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Abstract

A preliminary assessment of stock enhancement of *Haliotis laevigata* (Greenlip abalone) in Western Australia was undertaken with the release of 6,000 abalone near Augusta in 2004. The objective of the project was to obtain quantitative data on the likelihood of enhancement, as an additional management tool to TACs and size-limits, being successful in natural habitats in Western Australia. Baseline surveys coupled with an assessment of growth and survival of released 1+ and 2 + animals were undertaken at 12 sites within Flinders Bay, Augusta. Overall survival was 19% for 1+ age abalone and 27% for 2+ animals after 9 months. However, habitat had a significant effect on survival, with survival in high quality habitats being 35% for all animals. Mean densities of animals less than 96 mm shell length (1- 3 years age) increased five-fold in the 12 months between the baseline surveys, and the post-seeding survey.

Total cost of stock enhancement (production + release) was higher for 2+ animals compared to 1+ animals, but reduced with increasing numbers released. Maximum economic efficiency was gained with a release of 500,000 + animals, which cost $0.39 per 1+ animals, and $1.02 for 2+ animals. To ensure maintenance of existing genetic diversity of wild stocks, an enhancement rate of 35% of natural recruitment to the breeding stock was evaluated. Being within the expected variation in natural recruitment, this rate is considered unlikely to result in density-dependent effects on mortality and growth.

Under this scenario, a maximum annual release of 2.5 million 1+ animals, or 1 million 2+ animals to the state-wide stocks of *Haliotis laevigata* could be sustained. Yields from this release would be 35 – 40 t (meat weight) at estimated survival rates. At the current landed value ($126 / kg meat weight), a 14 tonnes (20%) annual increase in commercial catch is required for a break-even return on costs of enhancement. Similar estimates were also derived for smaller genetic zones. From a cost-benefit analysis, 2+ and 1+ releases were similar in performance. The options are: 1) a larger grow-out program and a smaller enhancement program will yield higher and less variable survival (2+ releases); 2) a smaller grow-program, and a larger release program, for lower overall survival (1+ releases).

A test case for commercial enhancement was proposed, and includes appropriate biological, environmental, and genetic targets against which success can be evaluated. If implemented, this programme would require annual monitoring, and a maximum annual release of 137,000 × 1+, or 53,000 × 2+ animals for a 5 – year period so that success can be gauged against natural variability in recruitment.

A larger experiment is required to critically investigate the effect of habitat on survival, and supply robust estimates of growth and survival to optimise the bio-economic analyses. The method described may be useful for populating depleted areas that are known to be productive, but subject to low recruitment. However, enhancement into the natural habitat should only be implemented as an activity that is integrated into wild-stock management, and subject to the existing suite of performance indicators currently used to manage the fishery. It also needs to explicitly recognise other risks, such as the possibility of disease introduction.

1 Introduction

Stock enhancement or 'seeding' of hatchery-produced abalone has been a sought-after strategy for wild stock management in most abalone-producing countries since aquaculture techniques were developed. The theoretical basis for stock enhancement is that fish stocks are recruitment limited (Bell et al., 2006), i.e., that carrying capacity is rarely reached except in exceptional year classes, and therefore additional recruits can be accommodated, up to the limits of the carrying capacity of the system. Evidence for recruitment limitation is found in fisheries where a constant catch level (e.g. a set Total Allowable Catch) does not mask natural variation in productivity. The *Panulirus cygnus* (Western Rock Lobster) fishery in Western Australia is an example of this. In this fishery, the ± 35% variability in annual catches from the long-term average (Caputi et al., 1998), is almost entirely caused by year-to-year variation in recruitment. Many examples of recruitment limitation have been demonstrated in unexploited tropical and temperate fish populations (Doherty, 1999).

