Sea ranching trials for commercial production of greenlip (*Haliotis laevigata*) abalone in Western Australia

An outline of results from trials conducted by Ocean Grown Abalone Pty Ltd

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Abstract

The sea ranching trials reported here took place in Flinders Bay, Augusta, Western Australia, between late September 2011 and early January 2013.

Aquacultured greenlip abalone seed stock of three different year-classes and sizes [year-2 (~40 mm), year-3 (~70 mm) and year-4 (~90 mm)] were placed on ten different artificial habitat designs on lease sites spaced one to two kilometres apart in depths of 15 to 19 m. Stocking densities were not consistent on all habitat types. However, in general year-2 animals were stocked at ~30 m^{-2}, year-3 at ~9 m^{-2} and year-4 at ~3 m^{-2}.

Growth increments were similar on all artificial habitat types and for the three R&D leases. When growth for the three year classes was integrated into a modelled growth curve, the projected growth was very similar to growth recorded by a different study for aquacultured greenlip abalone seeded in the wild fishery off Augusta in less intensively stocked numbers.

Survival characteristics were considered as initial survival (within weeks of seeding) and long-term survival (over one year after seeding). Initial survival in this study was related to the age of the seed stock, to the habitat type and to the lease site. The 3 and 4-year old seed stock had an initial survival of 80-98% and 2-year olds 50-85%, depending on the lease site. One lease site had substantially lower initial survival rates compared to the other two leases, which would indicate that the stock seeded on this site may have been stressed in transit prior to release. Two habitat types had disproportionately low initial survival rates of 2-year old seed stock which was attributable to their having been seeded by hand rather than with release units.

Long-term survival ranged from 80-95% for 2-year old, 85-95% for 3-year old and 75-95% for 4-year old seed stock depending on lease site. There were differences in the long-term survival rates for the three year classes on different habitat types on the three leases. However, these differences were clouded by the movement of seed stock between neighbouring habitat types.

Perhaps the most useful survival data in terms of using sea ranching trials to project the survival of seeded abalone from seeding as 2-year olds to 5+year olds, is the integrated survival data for the three year classes. That shows the survival after initial stocking and three subsequent years (i.e. 37 months) to be around 40 to 55%.

Overall, this sea ranching trial has produced very promising outcomes in terms of the potential for commercial scale production of greenlip abalone in Flinders Bay, Augusta. The key findings from this research were that:

- after an initial mortality phase, that with good management (including predator removal) mortality rates of 2 to 4-year old seed stock can be limited to as little as 5 to 10% a year
- that growth rates comparable with abalone in the wild environment can be achieved at relatively high stocking densities and the densities of 20-60m^{-2} used in this study appear to be within the bounds of what can be supported by the habitat
- that growth and survival rates are similar in different lease sites within Flinders Bay. This shows that conditions for sea ranching are suitable over a wide area within the Bay opening the way for future opportunities of orderly expansion of sea ranching activity in this location

Acknowledgements

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1 Introduction

Abalone is a high value product and innovative ideas aimed at increasing its production are not new. The Japanese have had hatcheries producing juvenile abalone for enhancing their commercial fisheries for several decades ((Imamura 1999)) and experimental releases of juveniles have been trialled elsewhere (e.g. in the United States of America (Tegner and Butler 1985)), Australia (Shepherd *et al*. 2000), South Africa (Sweijd *et al*. 1998) and New Zealand (Roberts *et al*. 2007). The results from these and many other studies have been variable, with size at release and site selection being key factors determining the survival of seed stock to harvestable size and therefore the economic viability of any such venture.

Hillborn (1998) suggests that enhancement activities generally fall into (i) habitat construction or restoration and (ii) the stocking of juveniles. These different forms of enhancement are not exclusive; Shepherd *et al*. (2000) and Roberts *et al*. (2007) for example, constructed purpose built boulder reefs for their abalone enhancement experiments. There is however, an important difference associated with enhancement where habitat is constructed over that where juveniles are released into the wild to enhance natural recruitment, in that the former option can more easily overcome the issue of ownership of seeded abalone.

The creation of new habitat and additional production in the wild over and above sustainable yields falls into the definition of 'sea ranching', as distinct from the terms 'restocking' and 'stock enhancement' (see Bell *et al*. (2008) for detailed definitions). Sea ranching is an easier economic proposition to deal with than the other two objectives which focus on the release of cultured juveniles into the wild to augment natural recruitment. The costs of enhancing a fished area are substantial and agreement amongst stakeholders as to any additional benefits to production from their investment is likely to be a point of contention. However, in the case of sea ranching, the objective is to harvest the animals that are released at a larger size and therefore by implication, to achieve that goal the animals that are released should be easy to recover.

Ocean Grown Abalone Pty Ltd (OGA) is currently the only company in Western Australia with an approved aquaculture licence for the purpose of commercial ranching of abalone. The licence has been granted by the Department of Fisheries Western Australia under Section 2 of the Fish Resources Management Act of 1994 and is for a 40.02 ha area in Flinders Bay, Augusta (Figure 1). Application has been made for a further two similar sized areas to the north west of the Main Lease (Figure 1). This application is currently being considered by the Department of Fisheries.

This report outlines the results from a one-year proof of concept trial that was undertaken between late 2011 to the start of 2013. As part of that trial, juvenile hatchery reared stock were placed into the marine environment on purposely designed concrete habitat modules in a location that was specifically selected as having the required biological and ecological requirements to optimise the natural growth of greenlip abalone.

OGA has been responsible for the deployment, seeding and regular monitoring of the habitat structures over the duration of the experiment. Curtin University has been responsible for validating the experimental sampling results, for the analysis of the data and for writing this report.

2 Methods

2.1 Seed stock production

Hatchery reared seed stock abalone were sourced from 888 Abalone Pty Ltd in Bremer Bay. Theses F1 juveniles were the progeny of brood stock that had been collected as adults from Flinders Bay, close to the aquaculture site. Three different size classes (cohorts) of juvenile abalone were used in this grow-out trial: 2-year (~40 mm shell length), 3-year (~60 mm shell length) and 4-year (~90 mm shell length). In the case of each cohort, the spawnings were from different parent brood stock.

The seed stock were held in tanks with the water supply pumped directly from the ocean and supplied at ambient temperature. The juveniles were held on cultured diatom nursery plates for approximately nine months, before being weaned onto commercial formulated feeds at approximately 15 mm shell length.

2.2 Transport of seed stock

Seed stock were transported on several different occasions from the hatchery at Bremer Bay to the Augusta study site. Stocking occurred over a prolonged period from 30 September through 16 December 2011.

On the day of transporting, the juvenile abalone were encouraged to detach from the substrate to which they were clinging by spraying surfaces with a strong salt solution. The detached abalone were then randomly placed into onion bags according to numbers allocated by the experimental design to be seeded to each habitat structure. Each bag was labelled with the type of habitat structure to which they were to be attached. The labelled onion bags were placed inside plastic oyster baskets stacked inside an insulated container that had recirculated chilled seawater spraying over the contents.

The journey from Bremer Bay to the study site at Augusta is approximately five hours. On arrival at Augusta, oyster baskets with the juvenile abalone were transported to the study site by boat for placement by divers onto the habitat structures.

The content of each onion bag was attached to the structure to which it had been allocated. In the case of the 2-year old year classes, the contents were emptied into different types of release modules similar in concept to those used by (McCormick et al. 1994) and the exits of the release modules were shut with shade cloth netting. The shade cloth was removed after two days to allow the abalone to move freely on the habit structure. Two habitat types (kerb and besser blocks, see below for description) had shapes which were not suitable for the attachment of release modules and in these cases the two year-old year juveniles were attached by hand.

Because of the size of release module necessary to contain year-3 and year-4 abalone, this type of release mechanism was found to be unsuitable. These year classes were therefore individually placed on the habitat structures by hand.

2.3 The study site

The aquaculture lease sites which are the focus of the sea ranching reported on in this study are located in Flinders Bay outside the town of Augusta (Figure 1). Greenlip abalone are generally distributed shallower than 40 m and southwards of Cape Naturaliste and given that Flinders Bay is approximately 100 km south of Cape Naturaliste, the wild stocks of greenlip abalone in this area are towards the north and western most distribution of the species along the Western Australian coast.

Flinders Bay covers a large area, all generally shallower than 20 m. The southern part of the bay is fringed by offshore reef covered with seaweed and kelps. Inside the bay, there is generally hard bottom reef area to the east and in the west, where the study sites are located, there is generally soft sandy bottom with extensive seagrass beds.

As has already been mentioned, Ocean Grown Abalone has a 40 ha aquaculture approved lease site, hereafter known as the Main Lease. The habitat modules on this lease site were on flat sandy bottom interspersed with irregular sea grass, at a depth of ~ 19 m between the west (34^{o} 22.461’S, 115^{o} 12.167’E) and east (34^{o} 22.463’S 115^{o} 12.242’E) mooring (Figure 1).

Two other small site locations have been given temporary approval by the Department of Fisheries for OGA to conduct abalone sea ranching trials. These two sites, termed R&D1 and R&D2 (Figure 1), are slightly shallower than the Main Lease site. R&D1 (34^{o} 21.772’S 115^{o} 11.505’E) is in the western corner of one of the two lease sites that have been applied for by OGA and which are presently under consideration by the Department of Fisheries. This site, as with the Main Lease site, is on sandy bottom with sea grass cover at a depth of ~15 m. R&D2 (34^{o} 21.254’S 115^{o} 11.063’E) is to the north of both R&D1 and the two aquaculture lease sites being considered for approval (Figure 1). It too is on flat sandy bottom with sea grass cover and is at a maximum depth of 16 m.

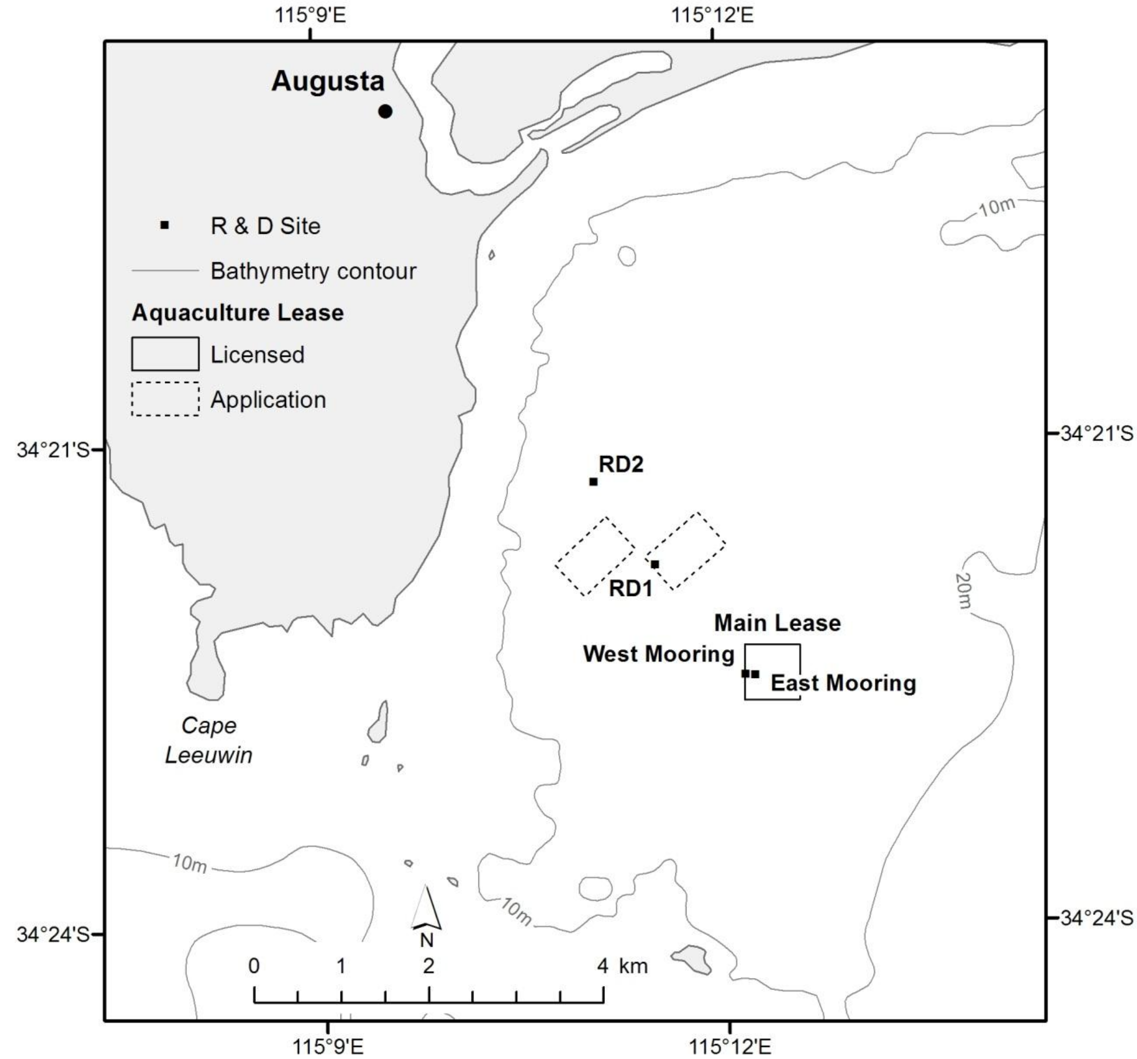


Figure 1: Map showing boundaries of the Two Oceans Pty Ltd greenlip (*H. laevigata*) abalone aquaculture lease in Flinders Bay, offshore from Augusta, Western Australia and two additional sites for which application has been made to the Department of Fisheries. The three sea ranching trial lease sites forming the basis of this study are shown on the map as Main Lease, R&D1 and R&D2.

2.4 Habitat structure designs

Several different types of concrete habitat structures have been trialled in this study. A description of each is provided below.

(i) ***Star units:*** These units have eight fins 200 mm wide, radiating out of a central axis (Figure 2a). The unit stands 0.6 m high and has a total surface area of ~ 2 m^2. Varying numbers were positioned on all three lease sites.

(ii) ***Tube units*** (culvert drains), are 400 mm in diameter and 1.4 m in length (Figure 2b). They have been laid together lengthways in groups of three, each group representing one replicate. The total area of the inside and outside surfaces of the three pipes making up a tube unit is ~10.5 m^2. Varying numbers were positioned on all three lease sites.

(iii) ***Tubes 'V' reef*** is a variation of the tube unit habitat. This is a habitat structure only used on the Main Lease, made up of tube units placed in 'V' formation with the point of the "V' facing inshore so as to most efficiently 'trap' drift algae. The 'V' reef has five tube units (i.e. groups of three tubes) on each side of the 'V', providing a total surface area of 105 m^2 for the whole 'V' reef structure.

(iv) ***Hollow block units*** comprise four blocks of dimensions 400*400*400 mm, hollow on the inside and standing sideways on a base plate 2 m long by 600 mm wide (Figure 2c). The total area of exposed surfaces is ~4.4 m^2. Varying numbers were positioned on all three lease sites.

(v) ***Train hollow block units*** are a variation of the hollow block unit habitat. This habitat structure, only used on the Main Lease, is made up of square units placed in line formation approximately 0 – 10 cms apart. The line on the Main Lease comprised of 10 hollow block units placed in a roughly east-west direction to 'trap' drift algae being washed inshore. The Main Lease was the only site to have a train hollow block unit.

(vi) ***Solid block units*** are four trapezoid shaped blocks with gently tapering sides, 400 mm square on the top, tapering to 360 mm at the base, resting on a base plate 2 m long by 600 mm wide (Figure 2d). The total area of exposed surface is ~3.76 m^2. Varying numbers were positioned on all three lease sites.

(vii) ***Train solid block units*** are a variation of the solid block unit habitat. This habitat structure, only used on the Main Lease, is made up of solid block units placed in line formation approximately 0 – 10 cms apart. The line on the Main Lease comprised of nine solid block units placed in a roughly east-west direction to ‘trap’ drift algae being washed inshore.

(viii) ***Kerb units*** measure 150*160*600 mm (Figure 2e). The units were deployed in a roughly east-west direction so as to ‘trap’ drift algae being washed inshore. Varying numbers were positioned on all three lease sites. The surface area is 0.29 m^2. Ten kerbs were used to form a unit, so the dimension of the complete habitat unit is 2.90 m^2.

(ix) ***Besser blocks***, also known as concrete masonry units, are rectangular bricks of two standard sizes, 290*390*190 mm and 190*390*190 mm, both sizes having two hollow central cavities (Figure 2f). The larger sized besser blocks are used as habitat structure, with different combinations of between two and six blocks held together with cable ties to form a single replicate. The surface area of a single large block is 0.59 m^2. The smaller blocks were placed at regular intervals several metres away from the different habitat structures, to provide solid structure in the sand for any seed abalone that migrating off the artificial reef structures. Varying numbers were positioned on all three lease sites. The surface area of each of these small blocks was 0.48 m^2.

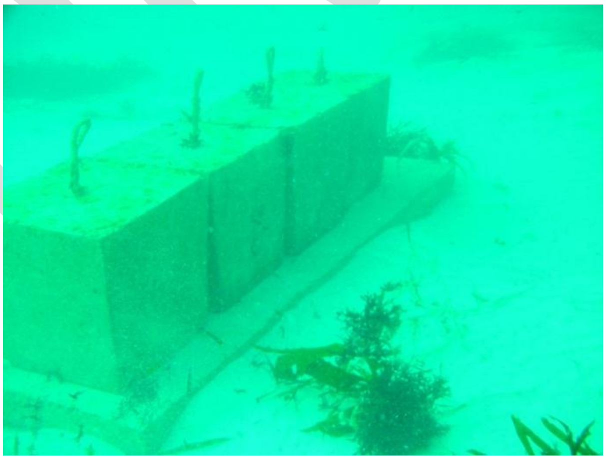
(x) ***Haejoo units*** are purpose designed structures built for shellfish (e.g. abalone and oyster) and juvenile fish production (Australian patent application AU2012202698) (Figure 2g). They are manufactured by international artificial reef specialists, Haejoo Pty Ltd. and have a surface area of 4.5 m^2 (Norwood 2012). The Main Lease site does not have any of these units.

(a)

(b)

(c)

(d)



(e)

(f)

(g)

Figure 2a-g: Different habitat types trialled in this sea ranching trial undertaken at Flinders Bay, Augusta, Western Australia: (a) star units, (b) tube units, (c) hollow block units, (d) solid block units, (e) kerb units, (f) besser blocks, (g) Haejoo units.

2.5 Stocking densities

As previously noted, ten different habitat designs were trialled and not all artificial habitat unit types were used on all three lease sites. The type and number of habitat designs trialled on the three R&D leases are summarised in Tables I to III. Also in Tables I to III is the number of abalone stocked overall, per habitat unit and per m^2 of potentially available space on each type of unit.

