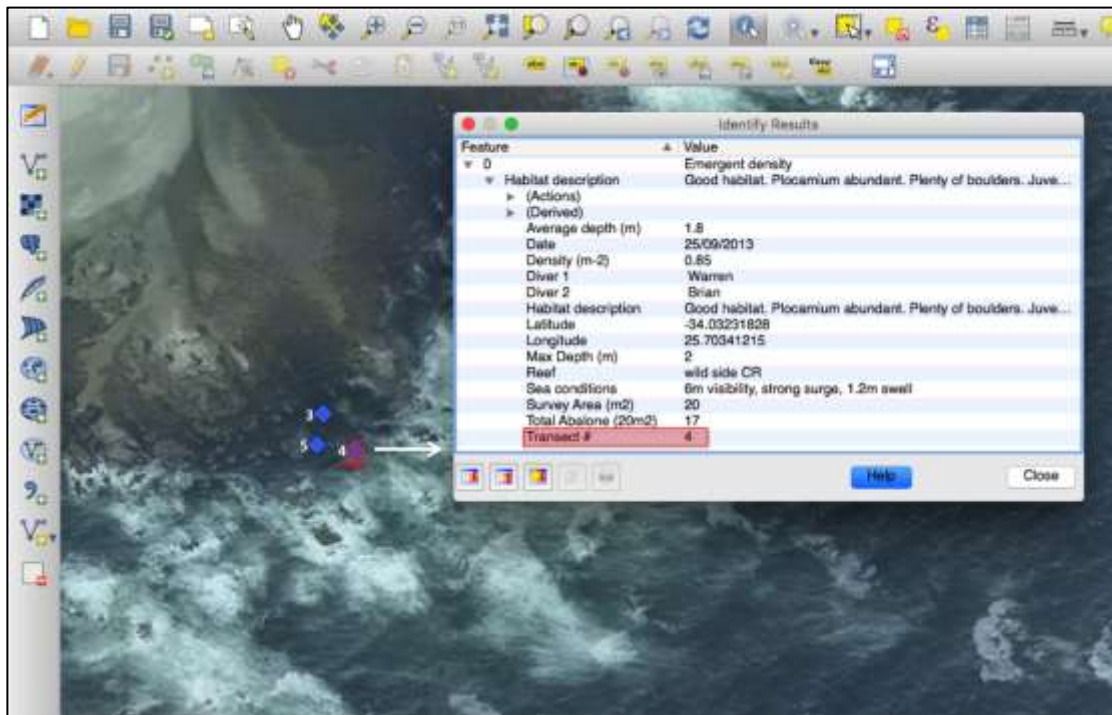
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Appendix 1

Appendix 1.1 Each survey location point on the GIS map had corresponding descriptive information, which is displayed when clicking on the point of interest.



Appendix 1.2 Description of the main habitat types surveyed in the study area at Cape Recife and surrounds.

Reef/ Area	Depth	Wave exposure	Profile	Substrate	Main Algal components	GoPro footage
Inside Bay	0.5-3m	Medium	Low/ medium	Gently shelving solid reef mixed with loose and stable (predominant) boulders. Sand patches	<i>Plocamium spp.</i> dominated	Yes
Rock Pool	0.5m	Minimal	Low/ flat	Loose boulders	Coralline algae and microalgae	Yes
Wild Side CR	1-8m	High	Medium/ High	Very variable habitat changing over small spatial scales. Solid outcropping of quartzite reef interspersed with cobble and sand filled gullies between raised reef sections.	Mixed, geniculate Rhodophyta, encrusting algae, finely forked coralline (<i>Jania verrucosa</i>) and <i>Plocamium spp.</i>	Yes
CR pinnacle	4-6m	High	High	Solid undulating quartzite outcrops. Pinnacles are dominated with Redbait (<i>Pyura stolonifera</i>).	Mixed, dominated with <i>Plocamium spp.</i> and <i>Ulva</i> along with coralline algae.	Yes
Thunderbolt	5-10m	Very high	High	Variable reef. Undulating solid quartzite reef with high rising pinnacles interspersed with large boulders and cobble areas. Areas on the periphery are flat with loose boulders and influenced by sand.	Mixed, geniculate Rhodophyta, encrusting algae, finely forked coralline (<i>Jania verrucosa</i>) and <i>Plocamium spp.</i>	Yes
Suicide	7-10m	Very high	High	Solid quartzite reef, with high rising pinnacles, crevices present.	Mixed. <i>Plocamium spp</i> and coralline algae	No

Appendix 1.3 Summary of the in situ emergent abalone density estimates for Cape Recife from 1993 – 2012.

Year	Density per m2	abalone counts	Area (m ²)	Study
1993	1.6			Elliot
1999	1.2	220	180	Godfrey
2001	0.8	122	120	DeWaal
2004	0.5	94	180	Godfrey
2006	0.3	87	320	Daly
2012	0.1	105	1007	Hutchings & Biccard

Appendix 1.4 Summary of the in situ emergent (> 80 mm SL) size measurements of abalone for Cape Recife from 1998 – 2012.