Despite its obvious potential, stock enhancement has had limited success as a fisheries management tool (Molony et al., 2003). This appears to be the case for the decades long enhancement programs for abalone in Japan. Some success has been noted (Kojima, 1995, Masuda & Tsukamoto, 1998), however the program has not halted the continual decline in wild stock production (Prince, 2004). Within Australia, considerable stock enhancement work has been carried out on *Haliotis rubra* in NSW, and 6 – 9 mo-old juveniles dispersed over a wide area at low densities is the recommended technique for this species (Heasman, 2006). For *H. laevigata*, experiments in South Australia with older individuals (1+ age; ~ 28 mm) showed survival of 20 to 40% after 6 months, however the study utilized artificially constructed reefs, not natural habitat (Dixon et al., 2006).

Strategies for marine stock enhancement recommend that success be gauged by explicit objectives and policies that incorporate all knowledge of life history traits, including genetic management (Blankenship and Leber, 1997; Ward, 2006). Loss of genetic variation has been shown to occur in hatchery progeny of wild broodstock of *Haliotis rubra* and *Haliotis midae*, when compared with wild stocks in the respective areas of broodstock collection (Evans et al., 2004). While such outcomes are not necessarily deleterious to progeny, they demonstrate how quickly genetic diversity can be altered within a hatchery environment (Ward, 2006). Mindful of these concerns, the Department of Fisheries has developed policy guidelines on stock enhancement and re-seeding of molluscs in Western Australia that apply responsible enhancement strategies in the local context (Borg, 2002). The policy stipulates genetic boundaries for translocation and stock enhancement based on current scientific knowledge (Table 1). Responsible hatchery protocols are required to maintain the integrity of these boundaries, as preliminary genetic diversity surveys for *Haliotis laevigata* in Western Australia show genetic differences between populations (Elliot and Conod, 2001). Properly managed, an enhancement strategy will help maintain diversity, and hence resilience, of wild stocks that may be exposed to accelerated selection processes (e.g. for a lower size at-maturity) as a result of size-selective fishing (Olsen et al., 2004).

Haliotis laevigata is the most valuable abalone species in Western Australia. To date, stock enhancement of this species has not been investigated. Enhancement is likely to be more effective in the long-term in habitats where natural recruitment is limited by a paucity of adult stock, juvenile habitats, or localised retention of larvae. However, recruitment limitation theory suggests that all habitats are likely to be sub-optimally inhabited most of the time. Consequently, a targeted, broad-scale enhancement project can potentially increase stock productivity, and provide a buffer in years of low natural recruitment.

The overall objective of this project was to obtain quantitative information on the feasibility of *Haliotis laevigata* stock enhancement, as an additional management tool to TACs and size-limits, being successful in natural habitats in Western Australia. The specific objectives of the study were:

a) To obtain preliminary growth and survival estimates of seeded abalone in natural habitats in the medium term (10 months post-seeding).

b) To assess bio-economics of enhancement based on known biological parameters (growth, survival) and known costs of production and income.

c) To evaluate the biological and economic parameters of an optimum release strategy for Western Australian habitats that will maintain existing genetic diversity.

Table 1. Genetic zones within Western Australian for the southern abalone species (*Haliotis laevigata, H. conicopora and H. scalaris*). The zones have been established as a precautionary measure against any possible impact from the mixing of genetic stocks, however it is recognised that boundaries may be reviewed when additional scientific information is available

Genetic Zone	Zone Boundaries
1	Carnarvon to Drummonds Point[1]
2	Drummonds Point to Guilderton[1]
3	Guilderton to Cape Bouvard[1]
4	Cape Bouvard to Windy Harbour[2]
5	Windy Harbour to Hopetoun[2]
6	Hopetoun to Pt Culver[2]
7	Pt Culver to South Australia[3]

[1] Primarily *Haliotis scalaris* zones. No commercially fished stocks of *Haliotis laevigata* within these areas.

[2] Commercially fished genetic zones. Discussion in this reported restricted to these areas.