Table I: Details of habitat structure designs on the Main Lease of the sea ranching lease sites in Flinders Bay, Augusta, Western Australia, including number of *H. laevigata* stocked in each year class, number of habitat units and numbers stocked per m^2 of habitat area

UNIT DESIGN	Initial Stocking Density (total number of abalone)	Number of habitat units	Number stocked per habitat unit	Number stocked per m^2 of habitat area
Star Units		20		
Year-2	1200		60	30
Tubes – V reef		10		
Year-2	2400		240	22.9
Tubes – Groups of 3		10		
Year-2	2640		9x240; 1x480	22.9; 45.7
Hollow Block Units		10		
Year-2	1980		9x180; 1x360	40.9; 81.8
Solid Block Units		10		
Year-2	1980		9x180; 1x360	47.9; 95.7
Kerb Units		11		
Year-2	1440		10x120; 1x240	41.4; 82.8
Train – Hollow Blocks		10		
Year-2	1800		180	40
Year-3	200		20	4.4
Year-4	50		5	1.1
Train – Solid Blocks		9		
Year-2	1620		180	60
Year-3	180		20	6.7
Year-4	45		5	1.7
Besser Block Units		72		
Year-2	1960		10 per block	22.2
Year-3	392		2 per block	4.4
Year-4	78		0.25 per block	0.6
Total year-2 seed	17020			
Total year-3 seed	772			
Total year-4 seed	173			

Table II: Details of habitat structure designs on the R&D1 lease of the sea ranching lease sites in Flinders Bay, Augusta, Western Australia, including number of *H. laevigata* stocked in each year class, number of habitat units and numbers stocked per m^2 of habitat area

UNIT DESIGN	Initial Stocking Density (total number of abalone)	Number of habitat units	Number stocked per habitat unit	Number stocked per m^2 of habitat area
Star Units		5		
Year-2	300		60	30
Year-3	30		6	3
Year-4	10		2	1
Solid Block Units		5		
Year-2	500		100	26.6
Year-3	200		40	10.6
Year-4	50		10	2.7
Hollow Block Units		5		
Year-2	500		100	22.7
Year-3	200		40	9.1
Year-4	50		10	2.3
Tube Units		5		
Year-2	500		100	9.5
Year-3	200		40	3.8
Year-4	50		10	1
Kerb Units				
Year-2	500	5	100	34.5
Year-3	200		40	13.8
Year-4	50		10	3.4
Besser Blocks		18		
Year-2	360		20 (10 per block)	22.2
Year-3	114		6 (3 per block)	6.7
Year-4	38		2 (1 per block)	2.2
Haejoo Units		15		
Year-2	900		60	13.3
Year-3	675		45	10.0
Year-4	375		25	5.6
Total year-2 seed	3560			
Total year-3 seed	1619			
Total year-4 seed	623			

Table III: Details of habitat structure designs on the R&D2 lease of the sea ranching lease sites in Flinders Bay, Augusta, Western Australia, including number of *H. laevigata* stocked in each year class, number of habitat units and numbers stocked per m^2 of habitat area

UNIT DESIGN	Initial Stocking Density (total number of abalone)	Number of habitat units	Number stocked per habitat unit	Number stocked per m^2 of habitat area
Star Units		5		
Year-2	300		60	30
Year-3	30		6	3
Year-4	10		2	1
Solid Block Units		4		
Year-2	400		100	26.6
Year-3	160		40	10.6
Year-4	40		10	2.7
Hollow Block Units		5		
Year-2	500		100	22.7
Year-3	200		40	9.1
Year-4	50		10	2.3
Tube Units		5		
Year-2	500		100	9.5
Year-3	200		40	3.8
Year-4	50		10	1
Kerb Units		5		
Year-2	500		100	34.5
Year-3	200		40	13.8
Year-4	50		10	3.4
Besser Blocks		16		
Year-2	340		10 per block	22.2
Year-3	96		3 per block	6.7
Year-4	30		1 per block	2.2
Haejoo Units		15		
Year-2	900		60	13.3
Year-3	675		45	10.0
Year-4	375		25	5.6
Total year-2 seed	3440			
Total year-3 seed	1561			
Total year-4 seed	605			

2.6 Lease site sampling regime

The habitat structures on the different lease sites were deployed six weeks or longer before stocking, to allow for the units to condition. Stocking of the lease units with seed abalone took place over an extended period.

The Main Lease was stocked from 30 September through 11 October 2011. R&D1 lease was stocked on 3 December 2011, apart from the Haejoo units which were stocked on 13 July 2012. R&D2 lease was stocked on 16 December 2011 with the Haejoo units stocked separately on 13 July 2012. We have referred to stock sizes at this point in time as being the initial stock size on each R&D lease

The main focus of this study, being the monitoring of long-term growth and survival of the seed stock, began in early January 2012 and went through to early January 2013. Sampling took place at quarterly intervals, thereby providing an estimate of the number of seed abalone at the start of the experiment and four quarterly estimates of the number surviving on each of the habitat types on each lease site.

The first estimate of seed stock survival in January 2012 is considered to be the stocking density excluding mortality attributable to transport stress and associated factors. We have termed this 'initial' survival and all subsequent quarterly survival estimates as 'long term' survival.

Each of the five sampling events took several consecutive days to complete. The same diver, Brad Adams, counted every abalone on each habitat structure to provide an actual (not estimated) number of individuals of each year class on the units at that point in time. Additionally, he measured a random subsample of generally N >100 year-2, N >50 year-3 and N >40 year-4 abalone on each habitat type on the Main Lease and an amalgamation of several habitat types on R&D1 and R&D2. These measurements were to provide estimates of growth for the three size classes over the course of the experiment.

In addition to the quarterly sampling, Brad Adams and his staff also undertook regular dives, at least once a week on the lease site, to monitor and remove any octopus, which are potential abalone predators, and to record indices of food availability.

The numbers of octopus (*Octopus tetricus*) removed when the study site was visited, were recorded separately for each of the three lease sites. Any empty abalone shells from the study site were also retained to examine for external indicators of predator damage. Aside from octopus, small numbers of lobster (*Jasus edwardsii*; *Panulirus cygnus*) and baler shells (*Melo miltonis*) were encountered and removed from the study site.

Greenlip abalone feed on a wide range of algae, but prefer red algal species which are often attached as epiphytes on seagrass. Food availability in the form of edible algae was estimated for each lease site when the study area was visited, using a scale of 0 to 10. Small numbers indicated less food available than large numbers.

2.7 Environmental data

Data on water temperature, wind speed and direction and swell height were collected whenever the lease sites were inspected. Although the sites were inspected on a weekly or even more frequent basis over the course of the experiment, there were days that were unsuitable for diving due to wind or sea conditions. Clearly, the use of these data would therefore have biased interpretation of environmental conditions on the experiment sites.

Environmental data on sea temperature and swell conditions were therefore sought from the Department of Transport, Western Australia (DOT). The DOT had two potential data sources suitable for providing information for this project. They have had an acoustic wave and current profile (AWAC) recording instrument in place in Flinders Bay on the seabed at a depth of 9.4 m for the full duration of this project, while the marina close to the sampling sites is being constructed. This instrument records hourly significant wave height, mean period, peak period and swells direction for sea and swell as well as temperature. The use of this data source would have been ideal; however, use of the sea and swell data showed there to be serious errors in what had been recorded over certain periods which rendered this information unusable. DOT is now in the process of attempting to validate and rectify the data. The temperature information recorded by the AWAC instrument did however correlate well with OGA water temperature records and these data have therefore been used in this report.

Given that the DOT Augusta sea and swell data is unusable at this time, we have made use of the DOT's next closest swell recording instrument, a wave-rider buoy located at a depth of 50 m off Cape Naturaliste (33^{o}32'05" S; 114^{o}45'52"E).

2.8 Validation of OGA stock counts and measurements

As noted in the introduction, OGA was responsible for the design and monitoring of this experiment. One of the tasks of Curtin University in writing up the results from the OGA sampling was to independently validate the accuracy of the measuring and counting of the stock.

The validation process involved two Curtin University divers (Roy Melville-Smith and Simon Longbottom) repeating Brad Adams' counting and measurement subsamples from his last sampling event which he had undertaken between 30/12/12 and 8/01/13. The validation sampling occurred on 15 and 16 January 2013.

There were exceptions where either more or less habitat structures were measured, but in general all the seed stock on two of each type of habitat were counted and compared with Brad Adams' counts for the same units. A subsample of ~100 abalone was also measured on tube, star and hollow block habitat structures and the mean sizes as measured by the validation divers were compared with the mean size estimates recorded by Brad Adams for those habitat types.

2.9 Data analysis

2.9.1 Growth

Subsampling of the lengths of the abalone provided quarterly estimates of the three cohorts in the trials. As individuals were not tracked over time, each quarterly sample was independent of previous samples.

Mean growth per quarter was calculated for each habitat type in the Main Lease and for all habitats combined in the two R&D leases. Comparisons of growth increments across the year between all nine habitat types in the Main Lease were made using 1-way ANOVA. To compare growth between lease sites (and therefore depth), data for all habitat types in the Main Lease were combined and the average growth increment per quarter was compared with that of the two other sites.

Growth data for the three year classes monitored in this study have been combined and fitted to a Gompertz growth model ($L_t = L_\infty e^{[-e(-k(t-t0))]}$), where L_t is length (mm) at age t; L_∞ the maximum theoretical length; K a growth coefficient and t_0 the theoretical length (mm) at age 0. The modelled growth has enabled comparisons to be made between similar growth models for greenlip abalone grown under aquaculture conditions and as an enhancement experiment on natural reefs in the wild (Hart *et al*., in press a).

2.9.2 Survival

Survival rates were established at each quarterly count. The first count of the experimental abalone post-seeding was made in early January 2012 at all habitats. The difference between the numbers of abalone stocked and the numbers counted in January 2012 have been used to establish initial mortality. Quarterly counts from January 2012 to January 2013 were analysed separately and comparisons of survival between each habitat and across all sites were made using 1-way ANOVA.

Stocking densities on some individual habitat units were "doubled up" (see Tables I, II and III). These single, unreplicated units have been removed from the analysis.

Besser block habitat units were made up of different numbers of blocks stocked with the relevant multiple of abalone. In most cases, particularly on R&D1 and R&D2, two blocks were joined together and this arrangement has been considered to be the standard. Variations from the standard two block arrangement have been removed from the analysis in R&D1 and R&D2, but in the Main Lease non-standard combinations were too common and have therefore been included in the analysis.

There was some discrepancy between the stocking densities on individual units between lease sites (see Table I, II and III). For example, all kerb units in the Main Lease are stocked with 120 2-year old abalone only, whereas in the other two sites there are only 100 2-year old abalone, but also 40 3-year olds and 10 4-year olds per unit. For the purposes of this analysis, these inconsistencies in stocking density have been overlooked.

As mentioned previously (see (ix) in 2.4 Habitat structure designs) small besser blocks have been placed several metres away from some habitat types to provide a refuge for abalone migrating off those habitat units. In one instance, the number of migrating animals on besser blocks close to tube units amounted to nearly 25% of the total count for that particular habitat type (tubes, January 2012). In the analysis, it has been assumed that all abalone found on besser blocks close to a particular habitat type originated from those units. However, this cannot be determined with any certainty.

Similarly, it is not possible to determine whether abalone counted on a particular habitat type were originally seeded to that habitat. In occasional cases this has led to survival rates of over 100% being recorded for some habitat types and presumably to erroneously low survival rates in adjoining habitat types that contributed stock to the neighbouring habitat units.

2.9.3 Environmental Factors

Daily indices of food abundance that were recorded whenever the R&D sites were visited through the year have been averaged by month. ANOVA has been used to test for differences in food supply across the three R&D sites. Linear regression analysis has been used to test for possible relationships between quarterly growth increments and food abundance for the three seed stock year classes in the different R&D leases.

Drift algae, which are the basis of the food index, become detached in bigger volumes after rough sea conditions. We have examined the daily frequency of extreme swell conditions ($\geq$3 m, as measured on the Cape Naturaliste wave-rider buoy) and compared that with quarterly mean size increments on the three R&D lease sites.

2.9.4 Haejoo Units

Due to the shorter time period between when the Haejoo units were installed compared to other habitat types, the analysis of that data has largely been undertaken separately to that for other habitat types and is of a preliminary nature.

The Haejoo habitats were only installed on R&D1 and R&D2 and the seed stock on those units was not measured at the time that they were seeded. Comparative growth data between abalone stocked on the Haejoo units and other habitat types is therefore only available for quarter 4 (October 2012 to January 2013). Compounding the limitations of comparing growth between Haejoo and other habitat types over just one quarter, is the fact that the seed stock on the Haejoo units was smaller than their corresponding cohorts on the other units.

Comparisons between seed stock survival rates on Haejoo and other habitat types are also potentially flawed. The Haejoo units were stocked for 2.5 months between the seeding and the first count to follow after seeding, whereas similar initial counts for other habitats on R&D1 and R&D2 were done after just two weeks. Additionally, stocking of the Haejoo units took place at a very different time of year to other units, and the mean size of the abalone used were slightly larger, given that the seed stock were seven months older at time of stocking than those stocked on the other habitat types.

Even though there are important dissimilarities between the seed stock and the timing of stocking, this information has been used in the absence of other data to provide an indication of the performance of Haejoo units against other habitat types.

The analysis of mean quarterly growth increments, standardised increments and initial and long-term survival measurements was largely similar to that done for other habitats, but for a shorter time period.

3. Results

3.1 Validation of OGA sampling

(i) Counts

Counts were made of the seed stock on 38 habitat structures across the three sites. On 19 units the University counts were less than those of OGA, on four units counts were the same and on 15 units the OGA counts exceeded those of the University divers (Figure 3). More specifically, the differences in counts were generally small and in only three cases did counting tallies differ by greater than ±10%.

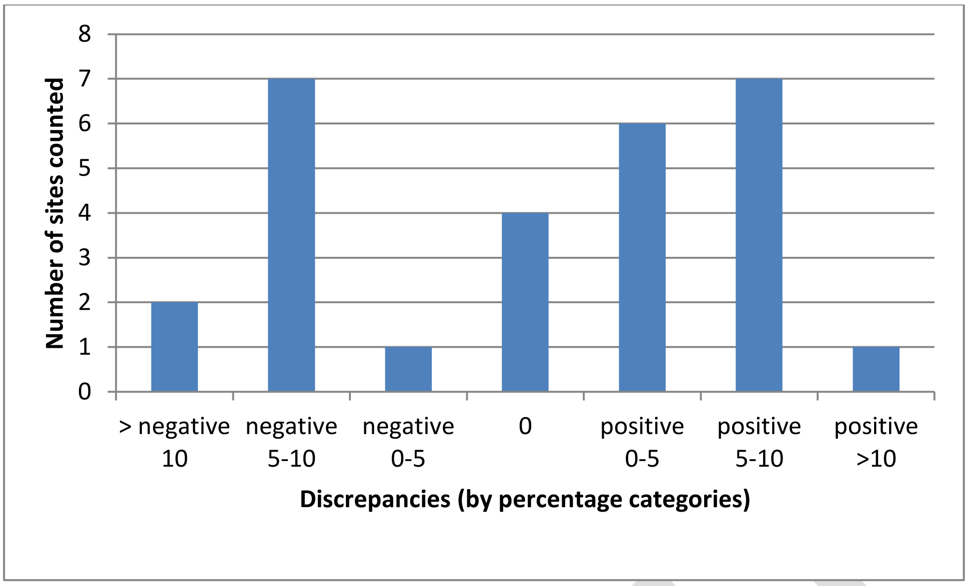


Figure 3: Discrepancies (expressed as deviations from counts recorded by Curtin University) in *H. laevigata* counts made on the sea ranching trial at Flinders Bay, Augusta, Western Australia

(ii) Subsample measurements

Comparisons between the mean sizes of seed stock measured by Brad Adams and by the Curtin University divers that validated the accuracy of his counts are shown in Table IV. The two sets of measurements were similar and were shown (Table IV) to be not significantly different (p>0.05).

Although measurements were only validated on three habitat types, there was not a large variation in the mean sizes of abalone across the different habitats. We are satisfied that the similarity between the OGA and Curtin University measurements on those habitat types that were measured, is indicative of the accuracy of measurements across other habitat types on the study site.

Table IV: Mean differences between length frequency measurements made by Curtin University and OGA divers, of *H. laevigata* 2-year old seed stock on three different habitat structures in sea ranching trials at Flinders Bay, Augusta, Western Australia

Habitat type	**OGA measurements Mean (SE)**	**Curtin University Mean (SE)**	**t-test result**	**P**
Star units	74.9 (1.0)	76.3 (0.8)	d.f. = 173, t = 1.14	>0.05
Tube units	82.2 (0.7)	83.4 (0.7)	d.f. = 191, t = 1.17	>0.05
Hollow block units	82.7 (0.8)	82.2 (1.6)	d.f. = 31, t = -0.23	>0.05

3.2 Growth

The mean size of stock at the start and end of the experiment, as well as the annual growth increments in the Main Lease for nine habitats with 2-year old stock and three habitats with 3- and 4-year old stock, is shown in Table V.

Table V: Mean length (±SD) of seeded *H. laevigata* at the start (December 2011) and end (January 2013) of sea ranching trials, and the resulting annual growth increment for different habitat types on the Main Lease site in Flinders Bay, Augusta, Western Australia

2-year size class	**Mean length –Dec (mm)**	**Mean length – Jan (mm)**	**mean increment ± SE (mm)**
Hollow Blocks	44.7 ± 5.3	82.7 ±8.0	38.0 ±1.0
Solid Blocks	44.4 ± 5.2	79.0 ±9.8	34.6 ±1.1
Tubes	44.2 ± 5.5	82.2 ±8.1	38.0 ±0.9
V Tube Reef	45.5 ± 6.0	80.9 ±8.3	35.4 ±1.1
Star	38.6 ± 5.5	74.9 ±10.2	36.3 ±1.1
Kerbs	45.6 ± 5.2	78.9 ±8.6	33.3 ±1.0
Hollow Block Train	46.1 ± 5.1	79.3 ±7.2	33.2 ±1.0
Solid Block Train	45.4 ± 5.7	76.2 ±9.5	30.8 ±1.2
Besser Blocks	43.3 ± 3.9	81.2 ±8.8	37.9 ±1.0

3-year size class	**Mean length -Dec**	**Mean length - Jan**	**mean increment ± SE**
Hollow Block Train	71.8 ± 5.5	108.0 ±5.3	36.2 ±1.1
Solid Block Train	69.4 ± 5.4	105.2 ±6.2	35.8 ±1.1
Besser Block	72.6 ± 6.9	107.7 ±6.3	35.0 ±1.4

4-year size class	**Mean length -Dec**	**Mean length - Jan**	**mean increment ± SE**
Hollow Block Train	95.6 ± 4.9	121.9 ±4.7	26.3 ±1.4
Solid Block Train	94.6 ± 6.7	119.5 ±2.7	24.9 ±1.4
Besser Blocks	93.6± 6.2	120.2 ±4.2	26.7 ±1.5

Direct comparisons of growth increments for the different habitat types may be biased by the differences in mean length of abalone at the start of the experiment. In particular, the mean length of 2-year old stock on the Star units was substantially smaller than on the other units. To compensate for these differences, growth data for all habitat types has been standardised to a percentage growth increment relative to the mean size of the animals at the start of the experiment (Figure 4).