Year	Site	Map area	Survey by	Sample (n)	Average size	Std. Dev
1998	Cape Recife	Yellow block	Scott	49	108	21.3
1999	Cape Recife	Yellow block	Godfrey	41	116	15.9
2000	Cape Recife	Yellow block	Godfrey	29	107	18.7
2001	Cape Recife	Yellow block	Godfrey	37	110	18.5
2004	Cape Recife	Yellow block	Godfrey	32	97	10.1
2006	Cape Recife	Yellow & white block	Daly	43	100	17.3
2012	Cape Recife	Yellow block	Godfrey	39	108	18.5

Appendix 1.5 Juvenile abalone density and size measurements at Cape Recife rock pool.

Date	Site	Survey by	Longitude ³	Latitude ⁴	Transects ⁴	Abalone counts	Density m ²	Std. Dev density	Ave size (mm)	Std Dev size (mm)
Dec-99	CR rock pool	Godfrey			9 x 10m ²	846	9.4	9.6		
Apr&Dec-00	CR rock pool	Godfrey			5 x 10m ²	883	15.7	5.5		
Dec-01	CR rock pool	Godfrey			10 x 4m ²	624	15.6	6.4		
Dec-05	CR rock pool	Godfrey & Raemaekers	25.7036142	-34.0289113	1 x 10m ²	89	8.9	4.6		
Jun&Dec-06	CR rock pool	Godfrey & Raemaekers	25.7036142	-34.0289113	2 x 10m ²	209	10	8.5		
Aug-07	CR rock pool	Godfrey & Raemaekers	25.7036142	-34.0289113	1 x 10m ²	39	3.9	2.3		
Dec-12	CR rock pool	Godfrey	25.7036142	-34.0289113	1 x 10m ²	222	22.3	8.8	19.41	11.92
Dec-13	CR rock pool	Witte	25.7036142	-34.0289113	1 x 10m ²	212	21.2	8.47	14.37	9.67
Dec-14	CR rock pool	Witte	25.7036142	-34.0289113	1 x 10m ²	244	24.3	3.92	20.37	12.88
Mar-16	CR rock pool	Witte	25.7036142	-34.0289113	1 x12m ²	279	23.25	9.82	17	8.71

³ Longitude and Latitude provided are the general vicinity of transects and not the exact location. Transects from 2012-2016 have been undertaken on the inside berm of the rock pool.

⁴ All 1 x 10m² transects consisted of 1m² quadrats along a line often spaced 1m apart and hence Std. Dev for those transects.

Appendix 1.6 Emergent density for the different reef areas around Cape Recife for the 2013 wild abalone survey.

Site	Transect (m ²)	Sample (n)	Total area (m ²)	Density (m ²)
Wild Side CR	20	20	400	0.74
Thunderbolt	20	9	180	0.33
Suicide	20	3	60	0.16
Inside Bay	20	1	20	0.2

Appendix 1.7 Detailed description of transect areas performed for emergent density in the 2013 baseline survey.

Transect	Date	Longitude	Latitude	Reef	Max Depth (m)	Average depth (m)	Diver 1	Diver 2	Survey Area (m ²)	Total Abalone (20m ²)	Density (m ⁻²)	Habitat description
1	25/09/2013	25.69859994	-34.0344326	wild side CR	4	3.5	Warren	Brian	20	18	0.9	Excellent habitat. Plocamium abundant. High profile reef surrounded by sand and small boulder habitat devoid of abalone. Cryptic space in crevices. Many good reefs found in the area.
2	25/09/2013	25.69895846	-34.03465169	wild side CR	4	3.5	Warren	Brian	20	33	1.65	Excellent habitat. Plocamium abundant. High profile reef surrounded by sand and small boulder habitat devoid of abalone. Cryptic space in crevices. Many good reefs found in the area.
3	25/09/2013	25.70316233	-34.03204327	wild side CR	2	1.8	Warren	Brian	20	17	0.85	Good habitat. Plocamium abundant. Plenty of boulders. Juveniles present under rocks. Fair amount of cryptic space (not abundant though)
4	25/09/2013	25.70341215	-34.03231828	wild side CR	2	1.8	Warren	Brian	20	17	0.85	Good habitat. Plocamium abundant. Plenty of boulders. Juveniles present under rocks. Fair amount of cryptic space (not abundant though)
5	25/09/2013	25.70311918	-34.03227692	wild side CR	2	1.8	Warren	Brian	20	41	2.05	Good habitat. Plocamium abundant. Plenty of boulders. Juveniles present under rocks. Fair amount of cryptic space (not abundant though)
6	26/09/2013	25.69920578	-34.03538243	wild side CR	5	4.6	Warren	Brian	20	13	0.65	Good habitat. Plocamium abundant. High