[3] Primarily a slow growing/stunted area. Subject to irregular commercial fishing under ‘stunted stock fishing protocols’. Enhancement unlikely to be viable in this area due to low natural productivity and inaccessibility of stocks

2 Methods

2.1 Spawning and culture of juveniles

Greenlip abalone used in this study were cultured at Great Southern Marine Hatcheries (GSMH) in Albany, Western Australia. Broodstock (> 140 mm shell length) were sourced from locations in Augusta, which are in the same genetic zone as the experimental reefs. A summary of spawning and culture protocols follows:

Spawning

Broodstock are placed into individual spawning containers and induced to spawn using commercial spawning techniques. Ultraviolet-irradiated seawater was heated to 21° C and than slowly reduced to ambient 17° C during the course of 8 hours. Spawning usually occurred after 12–24 hours.

Fertilisation

Abalone eggs of all spawning female abalone (3–10 per spawning) were collected with a small siphon and combined with sperm that was collected from 2–3 spawning males with a small jug. After determining egg and sperm density, the eggs were fertilised with 5–10 sperm per egg. Eggs were washed after 15 minutes in filtered seawater for 15 minutes to remove excess sperm and to avoid polyspermy. The fertilisation rate of each batch was determined by counting the eggs that were dividing after 1 hour (indicating that eggs have been successfully fertilised) in three 1ml samples.

Hatch rate

Eggs of each batch were placed into separate hatch tubs and formed a monolayer on the bottom of the tub. All tubs were set up with low water flow and low aeration. The water was turned off ca. 2 hours before hatch out started. The hatch rate (expressed as percentage) was determined by counting the number of unhatched eggs in three 1 ml samples, calculating the total of unhatched eggs and subtracting these from the total number of successfully fertilised eggs.

Larval survival

Larvae were reared in 300 L conical fibreglass tanks at a stocking density of up to 20 larvae per ml. All tanks were set up with low aeration and water flow after the larval shell was completely formed. Depending on the ambient water temperature, larvae were reared in these tanks for ca. 7 days (at 17° C).

Settlement and Nursery Plate System

Larvae were settled on commercially used PVC settlement plates (40 x 60 cm) covered by *Ulvella lens*, which was cultured on the plates for 2–3 weeks prior to larval settlement. Larvae were released into commercial concrete nursery tanks at a standard density of 0.2 larvae ml^{-1} (500,000 per tank). Nursery tanks hold ca. 2,600 L and were set up with 18 baskets holding 20 settlement PVC plates each. The term "settlement" describes the permanent attachment of the larvae to the substrate after shedding of the velum to complete metamorphosis. Tanks are inoculated with cultured diatoms (*Navicula jeffreyi*) every 2–4 weeks to enhance the natural diet growing on the plates. New plates covered with *U. lens* are added every 2–3 month. Juvenile abalone stay in that system for the first year or until they reach ca. 15 mm in shell length.

Grow-out System

Once juvenile reach 15 mm in shell length they are moved into the grow-out tanks and weaned onto a commercial formulated feed (Adam & Amos). Slab tanks in Australia are usually 12 – 20 m long and 1.5 – 3 m wide, they can be made out of PVC or concrete. Water through this system flows as a unit, which ensures that bacteria and wastes can be easily flushed from the system. Each tank has a "tipper" which will fill up with seawater over several hours, tip over and create and release a wave of seawater over the tank surface, to clean tanks of wastes, like faeces and left over food. Animals are fed at 1–2% body weight per day usually every second day. In commercial operations, abalone stay in that system until they reach market size 90–120 mm in shell length (after 1–2 years).

2.2 Growth and survival experiment

Disease-free certification of abalone to be released was achieved from the Department of Fisheries prior to enhancement experiments.