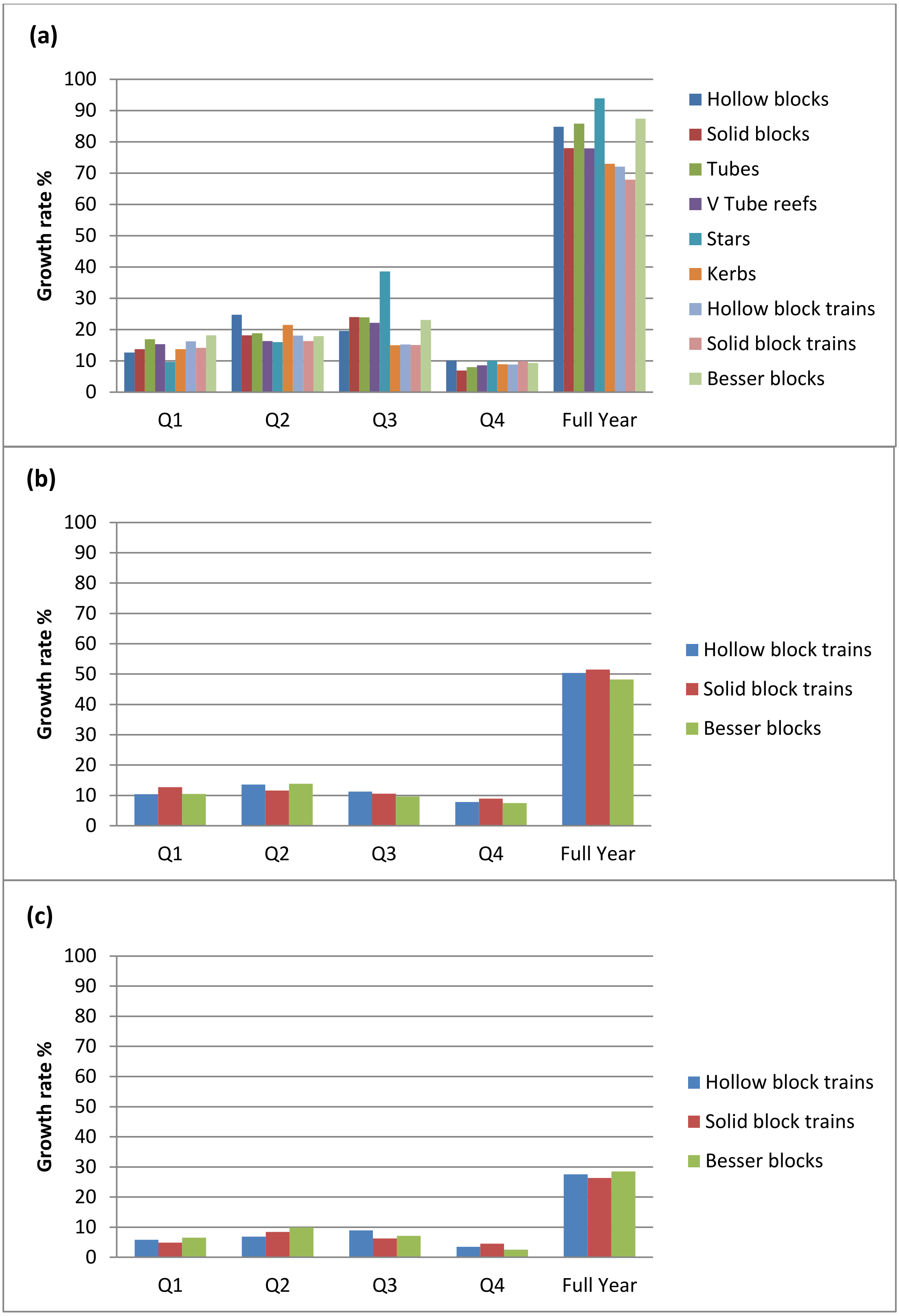


Figure 4: Standardised quarterly and full year growth increments for three habitat types on the Main Lease of the *H. laevigata* sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) 2-year old, (b) 3-year old and (c) 4-year old size classes

The annual growth rates between habitats in the Main Lease were not significantly different (p>0.05) for any of the size classes, indicating that growth rates were not influenced by the habitat designs that were tested (Table VI).

Table VI: ANOVA results for growth comparisons of *H. laevigata* across habitat types on the Main Lease site of sea ranching trials in Flinders Bay, Augusta, Western Australia

Size Class	d.f.	F	p
2- year	8,27	0.18	0.99
3- year	2,9	0.07	0.93
4- year	2,9	0.04	0.96

Growth increments for individual habitat types were not available for the R&D1 and R&D2 lease sites. However, pooled random measurements of abalone seeded on different habitat types in R&D1 and R&D2 and mean growth increments for all habitats sampled on the Main Lease, have allowed lengths to be compared across leases for 2, 3 and 4-year old stock (Table VII).

Table VII: Mean length (±SD) of seeded *H. laevigata* at the start (late December 2011) and end (early January 2013) of sea ranching trials in Flinders Bay, Augusta, Western Australia, and the resulting annual growth increment for the three R&D lease sites.

	Mean length – Dec (mm)	Mean length – Jan (mm)	mean increment ±SE (mm)
2-year size class			
Main Lease	44.1 ± 5.7	79.6 ± 9.1	35.5 ± 0.4
R&D1 Lease	38.0 ± 5.2	75.0 ± 8.3	36.9 ± 1.0
R&D2 Lease	40.8 ± 4.9	71.1 ± 7.1	30.3 ± 0.9
3-year size class			
Main Lease	71.0 ± 6.0	107.0 ± 6.0	36.0 ± 0.7
R&D1 Lease	70.2 ± 6.1	108.3 ± 7.3	38.1 ± 1.3
R&D2 Lease	69.4 ± 6.4	103.6 ± 7.2	34.2 ± 1.1
4-year size class			
Main Lease	94.6 ± 6.0	120.6 ± 4.1	26.0 ± 0.8
R&D1 Lease	96.4 ± 4.0	123.6 ± 4.4	27.2 ± 1.0
R&D2 Lease	93.6 ± 5.8	118.5 ± 5.5	24.9 ± 1.2

Once again, owing to differences in mean length of seeded abalone across habitats at the start of the study, these data have been standardised to represent average growth increment as a percentage of the starting length for each R&D Lease site (Figure 5). ANOVA (Table VIII), showed there to be no significant difference between mean growth increment across the three R&D leases ($p>0.05$).

Table VIII: ANOVA results for growth comparisons of three year classes of *H. laevigata* on the three R&D sea ranching lease sites in Flinders Bay, Augusta, Western Australia

Size Class	d.f.	F	p
2-year	2,9	0.371	0.70
3-year	2,9	0.05	0.95
4-year	2,9	0.01	0.99

Growth increments were not consistent across the year on any of the lease sites. Quarters 1 to 3 had similar growth (Figure 5), but there was a clear decline in increment for all three age classes in the fourth quarter.

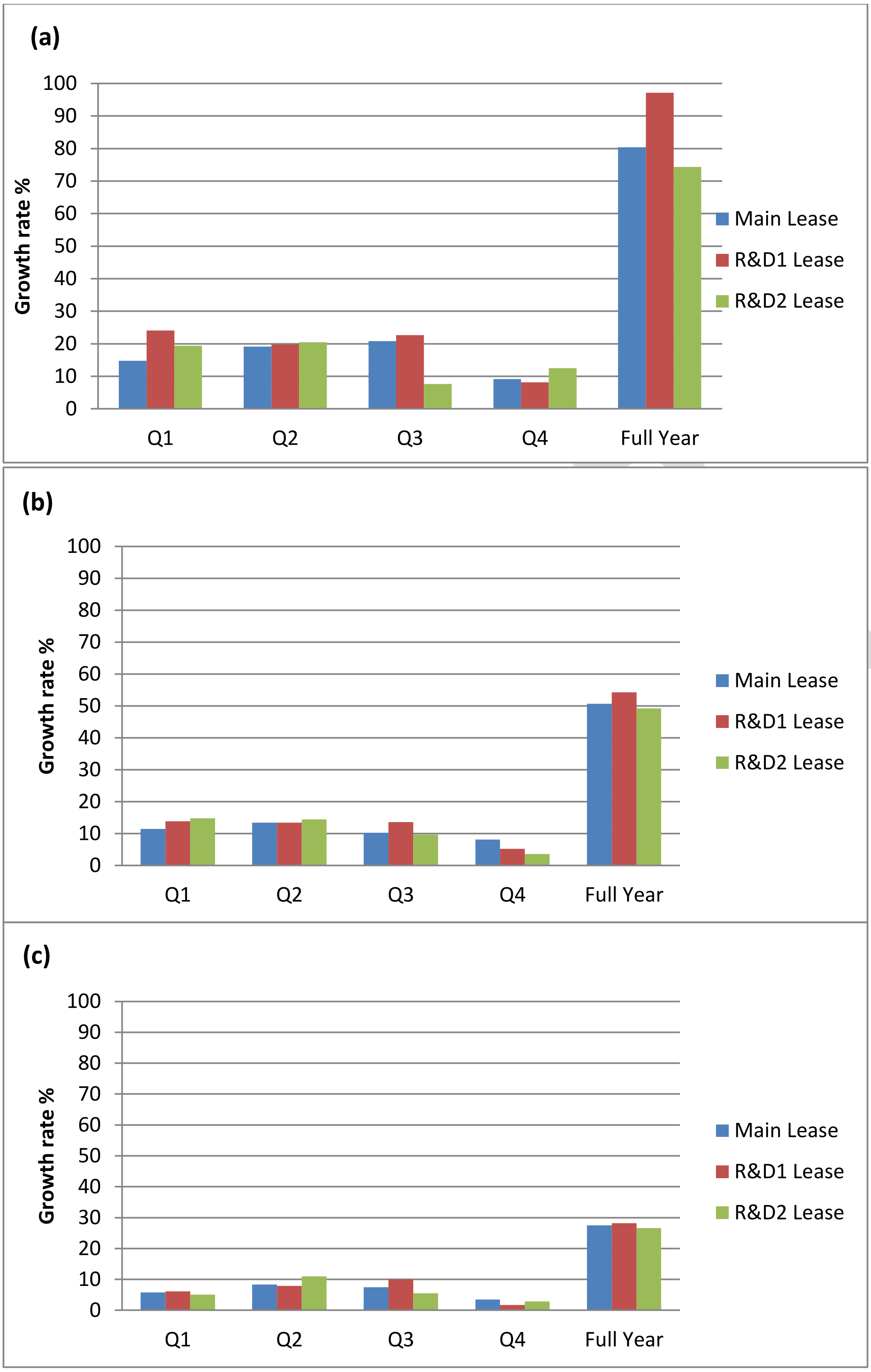


Figure 5: Standardised quarterly and full year growth increments for the three R&D leases used in the *H. laevigata* sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) 2-year old, (b) 3-year old and (c) 4-year old size classes

Data for the three lease sites has been combined in Figure 6 and is compared with growth rates recorded by Hart *et al*. (in press a) for aquacultured abalone that grew for four years in the wild at Augusta, and for growth rates recorded by Craig Kestel (888 Abalone Pty Ltd, pers. comm) for aquacultured abalone at his facility in Bremer Bay, Western Australia.

The increments for the three year classes in this study follow a stepwise pattern (Figure 6), with the starting size of the 3-year old abalone being smaller than the size of 2-year olds at the end of one growth year. Likewise, the starting size of 4-year old seeded abalone was smaller than the 3-year olds at the end of one growth year. The reason for this is that the aquacultured abalone grew slower on the farm than in the wild and were therefore smaller when seeded than they would have been after one year of growth in the wild.

If the steps between the three year classes in this study are ignored, it is evident that the growth rates from this study are similar to those of Hart *et al*. (in press a) for their abalone held for several years in the wild, and are faster than those recorded for aquacultured abalone in Bremer Bay. The growth increment for 2-year old animals in this study is 35 mm ± 0.33 SE, which standardises to 81% compared to the growth increment for the wild data (read from Figure 6) for the 2-3 year period) of approximately 39 mm, which standardises to 93%. For 3-year old stock, this study recorded an increment of 36 mm ± 0.54 SE (51%), whereas the wild data had a slightly lower increment of 33 mm (41%). With the 4-year old stock, this study recorded an increment of 26 mm ± 0.60 SE (28%), compared to 22 mm (19%) for the wild data (Tables IX and X).

Table IX: Growth increments and standardised increments for three year classes of *H. laevigata* after one year, using the combined data for the three sea ranching trial R&D leases sites in Flinders Bay, Augusta, Western Australia

Size Class	**December length Mean (SE) (mm)**	**January length Mean (SE) (mm)**	**Mean increment (mm)**	**Standardised increment (%)**
Year-2	43.3 (0.2)	78.5 (0.3)	35.2 (0.3)	81.3
Year-3	70.4 (0.4)	106.5 (0.4)	36.1 (0.5)	51.3
Year-4	94.6 (0.4)	120.9 (0.5)	26.3 (0.6)	27.8

Table X: Growth increments and standardised increments as estimated from Figure 6, for three year classes of *H. laevigata* seeded into the wild as two year olds by Hart *et al*. (in press a)

Size Class	December length Mean (mm)	January length Mean (mm)	Mean increment (mm)	Standardised increment (%)
Year-2	42.0	81.3	39.3	93.4
Year-3	81.3	114.3	33.0	40.6
Year-4	114.3	136.2	22.0	19.2

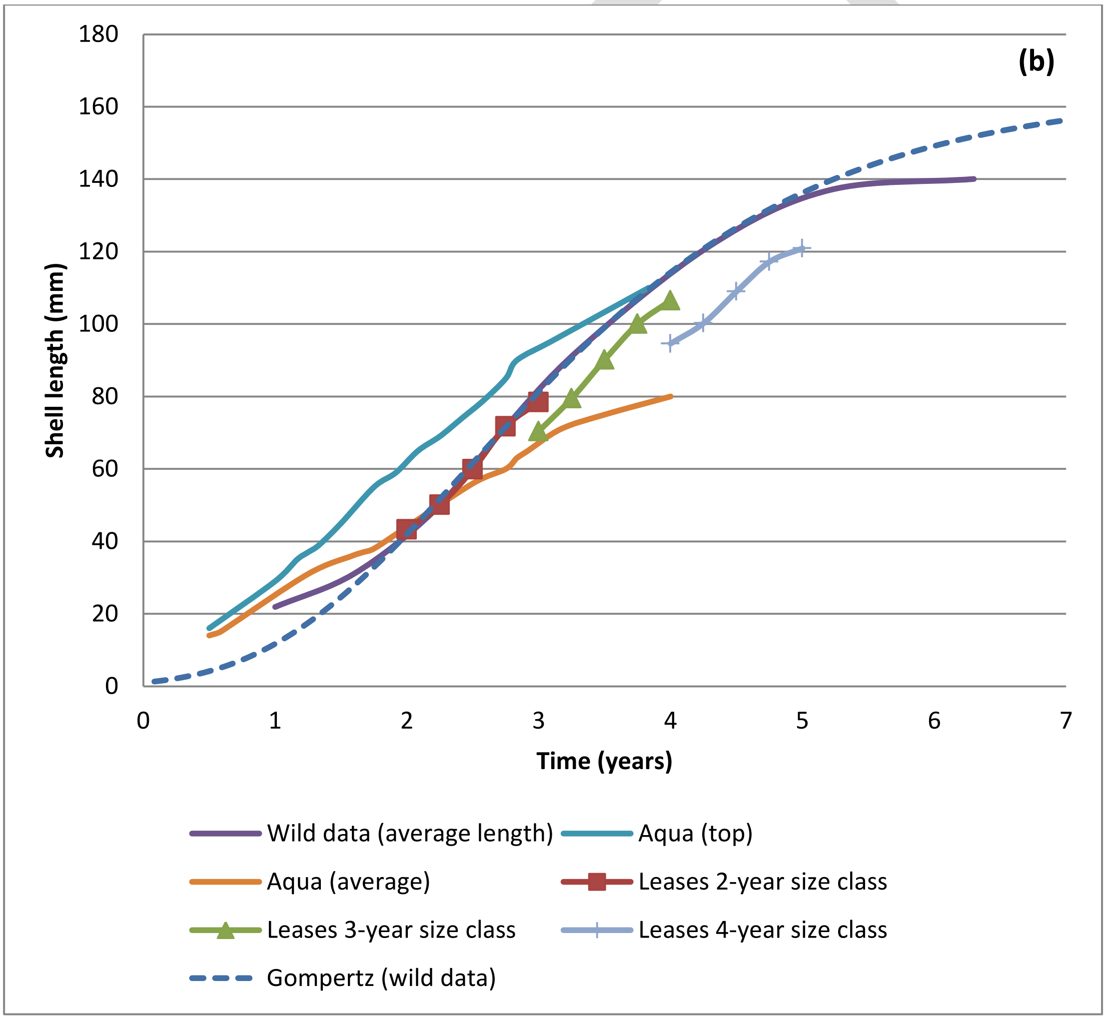


Figure 6: *H. laevigata* growth recorded in sea ranching trials at Flinders Bay, Augusta, Western Australia compared to best and average performing aquaculture data (Kestle pers. comm.) and growth from an enhancement trial in the wild fishery (Hart et al. in press a)

The period of the animals' growth that has been covered by the sampling in this study is that phase during which growth is linear. Accordingly, it has not been possible to provide an *accurate* description of growth, because there is insufficient data to provide growth rates into the non-linear growth phase of the life cycle. However, growth increment data for the three year classes in this study have been merged by length and have been fitted to a Gompertz growth curve (Figure 7a). The modelled growth curve in Figure 7a has been compared in Figure 7b to the modelled growth curve produced by Hart *et al*. (in press a) for abalone grown for four years in the wild. The two growth curves are very similar, suggesting that growth in this sea ranching experiment is similar to less intensively stocked situations in the wild.

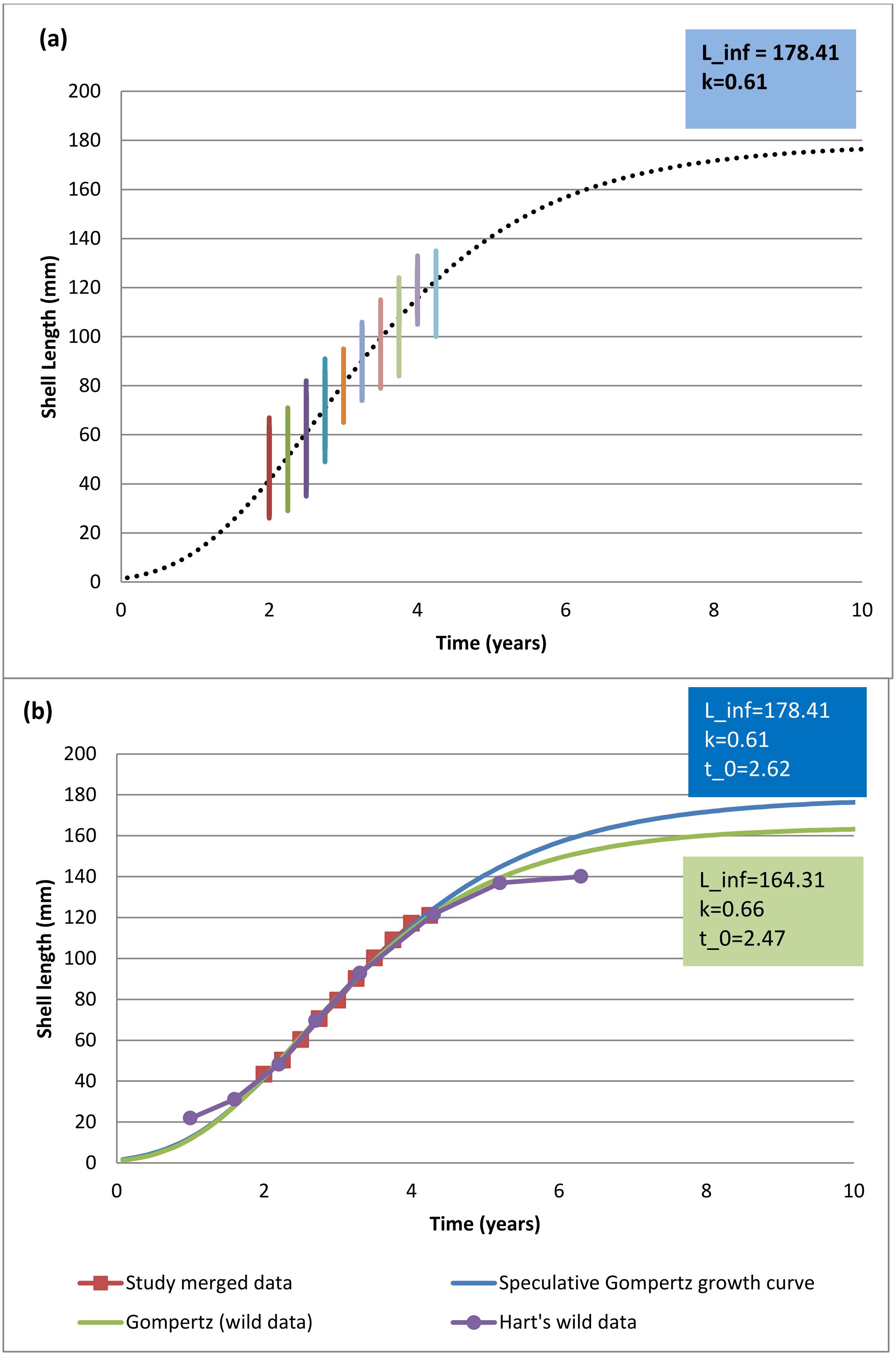


Figure 7: Speculative Gompertz growth curve created using growth data for the three size classes in the *H. laevigata* sea ranching trial at Flinders Bay, Augusta, Western Australia merged by length: (a) quarterly data and fitted curve and (b) compared to wild enhancement raw data Hart *et al*. (in press a) and fitted curves

3.3 Survival

Survival of seeded abalone is best considered in two phases. The first phase is *initial* survival in the weeks following stocking, because this phase has more to do with the quality of the abalone being stocked, the method used to attach them to their new habitat and how they adjust to their new surroundings. The second phase is *long-term* survival and is about how the animals adapt to their surroundings over time. This phase is considered over a one-year time frame in this study.