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												profile reef surrounded by either sand or small boulder habitat which were devoid of abalone. Abalone mainly found in crevices (few easily visible).
7	26/09/2013	25.69946376	-34.03533966	wild side CR	5	4.6	Warren	Brian	20	13	0.65	Good habitat. Plocamium abundant. Undulating reef with 1-0.5m gullies running through the transect with small boulder or sand habitat devoid of abalone or marine growth. Abalone mainly found in crevices (few easily visible).
8	26/09/2013	25.69879577	-34.03599506	wild side CR	5	5	Pete	Brian	20	6	0.3	Good habitat. Plocamium abundant. High profile undulating reef surrounded. Abalone mainly found in crevices (few easily visible).
9	26/09/2013	25.69902861	-34.03581477	wild side CR	5	4.8	Pete	Brian	20	4	0.2	Good habitat. Plocamium present. High profile reef surrounded by either sand or small boulder habitat which were devoid of abalone.
10	26/09/2013	25.6993828	-34.03570008	wild side CR	5	4.9	Pete	Brian	20	11	0.55	High profile solid reef with pinnacle close to surface.High energy zone. abundant ascidian growth on pinnacle. Abalone were found inbetween ascidians. Foliose red algae present (hard algae).
11	26/09/2013	25.69626605	-34.03482975	wild side CR	5.8	4.3	Warren	Pete	20	2	0.1	Habitat was satisfactory. Influence of sand movement onto the reef. Many Chitons found in crevices covered with sand. Plocamium present (not hugely abundant). Fairly high profile reef surrounded by either sand or small boulders.
12	26/09/2013	25.69627741	-34.03428184	wild side CR	5.8	4.3	Warren	Pete	20	11	0.55	Habitat was satisfactory for abalone. Less influence of sand movement onto the reef compared to transect 11. Plocamium present (not hugely abundant). Fairly high profile undulating reef. Abalone mainly found in cryptic spaces.
13	02/10/2013	25.699108	-34.035689	wild side CR	5.8	4.3	Warren	Evania	20	21	1.05	Great reef. Plocamium abundant. High profile. Crevices.
14	02/10/2013	25.699589	-34.035506	wild side CR	5.8	4.3	Warren	Evania	20	28	1.4	Great reef. Plocamium abundant. High profile. Crevices.
15	02/10/2013	25.69948685	-34.03505822	wild side CR	5.8	4.3	Warren	Evania	20	14	0.7	Great reef. Plocamium abundant. High profile. Crevices.
16	02/10/2013	25.70115653	-34.03515997	wild side CR	7.8	5.8	Warren	Evania	20	14	0.7	Good reef. Plocamium abundant. High profile. Gullies. Red bait large presence.

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17	02/10/2013	25.70172541	-34.03535125	wild side CR	7.8	5.8	Warren	Evania	20	24	1.2	Good reef. Plocamium abundant. High profile. Gullies. Red bait large presence.
18	02/10/2013	25.70221709	-34.03557513	wild side CR	7.8	5.8	Warren	Evania	20	5	0.25	Good reef. Plocamium abundant. High profile. Gullies. Red bait large presence.
19	02/10/2013	25.70400428	-34.03613093	wild side CR	9.8	8.5	Warren	Evania	20	2	0.1	Appeared to be good reef. Plocamium abundant. Very few abalone (spotted only a few large ones in the area). Undulating reef. Not sure if would be suitable for juveniles.
20	02/10/2013	25.70390102	-34.03636814	wild side CR	9.8	8.5	Warren	Evania	20	2	0.1	Appeared to be good reef. Plocamium abundant. Very few abalone (spotted only a few large ones in the area). Undulating reef. Not sure if would be suitable for juveniles.
21	03/10/2013	25.69256231	-34.0435278	Thunderbolt	5.8	4.3	Warren	Brian	20	7	0.35	small boulder habitat covered with growth. Plocamium abundandant. Bits of ship wreck along transect. Small patches of sand found among boulders.
22	03/10/2013	25.69306137	-34.04341824	Thunderbolt	5.8	4.3	Warren	Brian	20	9	0.45	Profile undulating. Crevices. Plocamuim present. Appeared to be suitable abalone habitat.
23	03/10/2013	25.69345281	-34.04314826	Thunderbolt	5.8	4.3	Warren	Brian	20	14	0.7	High profile reef. Large rocks. Large abalone found. Plenty of crevices. Little Plocamuim seen.
24	03/10/2013	25.69652653	-34.04304743	Thunderbolt	8.1	6.5	Pete	Evania	20	2	0.1	Fairly close to pinnacle
25	03/10/2013	25.69444891	-34.04426062	Thunderbolt	8.1	6.5	Pete	Evania	20	5	0.25	Fairly close to pinnacle
26	03/10/2013	25.695408	-34.043642	Thunderbolt	8.1	6.5	Pete	Evania	20	4	0.2	Abalone graveyard with hundereds of shucked shells lying about. Around Pinnacle
27	03/10/2013	25.69302231	-34.04268583	Thunderbolt	10.4	7	Warren	Brian	20	14	0.7	Closer to Wreck and habitat appeared appropriate for juveniles and abalone.
28	03/10/2013	25.69362723	-34.04209751	Thunderbolt	10.4	7	Warren	Brian	20	5	0.25	Scoured reef. Evidence of boulders being moved around in large surf. No growth on boulders.
29	03/10/2013	25.69371298	-34.04138882	Thunderbolt	10.4	7	Warren	Brian	20	0	0	Lots of sand patches present. Flat profile. Plocamuim abundant. Little to no habitat for juveniles. No crevices. Too deep.
30	03/10/2013	25.63802915	-34.05202277	Suicide	10.1	8.6	Pete	Evania	20	3	0.15	Very High Profile Reef. Lots of Red bait. High energy environment. Crevices present. Plocamium present. Large abalone found on reef. Can be dived in calmest of conditions
31	03/10/2013	25.63815932	-34.05165179	Suicide	10.1	8.5	Pete	Evania	20	3	0.15	Very High Profile Reef. Lots of Red bait. High energy environment. Crevices present. Plocamium present. Large abalone found on