2.2.1 Study sites

Abalone reefs within Flinders Bay, Augusta was selected for the experiments. It was hypothesized that areas selected had been depleted due to overfishing, with illegal fishing being the principal cause. A covert intelligence operation by the Department of Fisheries (Operation "Singapore Noodle") in the mid-1990s exposed a massive illegal fishing ring in WA, with 9 persons convicted of 24 offences resulting in $500,000 worth of fines. This hypothesis was confirmed by discussions with members of the abalone industry. A total of 15 sites were selected for the enhancement experiment by industry divers. Of these, 12 were randomly chosen for the experiment, and the other 3 remained as controls, i.e. they were not enhanced with hatchery-bred stock.

2.2.2 Experimental design

Growth and survival of greenlip abalone was examined under the following experimental treatments:

a) Age at release (0+, 1+, 2+). These ages translate into the following broad size-categories (10-20 mm; 20-40 mm; 40-70 mm);

b) Release mechanism (Hand release vs mechanical release);

c) Density (High = 500, 250, 100 abalone vs Low = 100, 50, 25 for the 0+, 1+, and 2+ age classes respectively). These numbers refer to the actual number of abalone released per experimental replicate.

There were three replicates of each of these treatments, and Table 2 describes the treatment codes. Replicates were randomly assigned amongst sites (Table 3). The mechanical release strategy involved placing the required number of abalone into square PVC pipe (dimensions: 40 x 10 x 6 cm) with a mesh ends.

Table 2. Treatment codes for the experimental evaluation of growth and survival of seeded greenlip abalone. Three examples are given.

Treatment	Age code	Density Code	Release Mechanism Code	Replicate code
OHH1	0 = age 0	H = High	H = Hand Release	1 = Replicate 1 (of 3)
1LM2	1 = age 1	L = Low	M = Mechanical Release	2 = Replicate 2 (of 3)
2LM3	2 = age 2	L = Low	M = Mechanical Release	3 = Replicate 3 (of 3)

2.2.3 Tagging and experimental allocation procedure

Benzocaine anaesthetic was used to release the juveniles from their various tanks and they were transferred into a tank lined with mesh for sorting into age classes. The 0+ and 1+ animals came from the nursery tanks, while the 2+ animals were sourced from the grow-out tanks. For each age treatment, animals were separated and into tagged and untagged individuals in readiness for counting and batching into mechanical and hand release containers (Release treatment).

Each size class was transferred into a divided tray with tagged and untagged of the same size class. The percent tagged and untagged were estimated and this estimation was used to determine the proportion of tagged and untagged used for the different experimental treatments.

A total of 6150 animals were allocated to the experimental treatments, of which 3314 were tagged. Volunteers (school students) tagged the animals with numbered yellow tags about 6 weeks prior to release. This allowed them to settle after being disturbed.

A considerable number of tags were lost prior to, and during sorting due to the type of glue used. Once juveniles were transferred to the mesh-lined tank they were adhering to each other. When separating them into different sizes tags were being dislodged. Future experiments will require more robust tags.

2.2.4 Transport, release and monitoring strategies

The 36 groups of greenlip juveniles (12 treatments x 3 replicates; Table 3) were transported from the Albany hatchery in two large tubs (400 L ea) with seawater aerated with O_2 rotating every half hour from one tub to the other. The trip from Albany to the Augusta study site (see section 2.3) took approximately 4.5 hours. Mortality from the time of sorting the experimental batches in the Albany hatchery (28/2/04) and distributing them to divers at the boat ramp 4/3/04 was very low, estimated at 50-100 animals of 6000.

Four commercial abalone dive boats were used in the reseeding exercise, and 7 industry members undertook the re-seeding: 1 - Darren Adams; 2 - Nathan Adams and Jamie Colquhoun; 3 - Brad Adams and Peter Gaebler; 4 - John Lashmar and deckie Tom. Corresponding batches for four sites were distributed to each boat, 12 batches/boat. Only Darren Adams' boat had a flow through seawater holding tank. The other three boats bucketed water over the abalone before distributing them to each site.