3.3.1 Initial survival

The percentage of abalone surviving after approximately three months after stocking on the Main Lease and one month after stocking on R&D1 and R&D2 is shown in Figures 8 to 10. From the three Figures, it is clear that survival is substantially lower on all three R&D leases for the 2-year old seed stock (Figure 8) than for the 3 (Figure 9) and 4-year old (Figure 10) animals. It is also apparent from the three Figures, that survival was substantially lower at the R&D1 lease site compared to the other two leases. This may indicate that the condition of the seed stock used to populate that lease site was compromised in some way, possibly through travel stress prior to stocking.

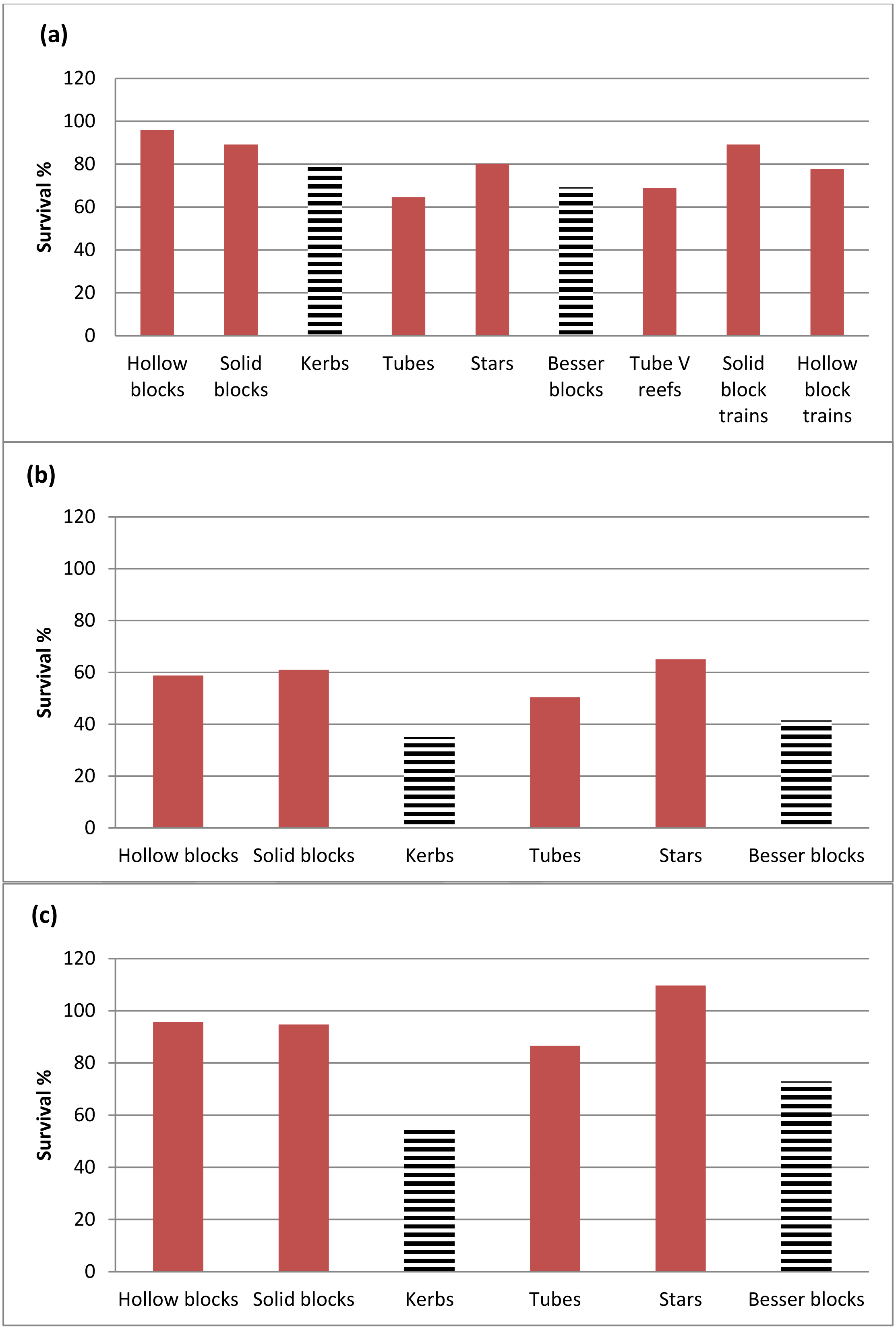


Figure 8: Initial survival for 2-year old *H. laevigata* stock within each R&D lease, shown as a percentage of the number stocked in the sea ranching trial at Flinders Bay, Augusta, Western Australia. Habitats that were stocked by hand are shown as striped bars: (a) Main Lease, (b) R&D1, (c) R&D2.

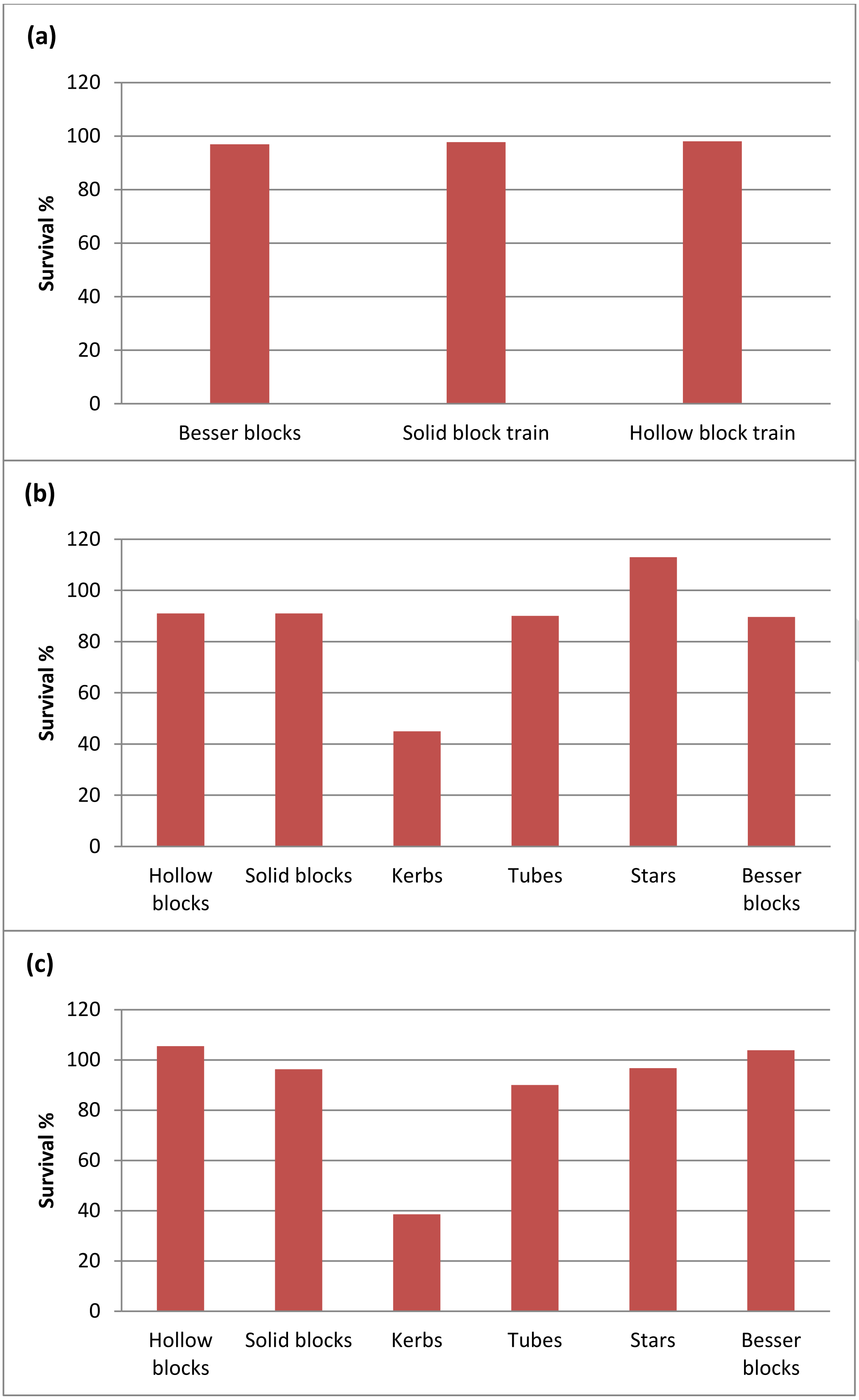


Figure 9: Initial survival for 3-year old *H. laevigata* stock within each R&D lease, shown as a percentage of the number stocked in the sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) Main Lease, (b) R&D1, (c) R&D2. All habitats were stocked by hand.

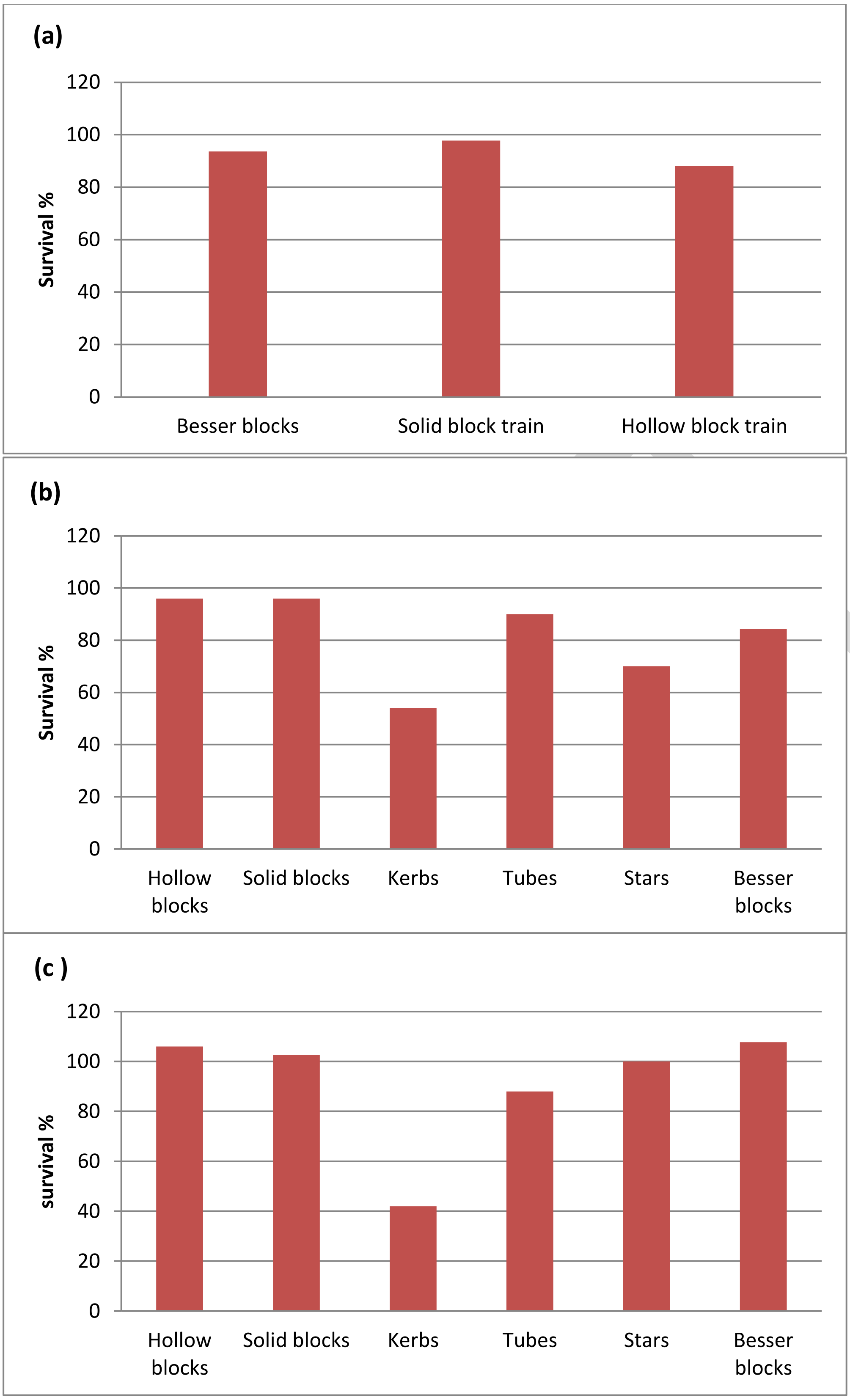


Figure 10: Initial survival for 4-year old *H. laevigata* stock within each R&D lease, shown as a percentage of the number stocked in the sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) Main Lease, (b) R&D1, (c) R&D2. All habitats were stocked by hand.

Survival of the 2-year olds (Figure 8) was consistently less on two habitat types (kerbs and besser blocks) on all three R&D lease sites. These two habitat types were stocked by hand as opposed to the other habitat units which were stocked using a release device. All 3- and 4-year olds (Figure 9 and 10) were stocked by hand, without the use of a release device. Apart from the kerb design, which was not used in the Main Lease, there was no consistent trend in survival on any one habitat type. Survival on the kerb design proved to be consistently poor (Figure 9 and 10).

There were a few habitat types in all year classes (Figures 8 to 10) which recorded survival rates of over 100%. These survival values can only be explained by counting errors or by migration from one habitat type to another close by.

3.3.2 Long-term survival

The period of long-term survival in this study was from the first quarterly sample in January 2012 to the last sample in January 2013. Survival rates over this period were compared across the three lease sites and the different habitat types using ANOVA.

There was no significant difference ($p>0.05$) in the quarterly survival rates for the nine different habitat types in the Main Lease, or for the six different habitat types in R&D1 and R&D2. However, there were significant differences in the cumulative survival rates for different habitat types on each of the three R&D Leases. These results are summarised in Table XI (a)-(c).

On the Main Lease site, the cumulative survival rates for the 2-year old stock were significantly different between habitat types (d.f. = 8,36, $F = 4.517$, $p = 0.001$). Survival rates on the star blocks differed significantly compared to other habitat types. There was no significant difference between long term survival rates of the 3-year old stock (d.f. = 2,12, $F = 2.981$, $p = 0.089$). The 4-year old stock showed significant differences between habitat types (d.f. = 2,12, $F = 5.646$, $p = 0.019$). Here the hollow block train units consistently outperformed the other two habitats. The results are summarised in Table XI (a).

On the R&D1 lease site, the cumulative survival for 2-year old stock was significantly different across habitat types (d.f. = 5,24, $F = 3.363$, $p = 0.019$). Besser blocks outperformed all other habitats with a final survival count of 113%, which differed significantly with the survival counts on the star units. Similarly, with the 3-year old stock, star units had significantly lower survival compared to all the other habitat types (d.f. = 5,24, $F = 9.703$, $p = 0.000$). With the 4-year old stock there was no significant difference between habitats (d.f. = 5,24, $F = 2.062$, $p = 0.106$). The results are summarised in Table XI (b).

The cumulative survival for the 2-year old stock on the R&D2 lease site was significantly different across habitat types (d.f. = 5,24, $F = 8.735$, $p = 0.000$). Kerb units had a cumulative survival of only 39%, compared to hollow and solid block units which both showed an increase in stock count, resulting in an ‘apparent’ survival of 112% and 117% respectively. The 3-year old stock also showed a significant difference in survival (d.f. = 5,24, $F = 8.035$, $p =$

0.000). The 4-year size class showed no significant difference in survival rates (d.f. = 5,24, F =0.392, p = 0.850). These results are summarised in Table XI(c).

Table XI: Long term survival percentages and the results of ANOVA comparison of long term survival rates between habitats of the three year classes of *H. laevigata* on the (a) Main Lease, (b) R&D1 lease and (c) R&D2 lease sea ranching sites in Flinders Bay, Augusta, Western Australia. Those habitats causing a significant difference within the year size class are shown with an asterisk.

(a)	**Hollow blocks**	**Solid blocks**	**Kerbs**	**Tubes**	**Stars**	**Tube V reefs**	**Besser blocks**	**Solid block train**	**Hollow block train**
2-year size class									
Survival %	84	80	75	77	56*	90	83	92	100
3-year size class									
Survival %							82	89	93
4-year size class									
Survival %							88	91	100*

(b)	***Hollow blocks***	***Solid blocks***	***Kerbs***	***Tubes***	***Stars***	***Besser blocks***
2-year size class						
Survival %	94	103	90	87	89*	113*
3-year size class						
Survival %	96	98	80	99	65*	90
4-year size class						
Survival %	85	90	63	73	86	89

(c)	***Hollow blocks***	***Solid blocks***	***Kerbs***	***Tubes***	***Stars***	***Besser blocks***
2-year size class						
Survival %	112	117	39*	89	88	93
3-year size class						
Survival %	105	87	62*	94	100	98
4-year size class						
Survival %	77	71	52	80	80	86

Survival comparisons between leases can only be made by comparing like habitats. For the 2-year old stock, comparisons have been made between leases by combining the counts in each lease of hollow blocks, solid blocks, kerbs, tubes, stars and besser blocks. There was a significant difference in cumulative survival between leases (d.f. = 2,87, F = 8.058, p = 0.001), with stock on the Main Lease showing lower survival than the other two leases (Figure 12(a)). However, this result needs to be treated with caution, because movement of abalone from one habitat to another must result in increases in numbers on one habitat type being offset by decreases in numbers at a different habitat type. Since not all habitat types in the Main Lease were included in this ANOVA comparison, there is a possibility that overall survival rates on the Main Lease could have been underestimated.