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32	03/10/2013	25.63857162	-34.05170015	Suicide	10.1	8.5	Pete	Evania	20	4	0.2	reef. Can be dived in calmest of conditions Very High Profile Reef. Lots of Red bait. High energy environment. Crevices present. Plocamium present. Large abalone found on reef. Can be dived in calmest of conditions
33	04/10/2013	25.70377369	-34.02616695	Beacon - Lighthouse CR	3	1.8	Warren	Brian	20	4	0.2	Shallow flat reef environment. Wave energy present but not destructive. Sand present. Small boulders. Plocamium present. Good juvenile habitat.
34	04/10/2013	25.706714	-34.035236	wild side CR pinnacle	7.3	5.2	Warren	Brian	20	0	0	Just off the high profile reef. Bits of boulders. Sand in places. No abalone found. Didn't appear to be good habitat.
35	04/10/2013	25.706503	-34.034861	wild side CR pinnacle	7.3	5.2	Warren	Brian	20	10	0.5	High profile, undulating reef. Lots of Red Bait present. High energy. Crevices. Large abalone found with a few smaller ones. Plocamium abundant.
36	04/10/2013	25.70637879	-34.0348361	wild side CR pinnacle	7.3	5.2	Warren	Brian	20	8	0.4	High profile, undulating reef. Lots of Red Bait present. High energy. Crevices. Large abalone found with a few smaller ones. Plocamium abundant.

Appendix 1.8 All Emergent (no size limit) abalone measurements from four reefs around Cape Recife area for the 2013 wild abalone survey.

Site	Longitude	Latitude	Search time (mins)	Sample (n)	Diver	Depth (m)	Min (mm)	Max (mm)	Average (mm)	Std Dev. (mm)
Thunderbolt	25.6955335	-34.0436971	50	40	Pete & Evania	7	65	141	104.2	21.2
Suicide	25.63823	-34.051779	20	10	Brian	9	37	124	92.9	32.6
Inside bay	25.7038613	-34.0259847	15	3	Pete	2.5	61	85	72.7	10.7
Wild side pinnacle	25.706398	-34.034974	60	35	Pete	5	37	128	85.9	26.3

Appendix 1.9 Total confiscations of abalone for the Eastern Cape province of South Africa

Year	Total units confiscated	Number of units sampled	Ave indiv mass (g) ± 95% CI	Std. Dev	95% CI	Min mass (g)	Max mass (g)
1998	9172	1068	136.0	49.47	2.97	48	329
1999	2449	2299	137.2	50.58	2.07	30	345
2000	28399	12687	140.2	58.14	1.01	15	1238
2001	25489	16356	148.9	68.58	1.05	13	652
2002	31437	20748	137.2	69.05	.94	10	540
2003							
2004	5305	2052	138.0	73.12	3.16	9	506
2005	48367	14271	130.8	72.28	1.19	6	2575
2006	21110	5958	97.7	63.79	1.62	7	459
2007	7116	3670	90.4	47.42	1.53	16	325
2008	20207	9745	73.7	45.47	.90	6	468
2009	15002	4102	114.4	51.61	1.58	19	421
2010	10647	2179	101.0	35.01	1.47	10	327
2011	6112	3489	112.8	38.09	1.26	19	343
2012	5559	3554	114.3	38.68	1.27	35	438

Appendix 1.10 Total confiscated abalone at Cape Recife in the Eastern Cape Province.