Average size of the greenlip assigned to each age class (± SD) was as follows:

0+ age (12-20 mm): 17 ± 2 mm

1+ age (20-35 mm): 27 ± 4 mm

2+ age (35-54 mm): 45 ± 5 mm

Star pickets and concrete blocks marked experimental release sites. The concrete blocks had treatment codes marked in florescent letters on the side of the block to ensure experimental releases were not mixed up. Abalone were released *in situ*; mechanical release involved removing one of the mesh ends on the release container and placing it deep into cracks and gullies on the reef to enable shelter and minimization of predators (Figure 1). Rocks were often placed on top of containers to prevent movement. Hand release involved individual selection and placement of juveniles.

All divers successfully completed their 4 sites, except for one, who had difficulty finding the concrete blocks for one of his sites, and may have released them slightly away from the preferred release site. The work took the best part of a day with boats leaving the boat ramp at 10:30 – 11:00 am and the last boat returning at 17:30 hours.

Animals were released in February 2004 and monitored for survival and growth in November / December 2004 (9 – 10 months post-release).

Figure 1. Newly opened mechanical release container with juvenile *Haliotis laevigata* (~ 30 mm shell length). The animal to the left is moving away from the release device into a suitable crevice.

2.2.5 Analysis of data

Variation in survival and growth of 1+ and 2+ age classes were analysed. Few 0+ animals were located after 9 months and it is unknown whether this was due to their cryptic behaviour, or very high mortality. Hence they were excluded from the analysis. A few tagged specimens of the 0+ release were located at 9 months post-release, but not enough to include in the statistical analysis.

2.2.5.1 Growth analysis

Growth increments were obtained from shell lengths of tagged individuals at 9 months post-release. Many tagged animals had lost their tags, however were easily identifiable as seeded animals due to their shell colouration. An example of an animal found at 18 months post-release, after the experiment was completed, still shows the hatchery shell colouration (Figure 2). Consequently, their growth could only be determined in relation to the average length of the experimental treatment at initial tagging. Thus, growth analysis was based on the mean growth increment per experimental treatment, with 2+ animals subject to a 10 months growth period (they were measured ~ 1 mo before the 1+ animals), and 1+ animals subject to a 9 mo growth period.

2.2.5.2 Survival analysis

Survival in seeded abalone is notoriously difficult to estimate due to size-dependent differences in sightability (Shepherd, 1990), and tag loss due to migration out of the study site (Dixon et al., 2006).

To standardise for differences in numbers released, survival was evaluated as percent survival. Initially, ANOVA's were used to assess the effects of age, density, and release mechanism on growth and survival. However preliminary data exploration showed these to be non-significant in comparison with habitat quality (see section 2.3). Survey sites were allocated a habitat quality of low, medium, high, based on the area of habitat estimated using the habitat survey method (Section 2.3). All residuals were examined and subject to Cochran's test for homogeneity of variances. Appropriate data transformation (log x+1) to reduce skewness in the distribution was enacted where necessary.

Following statistical analysis, a correction factor was applied to numbers found to generate more realistic mean survival estimates. Dixon et al. (2006) estimated maximum searching efficiency to be 75% for their reseeded *Haliotis laevigata*, which is equivalent to a correction factor of 1.33. Shepherd (1990) estimated mean sighting probability between 0.3 and 0.4 (30 to 40%) of tagged *H. laevigata* in the 2+ age class. This is expected to be even lower for 1+ age class. Based on these estimates, a correction factor of 1.2 was applied to survival counts of 2+ animals, and a factor of 1.5 was applied to survival counts of 1+ animals. These are considered conservative and will result in a minimal mean survival estimates to be incorporated into the bio-economic analyses.

Figure 2. Hatchery-bred *Haliotis laevigata* in the wild stock habitat. The red circle shows the outline of original size at release, apparent by its coloration.