Comparing survival between leases for the 3- and 4-year old stock has been restricted to besser block units, because that was the only habitat type common to all R&D lease sites for these age classes. There was no significant difference in cumulative survival across lease sites for either the 3-year old (d.f. = 2,12, F = 2.041, p = 0.173), or 4-year old (d.f.= 2,12, F = 0.515, p = 0.610) year classes (Figure 12b-c).

Overall survival for the three lease sites over the period October 2011 – January 2013 (i.e. which includes the initial survival phase) is summarised in Table XII and Figure 11. The total survival rate across all three lease sites is 67% from seeding.

Table XII: Percentage survival from October 2011-January 2013 of the three year classes of *H. laevigata* on each sea ranching site in Flinders Bay, Augusta, Western Australia, and the overall total for each year size class.

	Main Lease	R&D1 Lease	R&D2 Lease	Overall
2-year	65	50	79	65
3-year	84	75	80	80
4-year	86	68	65	72

For the period January 2012 – January 2013 (i.e. including only the long-term survival phase) the survival rates are summarised in Table XIII and (Figure 12). The total survival rate across the three lease sites from January 2012 is 86%.

Table XIII: Percentage survival from January 2012-January 2013 of the three year classes of *H. laevigata* on each sea ranching site in Flinders Bay, Augusta, Western Australia, and the overall total for each year size class.

	Main Lease	R&D1 Lease	R&D2 Lease	Overall
2-year	83	96	93	86
3-year	87	93	93	91
4-year	92	81	75	82

Survival data from the time of seeding as a 2-year old through three subsequent years has been projected using data from this study (Figure 13). The projection shows the initial mortality at stocking followed by survival rates through the first year (0-13 months). Survival data for 3 and 4-year olds from this study has been added for the subsequent years, to take the projection out to 37 months (three years) after stocking.

Survival rates after three years vary from around 40 to 55% for the three leases, with the mean survival around 50%.

Note that the Main Lease had a longer initial phase than the other two leases and that the longer period would have resulted in a slightly lower survival rate in that phase compared with the other two lease sites. Caution must be used with the projection in Figure 13, because the data has utilised animals that have grown for different amounts of time in aquaculture prior to release onto the artificial habitats and clearly this does not reflect true continuity.

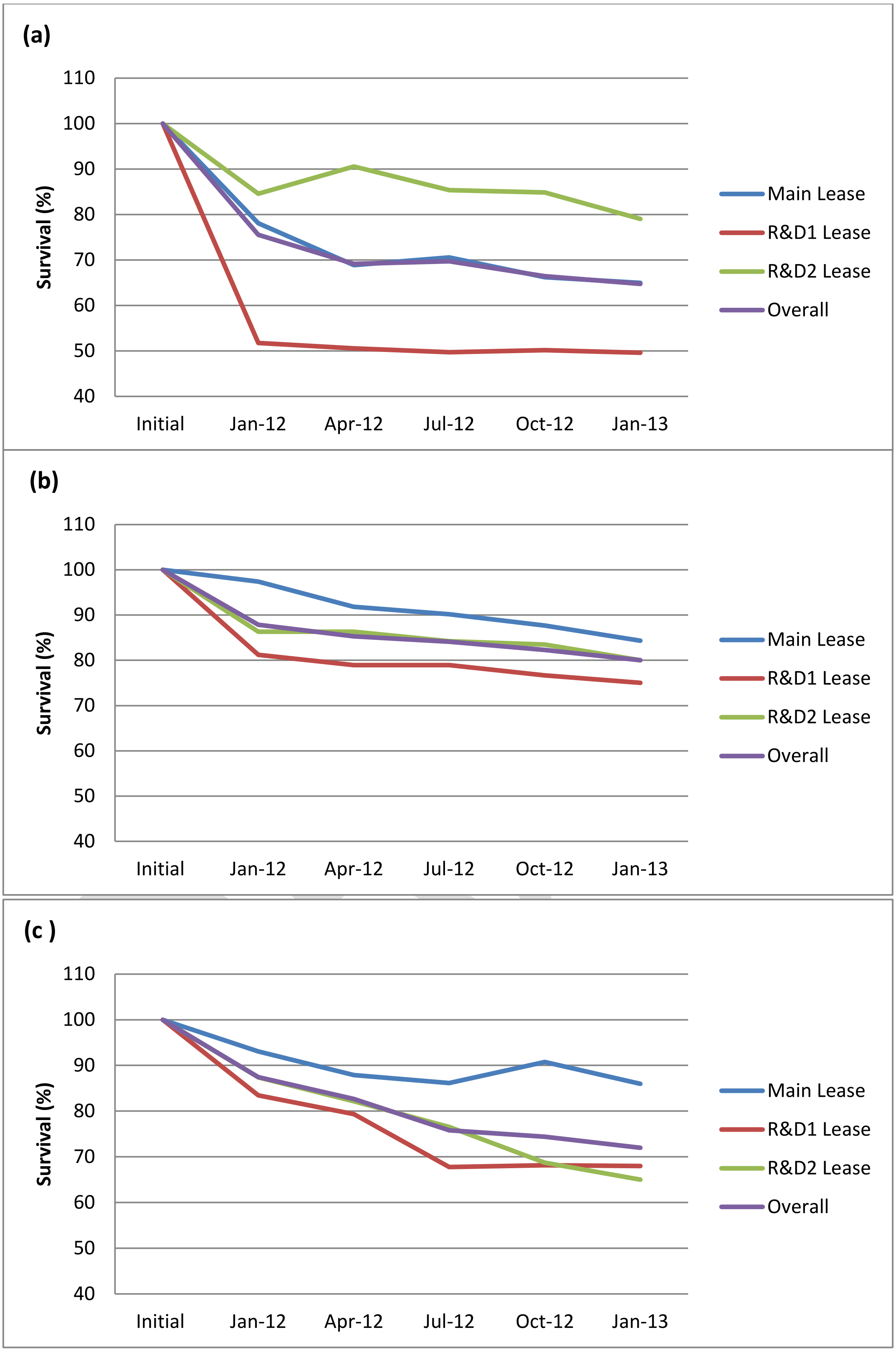


Figure 11: Survival from seeding, of *H. laevigata* stocked in three R&D leases, in the sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) 2-year, (b) 3-year and (c) 4-year old size classes

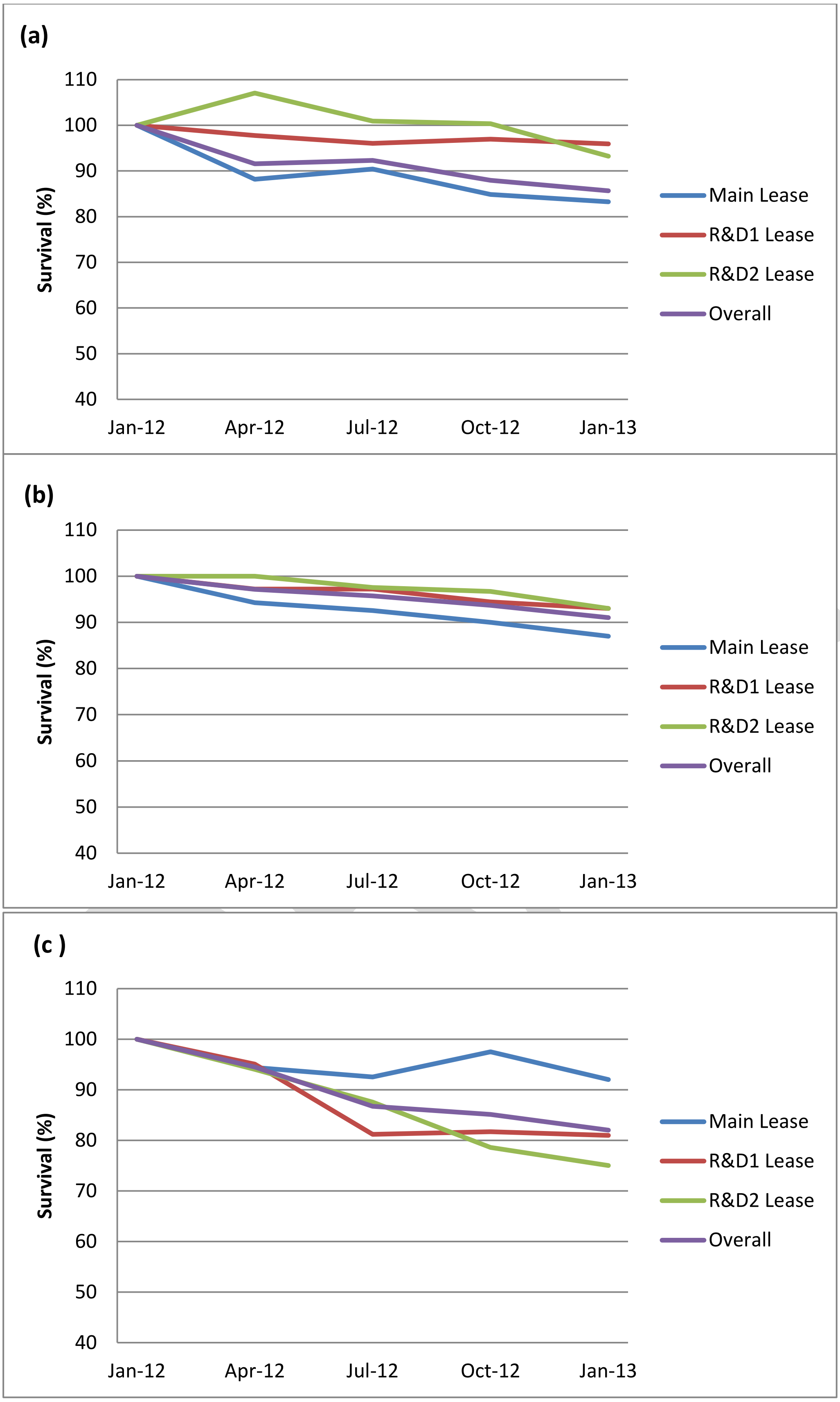


Figure 12: Survival of *H. laevigata* stocked in three R&D leases in the sea ranching trial at Flinders Bay, Augusta, Western Australia. The initial stocking phase has been excluded: (a) 2-year, (b) 3-year and (c) 4-year old size classes

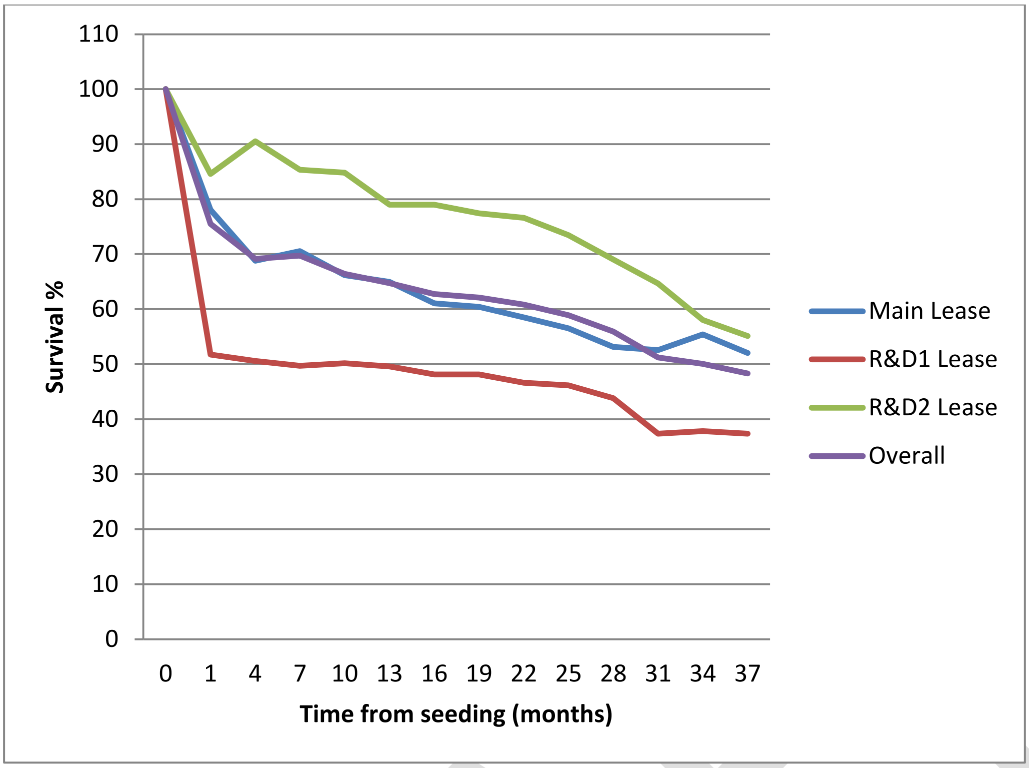


Figure 13: The projected survival of *H. laevigata*, overall and separately for the three R&D leases, using integrated survival data for the three year classes in the sea ranching trial at Flinders Bay, Augusta, Western Australia

3.4 Food Index

The average monthly food index for the three R&D sites is shown in Figure 14. It shows the Main Lease had its lowest food supply across summer/autumn 2012, R&D1 had its lowest supply across autumn/winter, and R&D2 across winter/spring. In Figures 15-17 the food index has been overlaid on a graph with quarterly growth increments. Most notable is that the reduced growth increment for quarter 4 is not reflected in the trend of the food index.

One-way ANOVA showed there was no significant difference between the overall food supply on each lease site (d.f. = 2,33, F=0.30, p=0.75). Linear regression analysis of growth increment related to food supply is unfortunately limited to only four data points and much detail is therefore lost. Nevertheless, there was a very weak negative correlation for growth related to food supply in 2-year old abalone on the Main (r^2 = 0.02) and R&D1 leases (r^2 = 0.09) and a moderately strong positive correlation for that relationship on R&D2 (r^2 = 0.63).

For the 3-year old size class, there was moderately strong negative correlation between growth and food supply (r^2 = 0.51) on the Main Lease, R&D1 has a moderate negative correlation (r^2 = 0.23) and R&D2 has a very weak positive correlation (r^2 = 0.37).

For the 4-year old size class, the Main Lease showed a weak negative correlation (r^2 = 0.**07**), R&D1 had a moderately strong negative correlation (r^2 = 0.41) and R&D2 showed no correlation (r^2 = 0.00).

The lack of any consistent trend in correlation would suggest that the sampling of growth increments was probably not frequent enough to provide the basis for establishing correlations between growth increment and food availability.

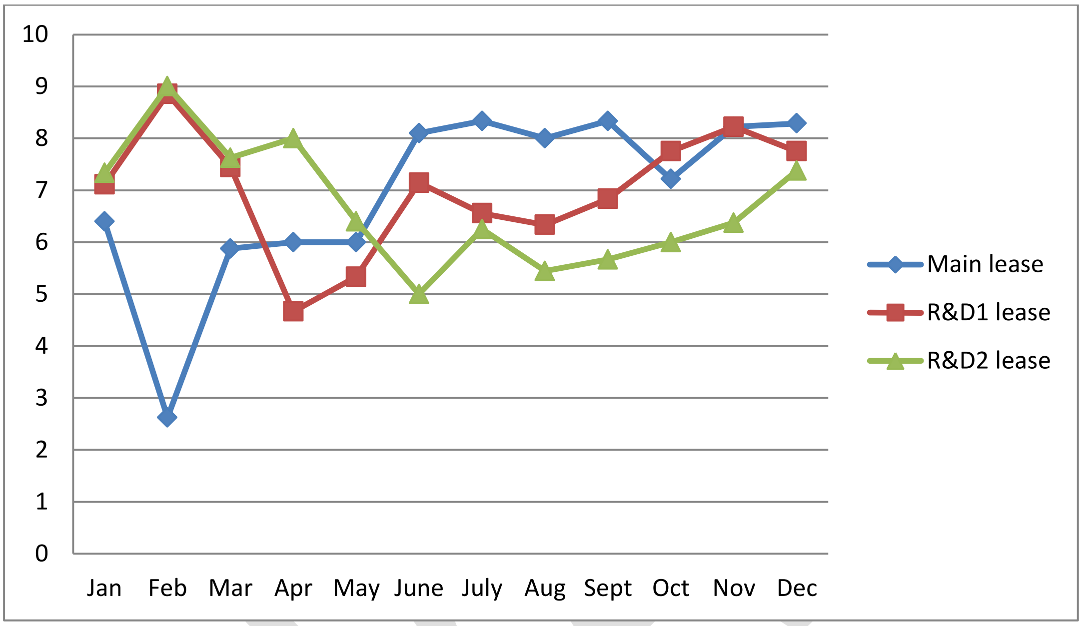


Figure 14: Average monthly food index for the three R&D leases in the sea ranching trial at Flinders Bay, Augusta, Western Australia

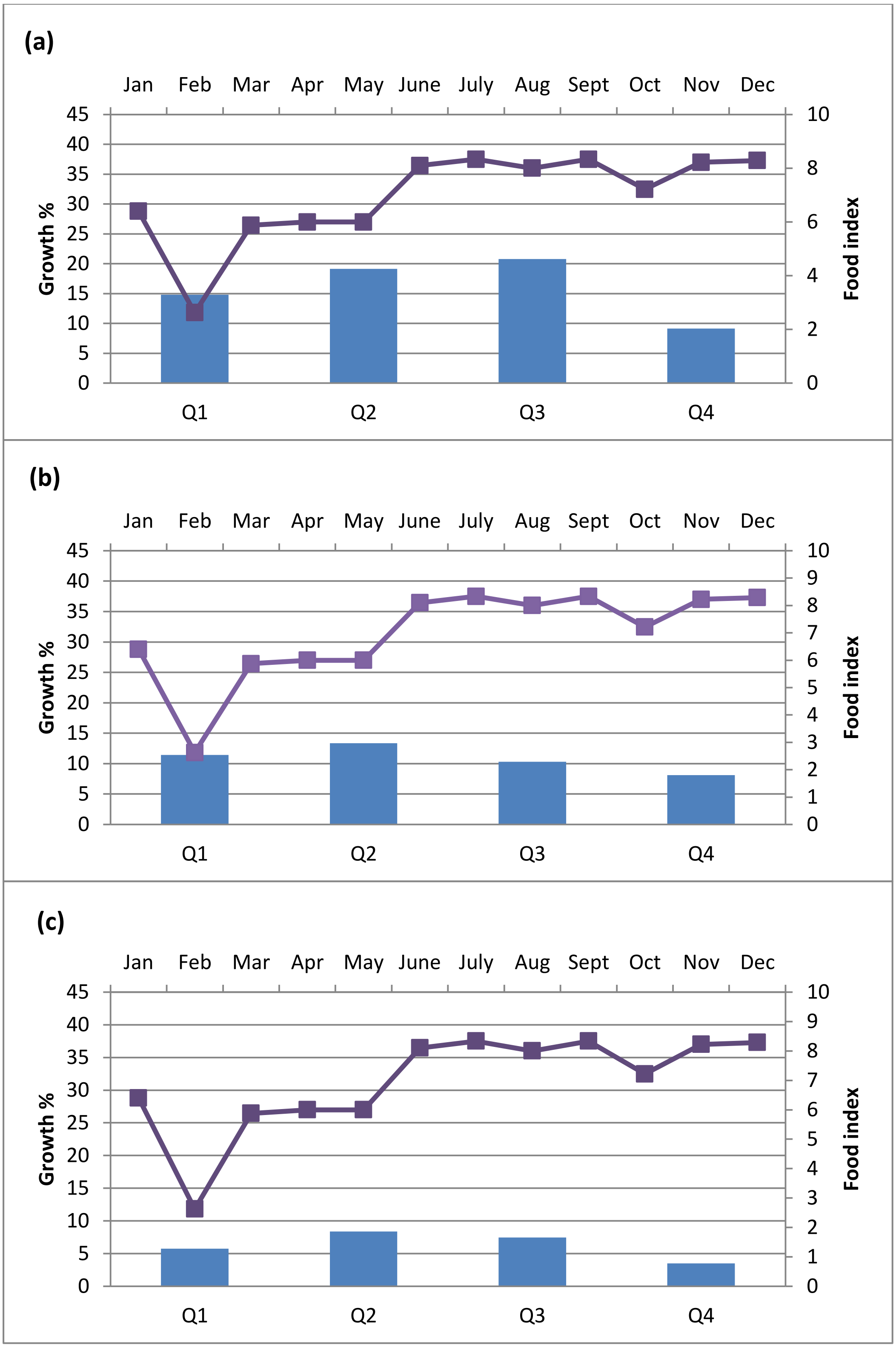


Figure 15: Average monthly food indices (line) compared with quarterly standardised growth increments (bars) for *H. laevigata* on the main R&D lease, in sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) 2-year old, (b) 3-year old and (c) 4-year old size classes