Year	Total Confiscation	Number Sampled	Mean (g)	Min (g)	Max (g)	Std. Dev
1999	1185	1035	128	18	304	43
2000	3012	2517	115	15	310	43
2001	2951	2942	102	13	652	50
2002	4570	4373	95	13	351	46
2004	437	400	77	24	246	36
2005	2742	1918	97	6	517	67
2006	1224	1070	64	9	229	41
2007	470	288	67	16	210	40
2008	432	432	45	16	152	18
2010	227	227	69	26	159	28
2012	264	264	93	35	177	29

Appendix 2

Appendix 2.1: Experimental plot seeding for all habitats (outside: plots 1-18 and inside the bay: plots 19-36)

Plot #	Latitude	Longitude	Box Ref	Density	Abalone bag weight (kg)	Abalone size	Ave Size (g)	Ave size (mm)	Diver Name	Dive start	Dive finish	Dive time (mins)	GoPro Seed/follow up	GoPro Plot Mark
1	-34.036201509	25.699721212	OB15	100	2.7	B	27.1	49.6	Brian	12:30	12:49	19	-	-
2	-34.0363295	25.699508982	OB17	100	1.2	S	12.2	37.5	Warren	12:23	12:45	22	-	-
3	-34.036057591	25.699263643	OB6	400	4.4	S	11.0	36.1	Warren	10:55	12:00	65	YES	-
4	-34.036299661	25.699634794	OB8	200	5.1	B	25.4	48.5	Brian	13:12	13:37	25	-	YES
5	-34.036411811	25.699718781	OB7	200	5.1	B	25.4	48.4	Cale	12:40	13:08	28	-	YES
6	-34.036321035	25.699382834	OB12	200	2.3	S	11.3	36.5	Brian	12:27	13:00	33	YES	YES
7	-34.035872519	25.698803393	OB11	200	2.1	S	10.5	35.5	Cale	11:45	12:10	25	-	YES
8	-34.035580158	25.698963068	OB13	100	2.7	B	26.6	49.2	Pete	12:15	12:32	17	YES	YES
9	-34.035043968	25.698279776	OB4	400	4.3	S	10.7	35.7	Warren	12:07	13:45	85	YES	YES

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10	- 34.03584695 4	25.69918921 2	OB14	100	2.7	B	26.8	49.3	Tom	11:35	11:50	15	YES	YES
11	- 34.03574687 4	25.69923975 5	OB16	100	1.4	S	13.6	38.9	Brian	11:55	12:10	15	-	YES
12	- 34.03552265 8	25.69934645 7	OB5	400	4.2	S	10.4	35.4	Brian	10:45	11:10	25	YES	-
13	- 34.03473652	25.69837801 2	OB9	200	5.1	B	25.4	48.4	Brian	11:30	11:40	10	YES	-
14	- 34.03463660 7	25.69838723 2	OB10	200	2.2	S	10.8	35.9	Brian	11:50	12:05	15	YES	-
15	- 34.03421432 7	25.69863466 5	OB18	100	1.4	S	13.6	38.9	Tom	12:00	12:13	13	YES	-
16	- 34.03461347 3	25.70221566 6	OB1 +OB3	400	10.5	B	26.2	49.0	Brian	10:10	11:15	65	YES	-
17	- 34.03470383	25.70244885	OB1 +OB3	400	10.6	B	26.4	49.1	Tom/ Warren	11:00	12:05	70	YES	-
18	- 34.03481002 9	25.70249327 5	OB2 +OB2	400	10.8	B	27.0	49.5	Pete/ Tom	-	-	70	-	-
19	- 34.02604097	25.70276745	IB13	100	3.0	B	29.9	51.3	Diane	14:20			-	-
20	- 34.02583368	25.7027739	IB4	400	5.1	S	12.8	38.1	Adrian/ Diane	10:45			-	YES
21	- 34.02561969	25.70264407	IB5	400	5.2	S	13.1	38.4	Cale/ Alita	YES			YES	YES
22	-34.026117	25.702837	IB6	400	5.1	S	12.7	38.0	Pete	11:00			YES	-
23	- 34.02599294	25.70267893	IB16	100	1.4	S	13.6	38.9	Tom	11:05			-	-
24	-34.025986	25.702939	IB12	200	2.5	S	12.3	37.6	Cale	14:35			-	-
25	- 34.02584483	25.70233779	IB15	100	2.9	B	29.2	50.9	Pete				-	-

26	- 34.02565263	25.70250467	IB14	100	2.9	B	29.3	50.9	Warren	14:25	-	-
27	- 34.02547234	25.70238867	IB8	200	5.7	B	28.7	50.6	Adrian	13:35	Yes	-
28	- 34.02531308	25.70275269	IB3	400	11.2	B	28.0	50.1	Cale/ Alita	13:00	-	YES
29			IB10	200	2.5	S	12.4	37.7	Warren	15:20	-	YES
30	- 34.02480958	25.70210653	IB1	400	11.4	B	28.4	50.4	Cale/ Alita	11:30	-	YES
31	- 34.02455661	25.70202355	IB9	200	5.4	B	27.1	49.6	Tom	11:30	-	-
32	- 34.02534594	25.70239982	IB7	200	5.8	B	29.2	50.9	Adrian	11:50	YES	YES
33	-34.0244759	25.70194141	IB17	100	1.4	S	13.5	38.8	Pete	12:00	YES	-
34	- 34.02518433	25.70194719	IB2	400	11.5	B	28.8	50.6	Warren/ Diane	13:25	-	-
35	- 34.02435293	25.70185298	IB18	100	1.3	S	13.5	38.8	Pete	12:25	-	-
36	- 34.02415076	25.70148728	IB11	200	2.4	S	11.8	37.0	Cale	14:00	-	-