2.3 Density and habitat monitoring surveys

Baseline surveys were carried out on all reefs in December 2003, two months prior to release of juveniles. To ensure concordance between baseline surveys and experimental release sites, an industry diver selected the suitable juvenile habitat and placed concrete besser blocks marked clearly with the experimental treatments, prior to the surveys. Four replicate $30m^2$ transects were undertaken at each reef within the vicinity of release sites, with all abalone counted and measured. These were re-surveyed 12 months later in December 2004, and estimates of abalone habitat area (in m^2) were also made. Estimates of habitat area were obtained by dividing the $30m^2$ transect into $1m^2$ quadrats and categorising the amount of habitat within each m^2 according to Table 4. For comparative purposes, pre-release densities at experimental sites were also compared with data from commercially fished reefs (19 sites) within the Augusta area.

Suitable abalone habitat was defined as granite or limestone surfaces of sufficient quality and area to allow effective attachment for a minimum of 1 abalone. The definition applied only to the late-juvenile and adult cohorts (i.e. animals 1+ years of age). Younger juveniles are cryptic, while the larvae settle preferentially on non-geniculate coralline algae, and require different habitat and sampling requirements (Daume et al., 1999; Shepherd and Daume, 1996). Importantly, the methodology allowed for a true account of the three-dimensional nature of the habitat.

Average area of suitable habitat for greenlip abalone varied between 0.004 to 0.135 m^2 per 1 m^2 of area surveyed (Table 3). To facilitate analysis of the effect of habitat, study sites were allocated a habitat quality code, with the 5 highest sites being High, the five in-betweens being Medium, and the five lowest Low (Table 3).

Table 3. Study sites and matrix of experimental treatments with habitat data. Habitat quality categories are based on habitat area. Boundaries of a site are notionally contained within the area surveyed by the 4 x 30m^2 transects.

Site Code	Habitat Area (per m2)	Habitat Quality	Experimental Treatments		
			T1	T2	T3
1	0.082	M	2HH3	1HH1	2LM3
2	0.098	H	CONTROL	CONTROL	CONTROL
3	0.020	L	1LM2	1HM1	1LH3
4	0.037	L	1HH2	2HM3	OHM1
5	0.048	M	OLH1	1HM2	2LH1
6	0.073	M	CONTROL	CONTROL	CONTROL
7	0.135	H	2LM1	OHM3	1LM1
8	0.050	M	CONTROL	CONTROL	CONTROL
9	0.120	H	1LH1	2LH2	1HH3
10	0.085	H	OHH2	1LH2	OHH1
11	0.085	H	1LM3	OLM2	2HM1
12	0.068	M	2LH3	OHM2	OLH2
13	0.004	L	OLM1	OHH3	OLH3
14	0.025	L	2HH2	2LM2	2HM2
15	0.036	L	OLM3	1HM3	2HH1

Table 4. Habitat survey criteria for *Haliotis laevigata*. Codes are applied to each 1m^2 quadrat within the larger sample unit (a 30m^2 transect is used here) and they estimate the areal extent of suitable greenlip habitat. The midpoint is the value used to estimate habitat area (m^2).

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

2.3.1 Analysis of data

The effect of seeding was evaluated by examining the abundance of animals ≤ 95 mm shell length before and after seeding. The rationale behind this was that the largest animal recaptured at 9 months post-release was 90 mm shell length, and it had grown 45 mm in the 10 months since it had been tagged. This equates to an exceptionally fast annual growth rate (54 mm $year^{-1}$), and since the largest animal released (54 mm) only grew to 72 mm, a 95 mm upper maximum was considered appropriate for detecting an enhancement effect. Furthermore, since the control reefs could not be closed to fishing, any evaluation of density of legal-sized animals (≥ 140 mm) would be confounded by a fishing effect.