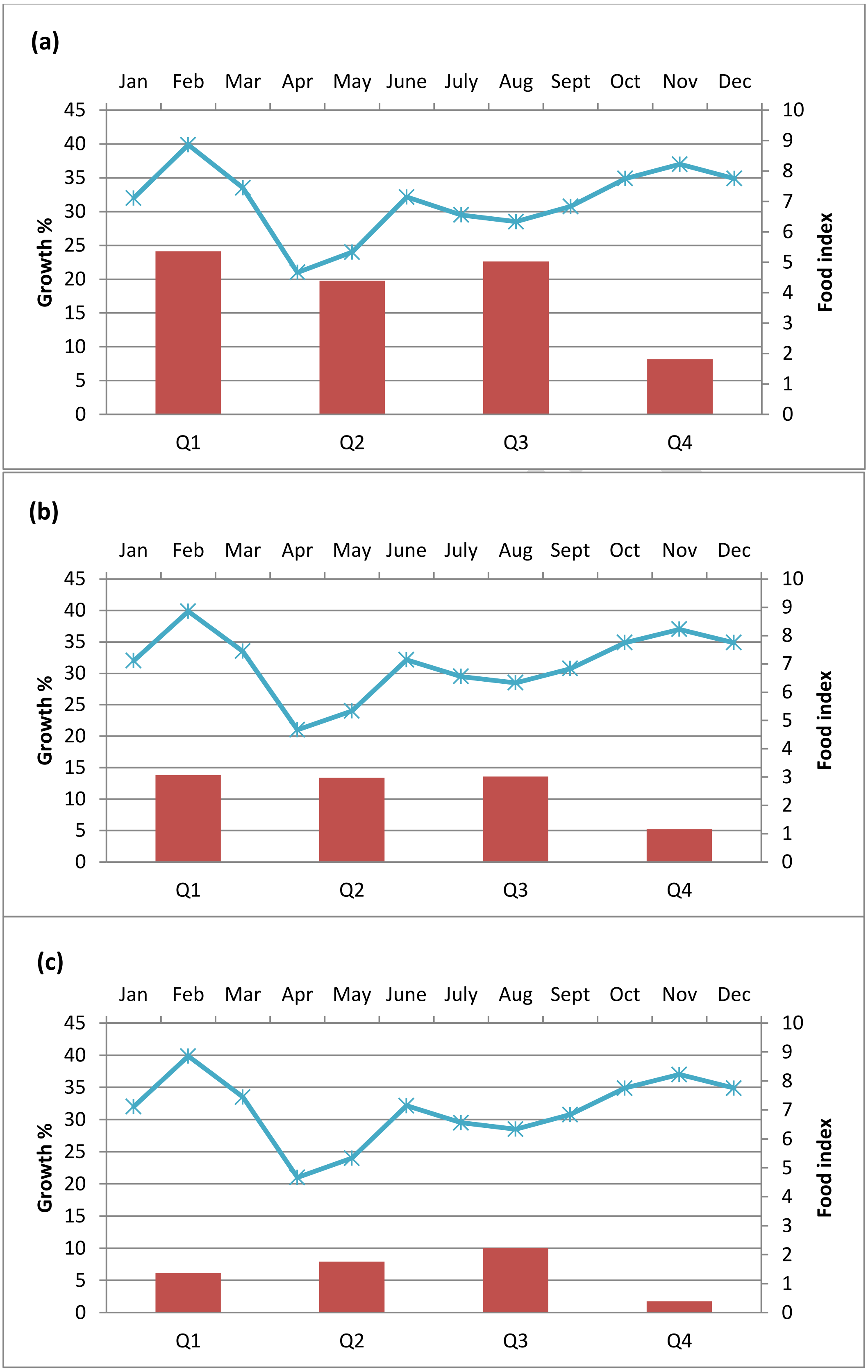


Figure 16: Average monthly food indices (line) compared with quarterly standardised growth increments (bars) for *H. laevigata* on R&D1 lease, in sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) 2-year, (b) 3-year and (c) 4-year old size classes

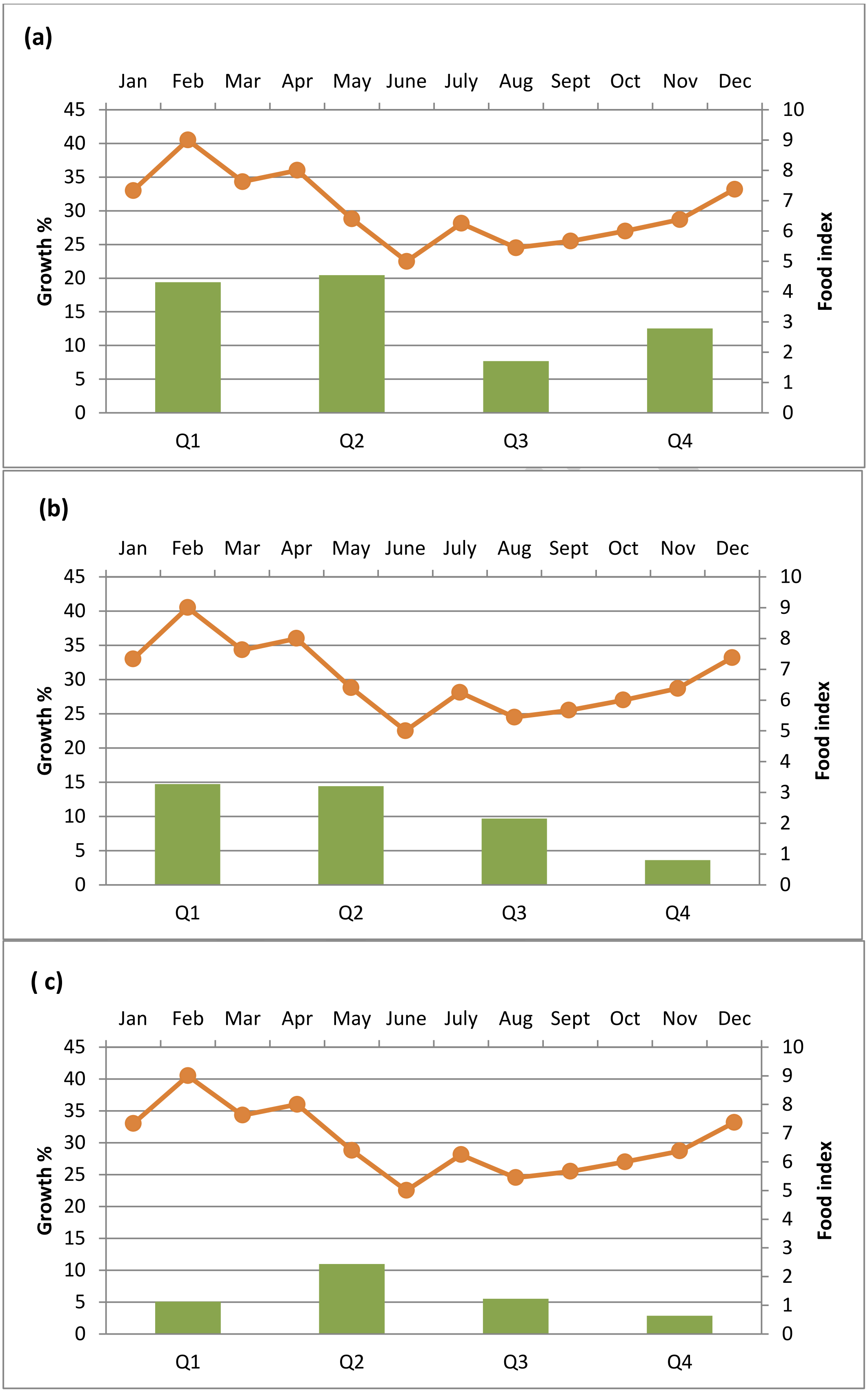


Figure 17: Average monthly food indices (line) compared with quarterly standardised growth increments (bars) for *H. laevigata* on R&D2 lease, in sea ranching trial at Flinders Bay, Augusta, Western Australia: (a) 2-year, (b) 3-year and (c) 4-year old size classes

3.5 Swell

Swell sizes over 3 m have been graphed (Figure 18) against quarterly growth increments for 2-year old animals in each R&D lease. Swells are clearly highest over the winter months (April – September). There were 56 days in 2012 where the swell reached in excess of 3 m, and of those, 45 were in this period. In general, growth over this period is at its highest for each lease site.

It has already been established that food supply varies seasonally across lease sites therefore any attempt to correlate food supply with this generic swell data was not considered to be useful.

3.6 Temperature

Mean daily temperature records for Flinders Bay close to the R&D leases are shown in Figure 19. The data show clear seasonal trends, with maximum temperatures being recorded in January and February (highest maximum 26.2^{o}C on 27/10/2012) and minimum in September (lowest minimum 16.6 ^{o}C on 15/09/2012).

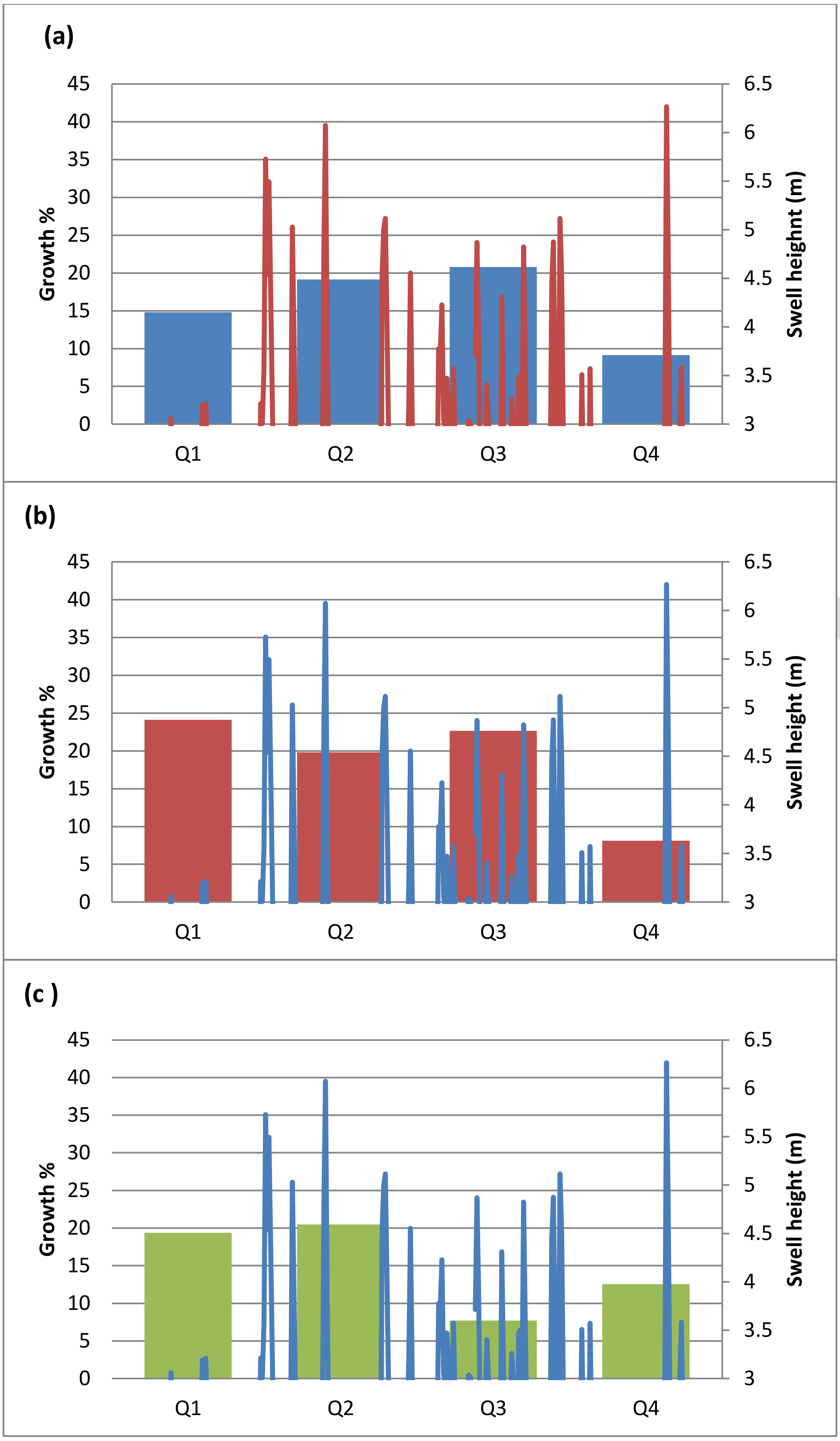


Figure 18: Swell height recordings of over 3 m at Cape Naturalise, Western Australia (line), compared to standardised quarterly growth increments for 2-year old *H. laevigata* (bars) on (a) Main, (b) R&D1 and (c) R&D2 lease sites in sea ranching trial at Flinders Bay, Augusta, Western Australia.

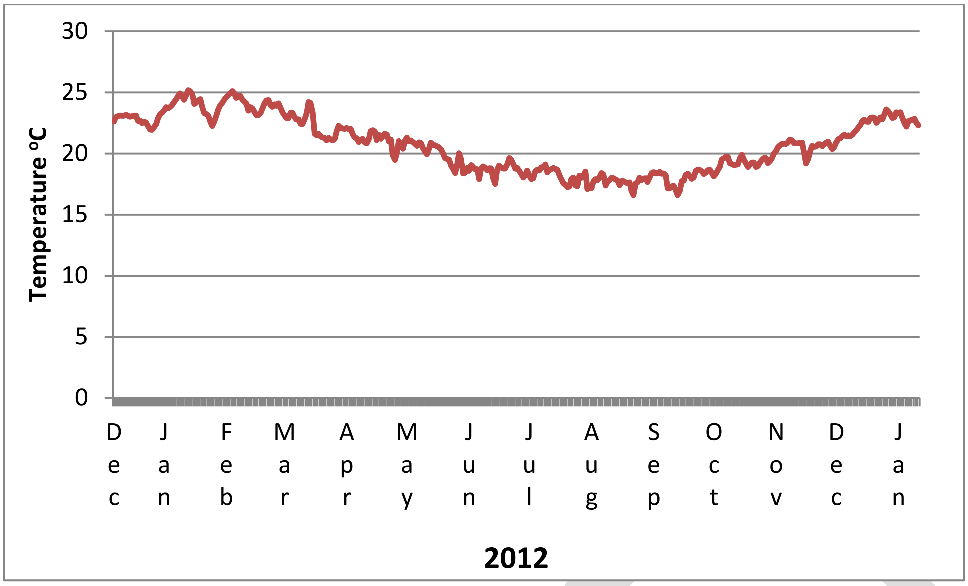


Figure 19: Mean daily temperature measurements for Flinders Bay, Augusta, Western Australia, from December 2011 through January 2013.

3.7 Predator removals

The numbers of octopus removed on the three lease sites over the one year sampling program are shown in Figure 20. There is a trend suggestive of higher numbers being captured in the summer months, although there is considerable variation between sites and between months. More octopus were generally caught on the Main Lease than R&D1 and 2; this was particularly true of summer 2012. The apparently higher abundance of octopus on the Main Lease may have to do with it having more available habitat structure than the other two leases, but could equally be due to it being closer to established reef area thereby making it more accessible to roaming octopus.

The only other potential abalone predators removed were three rock lobsters (*Panulirus cygnus* and *Jasus edwardsii*) and four baler shell (*Melo miltonis*).

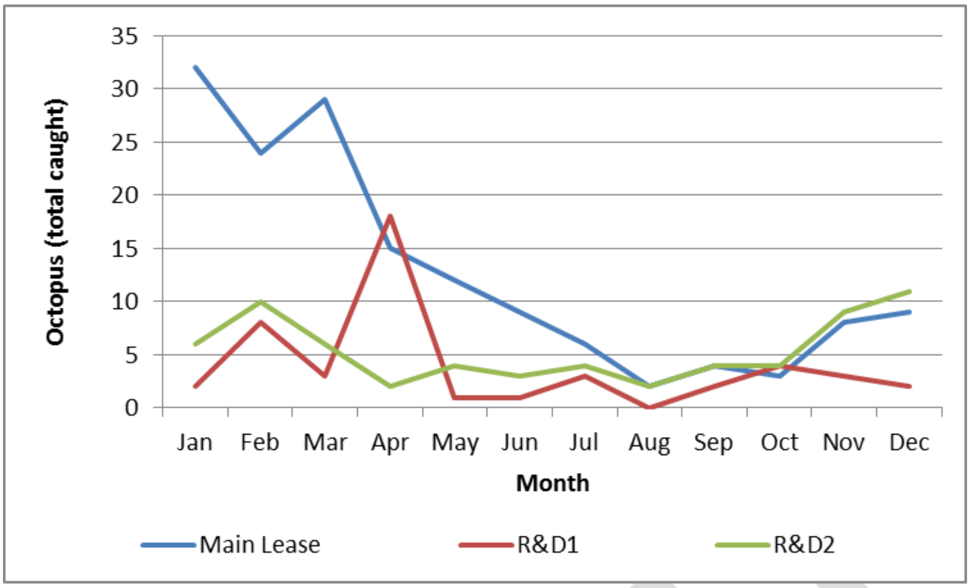


Figure 20: Number of octopus (*Octopus tetricus*) removed by month, from the three R&D leases in the sea ranching trial at Flinders Bay, Augusta, Western Australia.

3.8 Haejoo Units

3.8.1 Growth

Mean growth increments for the three cohorts of seed stock on Haejoo units are compared with the combined increments for other habitat types on R&D1 and R&D2 in Tables XIV and XV. The standardised increments (Table XV) show Haejoo units to have higher growth rates in all cases.