Appendix 2.2 Destructive sample of plots from the first round of sampling for all sites

Plot #	Density	Seed size	Diver	Mark located	Search (mins)	time	Bag (kg)	weight	Seeded counts	Wild collected	% of initial seeded
1	100	B	Diane	YES	100		1.5		5	11	5.0
2	100	S	Warren	YES	90		1.4		24	25	24.0
3	400	S	Warren	YES	130		4.2		123	55	30.8
4	200	B	Andrew	YES	120		1.4		15	13	7.5

5	200	B	Adrian	YES	110	3.1	51	27	25.5
6	200	S	Diane	YES	70	1.7	21	10	10.5
7	200	S	Diane	YES	85	2.3	39	20	19.5
8	100	B	Andrew/ Adrian Diane/ Adrian/	YES	130	1.5	13	24	13.0
9	400	S	Warren	YES	210	2.2	98	3	24.5
10	100	B	Andrew	YES	85	2.3	3	25	3.0
11	100	S	Adrian	YES	95	1.6	5	32	5.0
12	400	S	Adrian	YES	120	0.8	25	9	6.3
13	200	B	Warren	YES	125	2.2	41	4	20.5
14	200	S	Warren	YES	85	1.6	53	6	26.5
15	100	S	Andrew	YES	75	0.8	6	11	6.0
16	400	B	Warren	YES	135	4.5	78	21	19.5
17	400	B	Andrew	YES	100	1.4	33	6	8.3
18	400	B	Jacque/ Andrew	YES	120	2.4	37	12	9.3
19	100	B	Andrew	NO	150		4	21	4
20	400	S	(no search)	NO					
21	400	S	Diane/ Andrew	YES	175	2.5	34	18	8.5
22	400	S	Warren	NO	150	3.6	0	71	0
23	100	S	(no search)	NO					
24	200	S	Adrian	YES	140	3.5	36	43	18
25	100	B	Warren	YES	105	4.4	19	34	19

26	100	B	Cale	YES	105	1.8	10	24	10
27	200	B	Matt	YES	210	6.8	6	52	3
28	400	B	Alex/ Warren	YES	155	4.1	16	43	4
29	200	S	Warren/ Alex	YES	217	6.6	53	82	26.5
30	400	B	(no search)	NO					
31	200	B	Dave/ Warren	YES	250	8.4	13	91	6.5
32	200	B	Andrew	YES	140	3.5	27	22	13.5
33	100	S	Andrew	YES	98	2.2	20	26	20
34	400	B	Adrian	YES	135	4.7	15	44	3.75
35	100	S	Warren	YES	130	4.9	42	57	42
36	200	S	Adrian	YES	120	3.0	14	45	7

Appendix 2.3: Destructive sample of all plots for the second round of sampling.

Plot #	Density	Seed size	Diver	Mark located	Search time	Bag weight (kg)	Seeded counts	Wild collected	% of initial seeded
1	100	B	Cale	YES	115	0.43	3	5	3
2	100	S	Diane	YES	95	1.18	1	30	1
3	400	S	Cale	YES	80	0.89	14	10	3.5
4	200	B	Warren	YES	130	2.75	16	16	8
5	200	B	Warren	YES	95	3	15	34	7.5
6	200	S	Warren/ Cale	NO	80	1.06	6	20	3
7	200	S	Cale	YES	130	0.27	4	7	2
8	100	B	Warren	YES	95	1.6	9	17	9
9	400	S	Andrew	YES	95	0.98	11	14	2.75
10	100	B	Cale	YES	115	1.16	5	11	5
11	100	S	Andrew	YES	105	0.85	0	12	0
12	400	S	Warren	YES	135	0.98	15	7	3.75
13	200	B	(no search)	NO					
14	200	S	Andrew	YES	95	0.92	9	2	4.5
15	100	S	(no search)	NO					
16	400	B	Warren/ Cale	NO	70	1.1	10	9	2.5
17	400	B	Warren	YES	90	1.87	27	6	6.75
18	400	B	Cale/ Diane	YES	90	1.66	7	16	1.75
19	100	B	(no search)	NO					
20	400	S	(no search)	NO					

21	400	S	Andrew	YES	110	2.2	22	21	5.5
22	400	S	Adrian + Pete	YES - NO	185	7.69	1		0.25
23	100	S	(no search)	NO					
24	200	S	Cale	YES	70	0.43	10	4	5
25	100	B	Evania	YES		3.22	1	24	
26	100	B	(No search)	YES					
27	200	B	Warren	YES	105	1	5	12	2.5
28	400	B	Pete	YES	95	0.815	2	15	0.5
29	200	S	Evania	YES	82	1.73	3	26	1.5
30	400	B	(no search)	NO					
31	200	B	Evania	YES	65	1.265	3	16	1.5
32	200	B	Pete	NO	56	0.5	0	4	0
33	100	S	Warren	NO	60	2.26	3	32	3
34	400	B	Andrew/ Warren	YES	170	6.92	11	74	2.75
35	100	S	(no search)	YES					
36	200	S	Cale	YES	71	0.545	3	9	1.5

Appendix 2.4 Summary of annual growth measured from the outside bay and inside bay habitats for sample periods 1 and 2.