Initially, ANOVA's were used to assess the effect of time (before and after seeding), and seeding treatment (control sites, seeding sites) on mean density. However, the results detected an increased abundance at both seeded and control sites, and examination of spatial separation of sites found that control sites were confounded with seeded sites because the separation distances were too small (25 – 34 m). Hence, control sites were eliminated from the analysis, and it is acknowledged that no information on natural recruitment was available for comparison. This limitation is being addressed in a larger scale experiment.

All residuals were examined and subject to Cochran's test for homogeneity of variances.

2.4 Bio-economic scenarios

The gross income (total income – cost of production) of a harvest arising from the seeding of 100,000 to 1×10^6 *Haliotis laevigata* was investigated with data from three sources:

1) survival and growth estimates from this experiment;
2) costs of hatchery production from the Great Southern Marine Hatcheries in Albany (Sabine Daume, unpublished data);
3) current beach price value of H. laevigata ($126 per kg of meat weight).

2.5 Optimal enhancement scenarios

The effectiveness of stock enhancement of *Haliotis laevigata* in Western Australia will depend on the extent of available habitat, the requirement to maintain existing genetic diversity of stocks, and localised stock-recruitment relationships. Scenarios examined pertain only to progeny of wild caught broodstock, and were based on the premise of maintaining or enhancing existing genetic diversity of wild stocks, which is determined by the genetic diversity within the breeding population. Thus, recruitment to the breeding stock was the key parameter examined.

The **broodstock target enhancement rate** (BE_i) was set at 35% of average natural recruitment. Natural recruitment was estimated at 22% of total breeding stock, which is derived from a natural mortality rate (M) of 0.25 for *Haliotis laevigata* (Shepherd, 1990). Under equilibrium or unfished conditions, mortality rate (M) equals recruitment rate. From this, the optimal enhancement rate (35% of natural recruitment) was determined to be 0.07 or 7% of total breeding stock size. Therefore, to calculate the target enhancement rate, an estimate of total breeding stock size is required.

There are two aspects to estimating enhancement:

1) Estimating recruitment from seeded animals to the breeding population;
2) Estimating numbers to be released, which are based on survivorship from seeding to maturity.

2.5.1 Estimating recruitment from seeded animals to the breeding stock.

The broodstock target enhancement (BE_i) within genetic zone *i* in Western Australia is:

$BE_i = 0.07N_i$

where N_i is the breeding stock size (in numbers) in genetic zone *i*, and 0.07 is the desired rate of maximum enhancement to minimize deleterious genetic effects (see section 2.5). The breeding stock consists of greenlip abalone larger than the size at maturity. This varies from 90 - 110 mm shell length within Western Australian stocks of *H. laevigata* (Wells and Mulvay, 1995; Hart, unpublished data).

Total breeding stock size (numbers) in genetic zone *i* (N_i) can be expressed in the following terms.

$$N_i = \frac{N_E}{P_E}$$

where N_E is the size of the exploited portion of the breeding population, and P_E is the proportion of breeding stock that is exploited. This analysis assumes there is no size-dependent differences in egg production, i.e. that larger mature animals do not produce more eggs on average, than smaller animals. Evidence supporting this assumption has been found in wild and cultured stocks of *Haliotis laevigata* (Babcock and Keesing, 1999; Daume, unpublished data), and *Haliotis rubra* (Litaay and De Silva, 2001). However it is not generally recognised to be true, and is introduced here as a means for simplifying the estimation of recruitment.

The 5–year average (2001 – 2005) commercial catch (in numbers) of greenlip abalone within genetic zone *i* (C_i) was used to calculate the size of the exploited stock (N_E) by assuming that average fishing mortality (F) is 0.3 (or 26% of available stock per year). An additional 10% was added to C_i to account for recreational and illegal catch.

$$N_E = \frac{1}{0.26} C_i \times 1.1$$

P_E was calculated by comparing size-frequency data from commercial catch with that from the total breeding stock, which was obtained from fishery independent stock surveys (Hart, unpublished data).