Table XIV: Growth increment and standardised increment comparisons for *H. laevigata* on Haejoo units in sea ranching trials on the R&D1 lease site in Flinders Bay, Augusta, Western Australia

	October - mean length	**January - mean length**	**Mean increment**	**Standardized increment (% increase)**
		2-year size class		
Haejoo units	55.9 ± 3.3	65.2 ± 4.0	9.3 ± 0.6	16.6
R&D1 average	69.3 ±7.3	75.0 ±8.3	5.6 ±1.1	8.1
		3-year size class		
Haejoo units	89.0 ± 3.9	95.1 ± 10.3	6.1 ± 1.3	6.8
R&D1 average	103.0 ±7.3	108.3 ±7.3	5.4 ±1.1	5.2
		4-year size class		
Haejoo units	116.6 ± 8.9	122.8 ± 6.8	6.2 ± 1.5	5.3
R&D1 average	121.4 ±4.6	123.6 ±4.4	2.1 ±1.0	1.8

Table XV: Growth increment and standardised increment comparisons for *H. laevigata* on Haejoo units in sea ranching trials on the R&D2 lease site in Flinders Bay, Augusta, Western Australia

	October - mean length	**January - mean length**	**Mean increment**	**Standardized increment (% increase)**
		2-year size class		
Haejoo units	52.6 ± 2.3	61.5 ± 3.3	8.9 ± 0.4	17.0
R&D2 average	63.2 ±5.8	71.1 ±7.1	7.9 ±1.0	12.5
		3-year size class		
Haejoo units	85.2 ± 3.7	92.3 ± 3.8	7.1 ± 0.6	8.3
R&D2 average	100.0 ±7.9	103.6 ±7.2	3.6 ±1.1	3.6
		4-year size class		
Haejoo units	113.3 ± 8.7	121.3 ± 5.8	8.0 ± 1.4	7.1
R&D2 average	115.2 ±4.6	118.5 ±5.5	3.3 ±1.1	2.9

3.8.2 Survival

The initial and long-term survival rates for Haejoo units compared to other habitat types is shown for 2-year old (Figure 20), 3-year old (Figure 21) and 4-year old (Figure 22) cohorts. Note that, as has been mentioned in the Methods section, caution does need to be exercised in the use of these comparisons because of differences between the size of the seed stock at seeding and the time of year in which they were seeded.

The initial survival (July to October quarter) for all cohorts on the Haejoo units in R&D1, was consistently higher than for other habitat types. The reason for this may be that initial survival rates of the 2011 stocking for seed stock in R&D1 were considerably lower than for the two other lease sites, possibly due to the vigour of the seed stock that were used on that site (see comments 3.3.1).

Survival rates of the Haejoo units on R&D2 were either similar to (Figure 20) or at the lower end of those measured for other habitat types (Figures 21 and 22). However, on this lease site survival figures for the 2011 stocking were complicated by the migration of stock from some habitat types to others (see Figures 7 to 9).

Long-term survival rates (October to January quarter) were similar for Haejoo units compared to other habitat types (Figures 20 to 22). Only in a single case (4-year old stock on R&D2), did Haejoo units perform worse than other units, in this case achieving a survival of 93% compared to the best habitat type which achieved a survival of 110%.

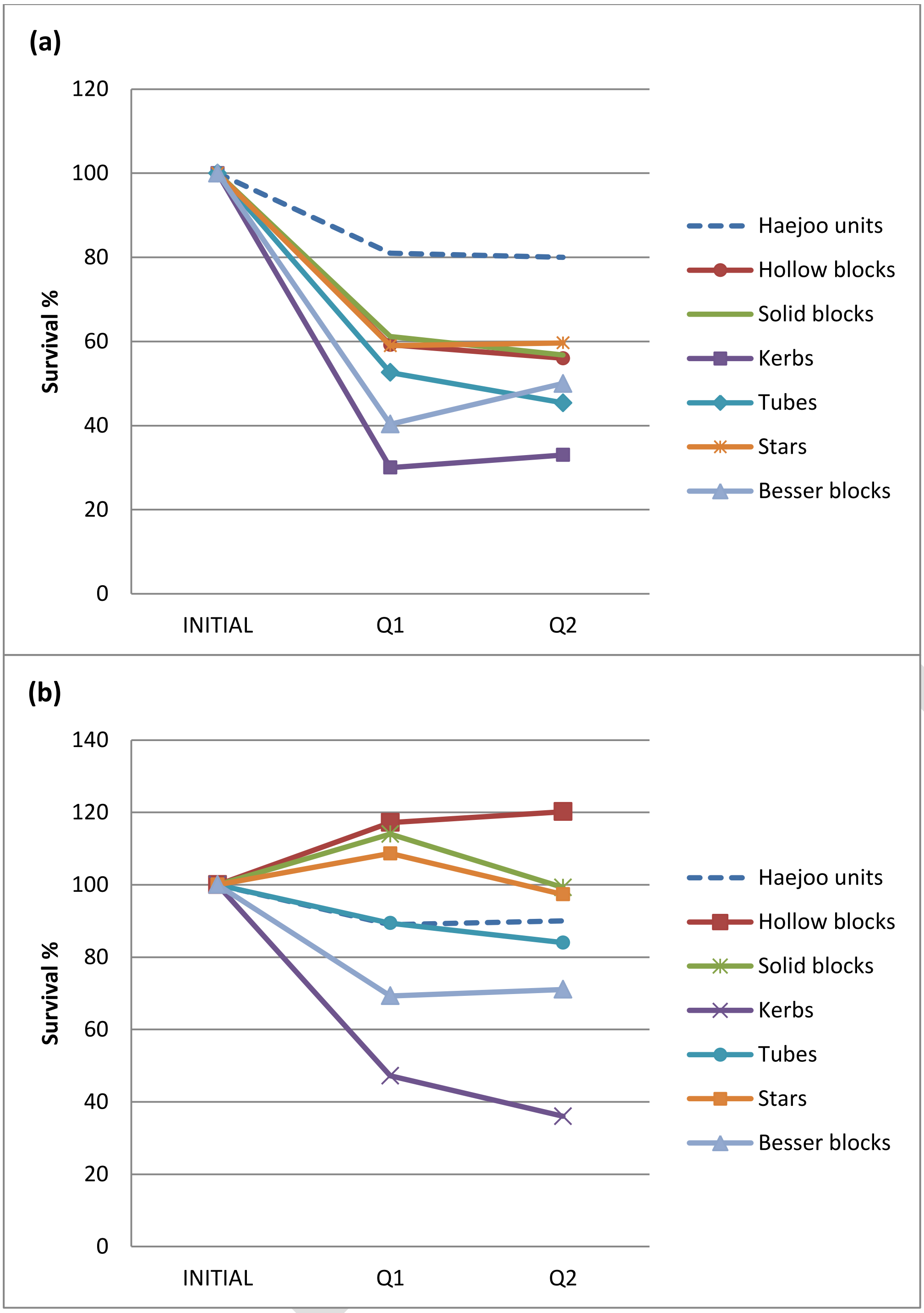


Figure 21: Comparisons of survival of 2-year old *H. laevigata* stocked on Haejoo and other habitat units in sea ranching trials at Flinders Bay, Augusta, Western Australia: (a) R&D1 and (b) R&D2 lease sites

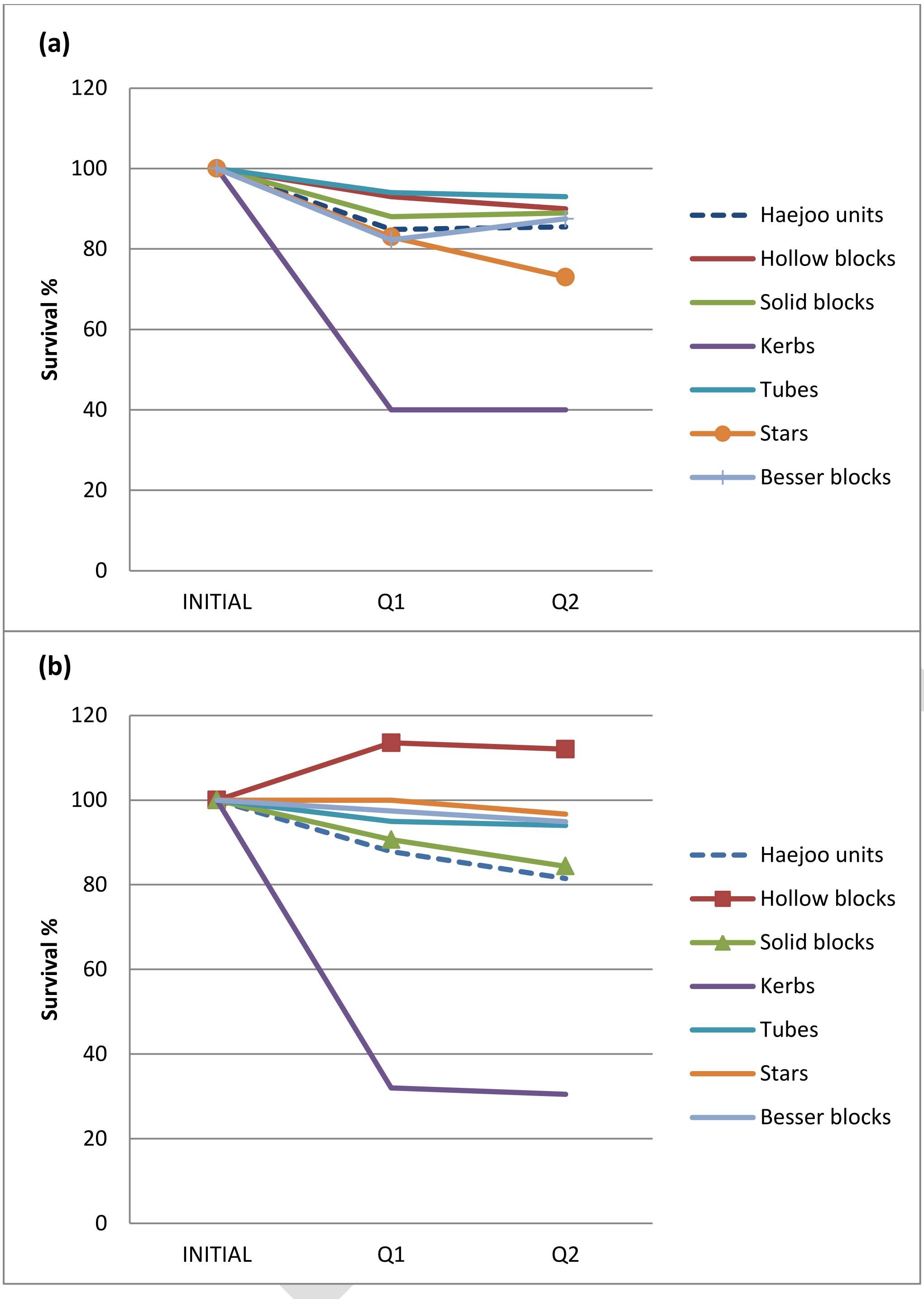


Figure 22: Comparisons of survival of 3-year old *H. laevigata* stocked on Haejoo and other habitat units in sea ranching trials at Flinders Bay, Augusta, Western Australia: (a) R&D1 and (b) R&D2 lease sites.

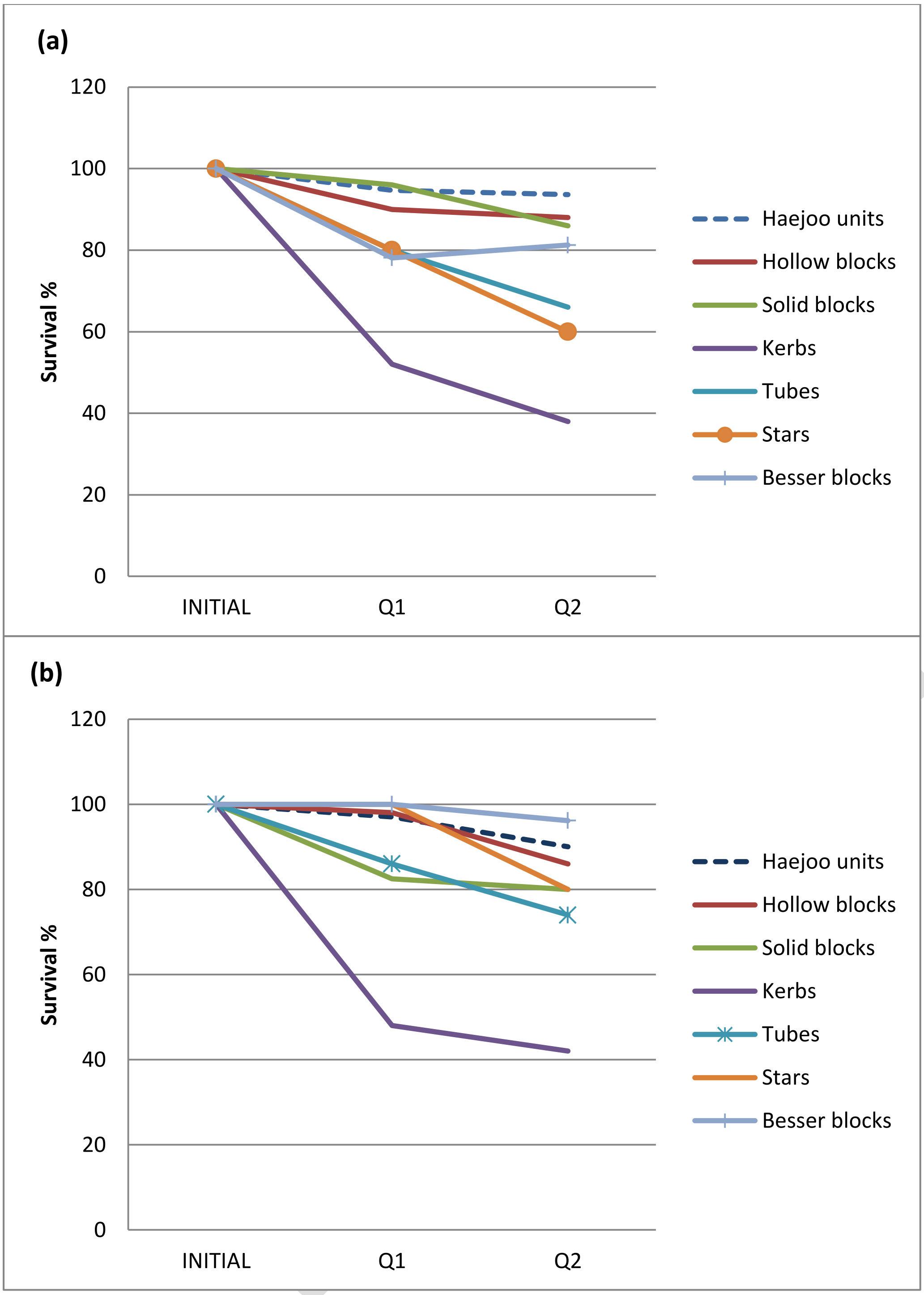


Figure 23: Comparisons of survival of 4-year old *H. laevigata* stocked on Haejoo and other habitat units in sea ranching trials at Flinders Bay, Augusta, Western Australia: (a) R&D1 and (b) R&D2 lease sites

4 Discussion

It is important to understand that this abalone sea ranching feasibility trial was undertaken as a proof-of-concept initiative, with the focus on establishing a commercial venture and was not an academic exercise. With a more research orientated focus it is likely that more rigor would have been applied to the sampling design and perhaps the length of the experiment may have been longer to provide better long-term estimates of growth. The sampling design has for example: not maintained similar stocking densities for all abalone year classes across all habitat types, has only measured abalone on individual habitat types on the Main Lease, has not maintained similar habit types across the three R&D sites and various other shortcomings. However, while these pose challenges for statistical comparisons of the performance of different habitat types across R&D sites, they do not detract from the obvious potential for this form of abalone aquaculture shown by the trial.

The idea of sea ranching of abalone on artificial habitat in Australia is not new. The seeding of juvenile abalone onto concrete modules was apparently practiced commercially at Flinders Island, Tasmania (Shepherd *et al*. 2000), although this has been discontinued in more recent times (Gardner, University of Tasmania, pers. comm.). Additionally, the stocking of artificial habitat with greenlip abalone have previously been undertaken at Port Lincoln, South Australia (Shepherd *et al*. 2000) and Port Phillip Bay, Victoria (James 2005; James *et al*. 2007). Neither of these trials translated into subsequent commercial ventures, in the former case because there was no further uptake by Industry and in the latter case because the study site was shown not to be suitable for sea ranching of abalone.

Compared to the results from the above Australian sea ranching investigations and to the many published stock enhancement research studies (*inter alia* (Masuda and Tsukamoto 1998; Sweijd *et al*. 1998; Tegner 2000; Hart *et al*. in press a), the results from this pilot abalone sea ranching project are very promising in terms of the ability to stock at relatively high densities and at the same time to support excellent survival and growth rates.

4.1 Validation

The validation work was done up to a couple of weeks after the counts were completed and there were variations (mostly small) between Brad Adams' counts and those of the Curtin University dive team. Those variations could have been the result of a number of different causes. They could have been counting errors by one or other party. Alternatively, they could have been caused by small movements of the abalone between habitat units and between days that the stock was counted. An equally likely cause for these discrepancies in counts is that at any one time there can be a portion of the seed stock covered by sand. Changing sea conditions continually lead to movements of sand on the lease sites and this can result in abalone being covered for short periods of time until a different set of sea conditions move the sand and expose previously buried animals.

4.2 Survival

While there was an initial spike in mortality in the weeks following the seeding of juvenile abalone onto the artificial habitats, survival rates thereafter were well beyond expectations based on the results of published enhancement studies (e.g. (Hart *et al*. in press a). The size of juvenile abalone at seeding is a critical aspect, with smaller individuals having substantially higher initial mortality rates. A spike in mortality following the placement of aquacultured juvenile abalone in the wild environment is a well-known feature of newly settled animals ((Saito 1984; de Waal and Cook 2001) which has been attributed to a multitude of factors.

De Waal and Cook (2001) have suggested that some aquaculture-reared animals may not develop sufficient muscle strength to withstand wave action in the natural environment, leading to them getting swept away after placement. Hatchery-reared animals are also not exposed to predators and it has been suggested by Shepherd *et al*. (2000) that this naivety to predators may lead to behavior characteristics that expose them to higher mortality rates than wild-spawned individuals.

Additionally, several published studies (Dixon et al. 2006; Roberts et al. 2007) have suggested that optimal survival of released juvenile abalone is maximized where the habitat is complex and cover for released animals is provided in the form of ledges, crevices and the undersurfaces of packed boulders. Shepherd (1986) has stated that crevices are the preferred habitat for greenlip abalone and that the animals move around until they find a suitable crevice, which may explain the high mortality rate after release if animals are searching for suitable shelter. Hart *et al*. (in press a), have emphasized the importance of releasing juvenile greenlip abalone into habit with cryptic locations within areas that have viable natural populations.

Finally, the physical condition of abalone at the time of seeding is an obvious potential cause for elevated mortality within the first few days. The process of transporting animals from a growout facility to the point of release in the wild is, even with the best of intentions and planning, always going to be stressful to the animal. Much can be done to minimize the stress and developing protocols for the holding and transport of seed stock from the hatchery to the point of release such as has been done for *H. rubra* by Heasman *et al*. (2004), is a worthwhile investment. Tegner and Butler (1985) reported that the mucus produced by stressed abalone attracted predators and this led to the development of “planting modules” along the lines of the module reported on in McCormick *et al*. (1994). The function of these modules is to provide shelter to newly settled abalone, and thereby protect them from predators for a day or two until they have become more settled and therefore less stressed in their new environment. The success of these units in improving immediate post-settlement survival is universally accepted and various adaptations of the modules are used in most abalone seed stocking deployments.