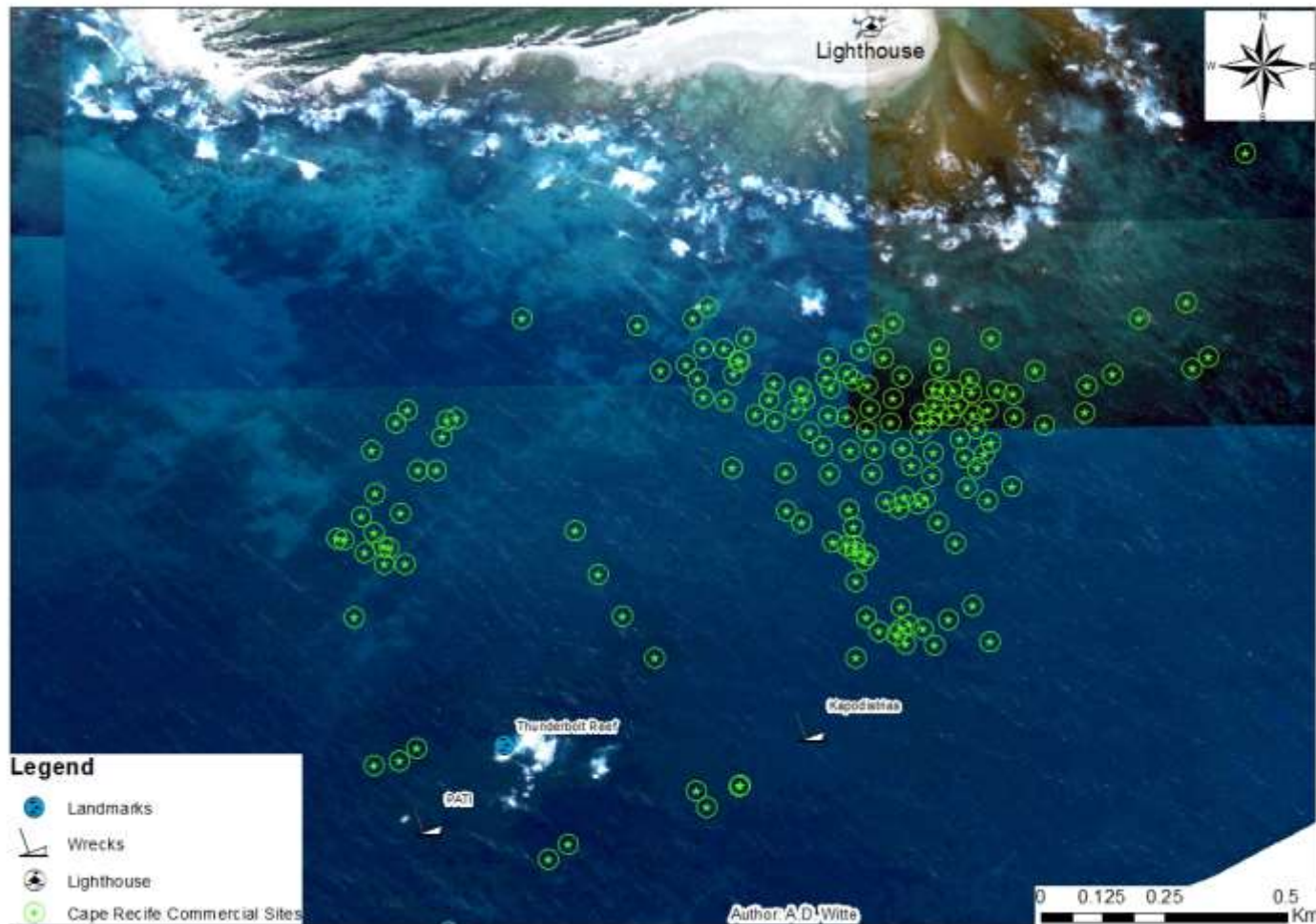
Habitat	Sample round	Valid n	Mean Monthly Growth (mm)	Minimum		Std. Dev.	Mean
				Monthly Growth (mm)	Max Monthly Growth (mm)		Annual Growth (mm)
Outside	1	594	0.78	0	3.62	0.55	9.39
Inside	1	296	1.93	0.04	3.33	0.49	23.18
Outside	2	144	1.20	0.25	2.55	0.44	14.49
Inside	2	64	1.67	0.24	2.73	0.44	20.1

Appendix 2.5 : Growth per month on plots for sample round 1 and 2.