This study showed higher initial mortality rates for the three year classes across and within each R&D site compared to any single subsequent quarterly period sampled. It is not clear which of the above possible causes contributed to the high initial mortality, but two habitat types in this study (kerb and besser) had significantly higher mortality rates compared to other habit structures. These two habitat types were the only ones seeded by hand without a planting module, because of difficulties in attaching the modules to those structures. Their higher mortality rate substantiates the importance of providing protection for seed stock at deployment.

The seed stock that were released by hand were slotted into the sand around the sides of the reef leaving the sand to hold the abalone against the surface of the star and besser blocks until the foot had attached to the structure. Brad Adams, who was doing the seeding, was aware that the mortality rates were likely to be higher on these structures than other habit types because he observed fish predators (mainly wrasses) predating on the abalone before they had chance to firmly attach themselves.

The results from this study show that size at seeding is an important determinant of survival. Across habitat types, 4-year old seed stock had higher survival than 3-year olds and 3-year olds better survival rates than 2-year olds. Decreasing mortality rates with size and age are a feature common to most animals and are therefore not an unexpected result. Improved survival rates using larger/older seed stock have been reported on in numerous enhancement studies for a variety of different abalone species (e.g. *H. iris* (Roberts et al. 2007); *H. midae* (de Waal and Cook 2001); *H. discus hannai* (Saito 1984). The relevance of this finding lies in its economic application, which is the need for any commercial sea ranching operation to optimize the lower survival of small individuals against the higher cost of large individuals.

Several abalone stock enhancement studies (Shepherd *et al*. 2000; Heasman *et al*. 2004; James 2005; Roberts *et al*. 2007) have reported on relationships between stocking density and survival. The conclusions from these studies were similar in that all showed their data to indicate a tendency suggestive of decreasing survival with increased stocking density, but in no case were these observed trends significant. Both Heasman (2004) and James (2005) commented on their data being suggestive of their different initial stocking densities converging towards a longer term range that probably reflected the carrying capacity of the habitat. More recent work by (Hart *et al*. in press a; Hart *et al*. in press b) has adopted these considerations in a practical sense, by using a size-dependent mortality model to tailor release densities of greenlip abalone used to enhance experimental sites, to match surrounding wild-stock densities.

Despite the lack of consistency in the stocking density of different habitat structures in this study, differences in survival after the initial drop off following seeding were not significant. This suggests that the stocking densities which ranged between 20-60 m^{-2}, were within the bounds of what could be supported by the habitat.

This range of stocking density is a theoretical level which is based on the area of available surface for abalone to colonise on the habitat structures. It assumes that the habitat structure rests on one surface and that all other surfaces are colonized. In reality, the abalone aggregate on the sides of the habitat structures at the interface between where the habitat structures lie above the sandy seabed on which they are located. This interface between sand and colonisable surface periodically changes in response to sand movement caused by strong sea conditions and therefore the amount of actual surface available for colonization is variable, but always below the theoretical available surface area. Routine diving on the habitat structures has shown that the abalone are content to remain attached to the habitat structures while covered by sand for several days.

Some habitat structures have been less successful in providing available habitat for colonization than others. Because of their low relief, the kerb units for example, have been shown to become submerged under sand more easily than some of the other habitat types. This has particularly been the case on R&D2, where the sand sediment is finer than on the other two sites (Brad Adams pers. comm.). Other habitat types such as the tubes, while apparently providing a large amount of surface area, provide far less *actual* colonisable area. Approximately a third to even a half of the pipe can be buried and therefore unavailable for habitation. In addition, the greenlip abalone avoid colonizing the large amount of available area inside the pipes and only utilize the inside front 20 cms at the opening of the pipes.

The Haejoo units have not been a focus of this study because trials for these units are still underway. However, it is obvious from observing these structures underwater, that they will be less affected by the buildup of sand against their surfaces than the other units, which will mean that more surface will consistently be available for colonization. Furthermore, the design with its holes and crevices leading into the central open area appears to be ideal for trapping algae and circulating water. It is clear from observing the behavior of the abalone, that they utilize most of the surfaces and seem to particularly favor the inside chamber which funnels the water upwards and out of the chimney, in the process putting the algae into suspension where it is trapped and fed on by the animals occupying the inside surface.

Although survival rates of Haejoo habitat units have been compared to other habitat types in this study, it does need to be borne in mind that such comparisons are not ideal, because the units were seeded at different times of the year and by abalone of the same age, but different mean size. Survival rates are closely related to the size at which they are seeded and the time of year that seeding takes place could also be an important determinant of survival if the type and abundance of predators were to show seasonal differences through the year.

4.3 Growth

Growth increments over the one-year sampling was found to be similar (differences were not significant) across all habitat types and across the three R&D sites. To some extent this result was a feature of the way that the data were collected and a more robust sampling strategy, possibly by measuring tagged individuals on the different habitats, may have provided stronger statistical evidence for differences in growth. Certainly, the three R&D sites showed evidence of different levels of food availability in different seasons (Figures 15 to 17), which might have been considered to result in different growth rates across the sites.

Stocking density would also be expected to be a factor affecting growth if stocking levels were high enough to negatively impact food availability for the abalone. As has already been discussed in survival (above), calculating surface areas of habitat without taking into account the actual area colonized rather than available area for colonization, is a theoretical exercise. The fact that growth rates were not significantly different across habitat types, suggests that areas colonized by the abalone on the various habitat types in this study were at a low enough density for food to not be a limiting factor.

Other authors (Dixon and Day 2004) have recorded enhanced growth of greenlip abalone after a reduction in density of as little as 40%, but a different study that manipulated densities of *Haliotis iris* (McShane and Naylor 1995a), failed to show any response in the growth rate of that species. Growth rates of abalone have been shown to be more responsive to experiments where animals have been translocated to areas of more abundant or better quality food and various authors (Emmett and Jamieson 1989; McShane and Naylor 1995b; Dixon and Day 2004) have shown increased growth rates in different species of abalone as a result of such translocation experiments. While growth increments in this study were not impacted by the stocking densities, they did show seasonal differences across the board for all size classes (Figures 15 to 17).

The smaller growth increments recorded in the fourth quarter for all size classes in this study are most likely due to the animals redirecting their energy away from somatic growth and into gonadal production. Greenlip abalone mature at around three years and ~75 mm in size and spawn in spring and summer from October through March (Shepherd and Laws 1974). Other possible causes for the downturn in growth in the fourth quarter could be due to a response to food quality or physical environmental variable such as temperature.

Growth increments decreased with age, particularly between 3 and 4-year old seed stock. This is because there is a non-linear relationship between length and weight, which means that small increases in length result in proportionally much larger increases in weight. The 2, 3 and 4-year old year classes in this study were still in a very strong growth phase in terms of increases in both their length and meat weight (meat weight increases not shown) and this is why these three year classes could not be used to estimate an asymptotic length (L_∞).

The growth rates recorded in this study were very similar to the average growth rates recorded by Hart *et al*. (in press a) for *H laevigata* in the wild at Augusta, close to the experimental sea ranching sites reported on in this study. A 1-way ANOVA analysis of the merged data from this study (as seen in figure 7b) compared with data from the Hart study shows there is no significant difference in the growth rates across the period 2.25 – 4.25 years (d.f. = 1,6, F = 0.000, p = 0.996). Caution must again be used with this result owing to the study data being merged.

Preliminary growth data have been included in this report for stock seed on Haejoo habitat units. There are important differences between data for Haejoo units and that for all other units, which necessitate considering any comparisons of growth between these habitat types being treated with caution.

The Haejoo units were seeded seven months after the other habitat types and during this time the seed stock abalone were held under aquaculture conditions. As a result of this longer holding period in tanks, their growth had been compromised and they were substantially smaller compared to the same aged abalone that had been stocked on other units at the start of these trials. The standardized increment (percentage increase in size) is probably the most useful index of comparison between growth on Haejoo and other habitat types and in all cases this showed the abalone on Haejoo units to be faster growing. However, it may be that smaller individuals, even of the same age, increase in size proportionally faster and this needs to be borne in mind when considering these data.

4.4 Environmental data

The temperature for Flinders Bay is at the warm end of the range considered by Gilroy and Edwards (1998) to be optimal for growth of greenlip abalone. These authors showed the species to have a preferred temperature of ~19^{o}C and they regarded ~18^{o}C as being most favourable for growth. They showed temperatures of >25^{o}C to be detrimental to the wellbeing of the animals, with increasing numbers of experimental animals being unable to survive temperatures above 25^{o}C. Lethal (i.e. 100% mortality) of Gilroy and Edwards' (1998) experimental greenlip abalone occurred at around 30^{o}C.

4.5 Comparisons with other abalone enhancement and ranching studies

The results recorded by this abalone sea ranching trial have surpassed all expectations in terms of the survival of the seed stock. The reason for this is that expectations of what might be achievable were based on previous stock enhancement and sea ranching research which while showing some promise, had not achieved outstanding rates of survival.

Whereas the integrated survival data for the three different year classes in this trial suggests that survival rates after three years would have been around 40 to 50% (Figure 13), those for Hart et al. (in press a) were suggestive of survival rates for a similar period of 6 to 20%. Dixon et al. (2006) recorded variable survival rates in their experiment of between 0 and 57%, but this was after the seed stock had only been at large for nine months.

The high survival rates of the two year old abalone seed stock (~40 mm) in this study was particularly unexpected, because previous studies have reported that greenlip occupy in cryptic habitats at this size. Dixon *et al*. (2006) for example, found in their study that 97% of juveniles with a mean size of 44 mm were cryptic and even when they had reached a mean size of 56 mm, only 17% had emerged into the open. The habitat structures in this study offered only exposed surfaces.

The reason for the very high survival rates recorded here might actually lie in the artificial habitats used in this study being non-complex in terms of structure and being relatively barren in terms of biological diversity compared to wild reefs. Exposed surfaces may harbor fewer predators than cryptic habitat. Additionally, invertebrate abalone predators were regularly removed from the habitats throughout the trials. We believe this ecologically artificial and uncomplicated environment might be a major contributor to its success, because without many of its known predators, the abalone had much greater chance of surviving.

Greenlip abalone, depending on their size, have numerous predators. Shepherd (1986) and Shepherd *et al* (2000) listed sting rays, wrasses, sea stars, crabs and whelks as potential predators and they specifically stated that they had not observed, nor did they suspect octopus of being predators of abalone. Other studies on *H. laevigata* and other species of abalone, have recorded octopus as being predators (e.g. (Hart et al. in press b) and Tegner and Butler (1985) recorded over 30% of seeded red abalone (*H. rufescens*) shells that they recovered as having been predated on by octopus. Tegner and Butler (1985) also recorded spiny lobsters predating on seed stock.

Octopus were observed predating on seeded abalone on several occasions in this sea ranching trial and there is little doubt in our view that had the 265 octopus that were removed during the course been allowed to remain, that survival rates would have been seriously impacted compared to those that were recorded. Only three spiny lobsters were removed from the study site over the course of the trial and it is well known that they can remain resident in one area for lengthy periods (Jernakoff 1987; Gardner *et al*. 2003), so had they not been removed it is likely that as with octopus, that they too could have made a localized impact on seed stock survival.

Wrasses and sting rays were consistently present on the lease sites throughout the experiment. In particular, wrasses were a major cause of predation during the stocking of the sites, particularly on those habitats (whatever they were) that were stocked by hand. However, once firmly attached, these species were not considered to actively predate on the seed stock and it is our belief that they only consumed abalone that for any reason became dislodged.

4.6 Using survival and growth rates from this study to estimate potential production

This pilot study has provided preliminary data on which can be used to estimate the potential production and therefore the potential profitability, of ocean ranching of abalone in Flinders Bay. A detailed analysis of potential profitability is beyond the scope of this report and will be undertaken as a separate exercise in the future.

Until such time as a more detailed report is produced, readers can make use of the growth data in Figure 7, survival data in Figure 13 and the length-weight relationship for greenlip abalone established by Hart *et al*. (in press c) : $W = 0.00003L^{3.343}$, where L is length (mm) and W is weight (gms), to obtain an indication of what production of biomass could be achieved for different quantities of abalone seeded.

An example of the way our data could be used in this way to indicate production for the seeding of say 50,000 greenlip abalone of 40 mm in length is shown in Table XIII.

Table XIII: An example of the potential biomass of greenlip abalone produced from an initial stocking of 50,000*40 mm animals after 1, 2 or 3 years, based on the survival and growth of *H. laevigata* in sea ranching trials conducted in Flinders Bay, Augusta, WA.

Growout period (Years)	**Survival (%)**	**Mean Length (mm)**	**Biomass (kg)**
0	100	40	340
1	66	80	2,278
2	60	110	6,000
3	50	130	8,750

Using pilot project data in this way does need to be viewed with some caution. Some considerations in this regard are outlined in 4.7 (below).

4.7 How applicable are these results to migrating from pilot to commercial scale?

There was no significant difference in growth rates across the three R&D sites and this together with the high food indices throughout the year at the R&D sites (Figure 14), would support a conclusion that drift algae is prolific and widespread across both the approved lease site as well as the two sites awaiting approval. With prolific food, one would expect there to be no difference between growth on the experimental sites compared to ones much larger in size.

There is no apparent reason to doubt that the good survival and growth rates that were recorded in this pilot project should not be valid for a commercial scale project, but Bartley and Bell (2008) have cautioned against assuming that results from small-scale experiments hold over larger management areas. They point to small scale experiments on scallops and geoduck reported in Bell *et al*. (2005), which were a misleading guide to future performance when scaled up to larger research trials.

If expanded to commercial scale, the relatively small and isolated R&D sites reported here would presumably form larger, probably self-sustaining, reef ecosystems. Whether or not ecological changes in competition and predation pressure would result, or whether such change would impact the results from this pilot ranching project are unpredictable. Furthermore, the substantial primary production available in Flinders Bay does have a finite carrying capacity and the only way of determining what that will be on rows of habitat structures spread across the lease sites, will be by regular monitoring of growth and survival of the stock.

The results in this pilot program are for seeding with largely 2-year old animals and lesser quantities of 3 and 4-year old abalone. A commercial project will *probably* seed habitats with 2-year old animals and let them grow for a couple of years before harvesting. The same habitat structures would probably be seeded annually with a fresh cohort, to coincide with the removal of the grown out cohort. It is unlikely that the ratios of 2, 3 and 4-year old animals would be in the proportions stocked in this experiment, which would mean that stocking densities of the cohorts will need to be carefully evaluated prior to scaling up to the commercial operation.

4.8 How applicable are these results to other study sites?

The results from this study are not directly applicable to other sites. In one list of lessons learned from restocking, stock enhancement and sea ranching initiatives to date, Bartley and Bell (2008) state that "good survival of released juveniles at one site is no guarantee that the methods can be transferred to other sites". Another lesson learned (Bartley and Bell 2008) is that "there are no generic methods for restocking and stock enhancement". Both of these lessons point to the fact that successful seeding into the wild is dependent on a multitude of different, often interacting, factors. Because of sedentary existence and dependency on drift algae for their food source, abalone survival and/or growth is particularly inconsistent and significant differences in these variables are often detected over small distances (e.g. (Dixon and Day 2004; Hart *et al*. in press a).

Across the distribution range of greenlip abalone, the stocks appear to have very different predation threats. For example Dixon *et al*. (2006) attributed high mortality of abalone seed stock in their study, to predation by starfish (*Coscinasterias muricata*) at one site, and to *C. muricata* and *Notolabrus tetricus* (a wrasse fish) at another site. Shepherd (1973) pointed to eagle rays and sting rays as being serious predators of young greenlip abalone in South Australia and leather jacket fish were suggested as being serious predators of juvenile abalone in an enhancement experiment conducted in Tasmania (Brad Adams, OGA, pers. comm.). This variation of abalone predators across the fishery implies that some sites will be less suitable than others for abalone sea ranching, due to the type and abundance of predators.

Suitable areas for ranching would also need to take into account the likelihood of storm damage which could impact either the food source (e.g. through destruction of sea grass beds), or the artificial habitat structures.

Appropriate stretches of coastlines and embayments are therefore likely to be extremely limited and all would need careful evaluation before being selected for commercial abalone ranching.

4.9 Conclusion

Bell *et al*. (2008) noted that there are several invertebrate species ideally suited to enhancement or sea ranching because of being sedentary, low down on the food chain and having a high economic value. Abalone are one of the ideal invertebrate species which fit all of these criteria.

The focus of introducing hatchery reared stock into the wild in Australia has been, and continues to be, for the purpose of enhancement rather than ranching. The reason that sea ranching has been neglected is twofold: firstly, there are relatively few species that are sufficiently sedentary to allow for sea ranching and secondly, aquaculture policy has been inadequate, certainly in Western Australia. However, this is in the process of being rectified. The Government of Western Australia has recently released a policy document clarifying deployment of habitat enhancement structures in the marine environment (Department of

Fisheries 2012) and there is a soon-to-be released proposed abalone aquaculture policy document (Anon. 2012).

The promising outcomes from this proof of concept trial together with progressive aquaculture policy, could be expected to provide a way forward for orderly expansion of abalone sea ranching in the state.

Key contributors to the potential future success of abalone sea ranching in Western Australia identified from the results of this trial are:

- That once seeded (with two-year old abalone) and having suffered the initial mortality phase, that thereafter mortality rates can, with good management, be limited to as little as 5 to 10% a year. This is a very significant result given that the habitat is non-complex and the abalone are very exposed and therefore visible to predators.
- That growth rates comparable with abalone in the wild environment can be achieved at relatively high stocking densities on artificial habitat.
- That growth and survival rates of seeded abalone are similar in different lease sites within Flinders Bay. This shows that food availability and sea conditions for abalone sea ranching are suitable over a wide area and that depending on the success of future commercial ventures, that there will be opportunity for Government to allow for orderly expansion within the Bay.

As with any research however, this pilot study has led to the identification of several questions that will require further investigation in the future.

(i) Modeling the financial viability of greenlip abalone ranching in Flinders Bay taking into account capital and operating costs for the farming activity.

(ii) Completing the preliminary analysis in this report, of the growth and survival of abalone on the Haejoo habitat structures at the end of a one-year trial. This may lead to ideas for improving the design in the future.

(iii) Research into experimentally establishing the "limiting density" for greenlip abalone sea ranching in Flinders Bay, i.e. the density where growth and/or survival is significantly reduced as a result of stocking density. . Adding to the complexity of this task is that the research will also need to consider density in terms of optimising the ongoing rotation of stocking new year classes and harvesting marketable sized animals. This is a particularly important research objective, because it will dictate the extent to which the research reported here can be scaled up.

(iv) Mortality rates in the initial phase of stocking appear to be unnecessarily high and methods should be investigated to minimize this impact through improved release technology and animal husbandry during transport.

(v) Water circulation past the aquaculture lease sites and within Flinders Bay would provide useful information on the source of the drift algae that are the food source for the seed stock and of the eggs and larvae that will be released from the farm.

(vi) Knowing more about seasonal differences in the quality and species composition of drift algae that provide the food source of the abalone seed stock will be important for determining seasonal and year-to-year variations in growth rates of the abalone.

(vii) Identifying the ecological significance of artificial structures as habitat for juvenile reef fish (such as dhufish and pink snapper).

The above research will be undertaken in future years, prioritized on an ‘as needs’ basis, in conjunction with the commercialization of abalone sea ranching activities by Ocean Grown Abalone Pty Ltd in Flinders Bay.

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