Plot #	SR1			SR2		
	Growth per month (mm)			Growth per month (mm)		
	Mean	Count	Std dev.	Mean	Count	Std dev.
1	0.91	5	0.30	1.45	3	0.49
2	0.44	24	0.40	1.45	1	
3	0.80	102	0.40	1.20	12	0.32
4	0.52	15	0.25	1.31	16	0.33
5	0.38	31	0.63	1.11	15	0.35
6	0.72	17	0.36	1.40	6	0.13
7	1.23	37	0.39	1.22	4	0.17
8	0.70	9	0.55	1.13	9	0.48
9	1.07	91	0.51	1.47	11	0.51
10	1.07	3	0.78	0.67	4	0.57
12	0.43	25	0.58	1.07	13	0.30
13	1.42	39	0.29			
14	1.08	50	0.42	2.08	9	0.30
15	0.70	5	0.39			
16	0.32	75	0.40	0.93	8	0.30
17	0.58	32	0.40	0.98	26	0.34
18	0.54	34	0.47	1.18	7	0.34
19	1.83	4	0.60			
21	1.92	55	0.49			
24	2.27	45	0.42			
25	1.64	16	0.34	1.38	1	
26	1.94	10	0.57			
27	2.04	11	0.51			
28	1.73	16	0.53	2.08	2	0.01
29	2.03	51	0.43	1.61	3	0.34
31	2.01	13	0.51	1.22	3	0.60
32	1.73	27	0.43			
33	1.66	20	0.46	1.68	3	0.10
34	1.60	15	0.58	1.26	10	0.61
35				1.80	39	0.33
36	2.09	13	0.33	1.86	3	0.54

Appendix 3

Appendix 3.1 Seeding sites at Cape Recife showing the central points for nearly a 160 commercial sites from which underwent seeding between June 2014 and September 2016. The depth of most sites ranged between 5 and 10m.



Appendix 3.2 Basic habitat ranking system to indicate the habitat suitability of an area based upon criteria regarded as important to the survival of *H. midae*

Reef profile		Plocamium/ seaweed cover		Crevices/ cryptic space & overhangs		Wild abalone		Sea-urchines		Total ranking	Habitat ranking	Category	Habitat ranking
Sand	0	<10%	1	none	0	none	1	none	0	2	Unsuitable	≥6	E
Flat	2	10-20%	1	some	2	few	1	few	2	8	Minimum requirement	7≥10	D
Some undulation	3	25-50%	2	moderate	3	moderate	2	moderate	3	13	Suitable	11≥15	C
moderate profile + undulation	3	50-75%	3	many	4	many	2	many	4	16	Good	16≥17	B
Undulating/ high profile/ ledges	4	>75%	4	most of site having cryptic space	4	lots	3	lots	5	20	Excellent	18≥	A

Appendix 3.3 Shell collections on sites for large-scale surface scatter seeding for abalone sizes ranging from 60-81mm SL. Divers would collect shells during quadrat surveys or in separate dedicated shell collecting trips for a set period of time.

Comm Site #	Days since release	Sample round	Dedicated shell collec	Ave size (mm)	Collect time (mins)	# of divers	Tot time (mins)	Shell collections	# seeded	# seeded minus M	% mortality (min)	Tot mortality
10	1	1	yes	76	25	3	75	101	2810			3.6
10	16	2	yes	5	30	2	60	50	2810	2709	1.8	5.4
10	266	3	no	76		2		69	2810	2659	2.6	7.8
10	309	4	yes	76	25	3	75	97	2810	2590	3.7	11.3
10	633	5	yes	76	20	2	40	47	2810	2493	1.9	13.0
13	1	1	yes	72	25	3	75	23	2481			0.9
13	36	2	yes	72	70	1	70	152	2481	2458	6.2	7.1
13	243	3	no	72		2		46	2481	2306	2.0	8.9
13	308	4	yes	72	25	3	75	97	2481	2209	4.4	11.9
14	1	1	yes	81	25	3	75	33	1764			1.9
15	55	1	yes	81	30	3	90	114	1719			6.6

15	71	2	no	81		2		74	1719	1605	4.6	10.9
15	199	3	no	81		2		28	1719	1531	1.8	12.6
15	293	4	yes	81	25	3	75	36	1719	1503	2.4	14.7
15	596	5	no	81				14	1719	1467	1.0	15.5
16	1	1	yes	79	25	3	75	123	1875			6.6
16	266	2	yes	79	35	2	70	176	1875	1752	10.0	15.9
16	596	3	yes	79	35	2	70	151	1875	1576	9.6	24.0
17	9	1	yes	64	25	3	75	114	4237			2.7
18	9	1	yes	60	20	4	80	70	5699			1.2
18	281	2	no	60		3		65	5699	5629	1.1	2.4
18	605	3	no	60				39	5699	5564	0.7	3.1