Estimates of various parameters of enhancement within each genetic zone are supplied in Table 5.

Table 5. Estimates of broodstock enhancement target (BE_i) and total breeding stock size (N_i) in genetic zones of the Western Australian *Haliotis laevigata* fishery. These estimates are based on the size (in numbers) of the exploited population (N_E), on proportion of breeding stock that is exploited (P_E), and the 5-year average (2001 – 2005) commercial catch of greenlip abalone (C_i = Numbers =; B_i = kg), within each zone.

Genetic Zone	BE_i	N_i	N_E	P_E	C_i	B_i (kg)
Cape Bouvard to Windy Harbour	53,000	762,000	305,000	0.40	72,000	17,600
Windy Harbour to Hopetoun	19,000	274,000	82,000	0.30	19,000	6,000
Hopetoun to Pt Culver	173,000	2,468,000	740,000	0.30	175,000	33,400
Pt Culver to South Australia1			N/A	N/A	N/A	N/A
TOTALS	245,000					

1 Primarily a slow growing/stunted area. Enhancement likely to be not viable in this area due to low natural productivity and inaccessibility of stocks

2.5.2 Estimating numbers to be released

Maximum numbers to be released (NR_i) in genetic zone i are estimated as follows:

$$NR_i = \frac{BE_i}{S_r}$$

where BE_i is the maximum enhancement into the breeding stock in genetic zone i, and S_r is the proportion of animals released surviving to maturity. S_r was estimated from the results of the pilot experiment on high and medium quality habitat reefs only, and assumes that wild-stock mortality rates apply to seeded animals after the first year of release (Section 3.4.2).

For 1+ animals, S_r is 0.075, for 2+ animals S_r is 0.15. Note that 2+ animals enter the breeding stock within 1 year of release, however 1+ animals take 2 years to reach the breeding stock, and are therefore subject to an extra year of natural mortality before they contribute to the breeding population.

3 Results

3.1 Survival

Overall survival for all released animals was 19% for 1+ abalone and 27% for 2+ animals after 9 months of release.

3.1.1 Effects of age, density and release mechanism on survival

There was no significant effect of age, density, or release mechanism on survival when habitat was not taken into account (Table 6). Following this, the effect of habitat area was investigated.

Table 6. ANOVA results for the effect of age (1+, 2+), density (high, low), and release mechanism (hand, mechanical) on survival of released greenlip abalone (*Haliotis laevigata*) in Flinders Bay, Augusta, Western Australia.

Variable	Survival at 9 months post - release			
	d.f	MS	F	*p*
Age	1	0.065	2.26	0.16
Density	1	0.070	2.41	0.15
Release Mechanism	1	0.009	0.32	0.58
Age × Density	1	0.001	0.03	0.86
Age × Release	1	0.002	0.07	0.80
Density × Release	1	0.019	0.64	0.44
Age × Density × Release	1	0.0001	0.005	0.95
Residual	12	0.2		

3.1.2 Effects of habitat area and age on survival

Once habitat had been included, the analysis detected a significant effect of age and habitat on survival of greenlip abalone (Table 7). This indicates that survival is critically dependent on habitat, regardless of age. *Post-hoc* tests indicate that standardised mean survival of 2+ abalone (28%) was significantly higher than that of 1+ abalone (15%), and that mean survival in High habitat reefs (35%) was significantly higher than that from low habitat reefs (10%). Overall mean survival by age and habitat is shown in Figure 3. Highest survival (35%) was achieved in high habitat area reefs (Figure 3).

Table 7. ANOVA results for the effect of age (1+, 2+), and habitat area (high, intermediate, low) on survival of released greenlip abalone (*Haliotis laevigata*) in Flinders Bay, Augusta, Western Australia.

Variable	Survival at 9 months post-release			
	d.f	MS	F	p
Age	1	0.118	7.36	0.017
Habitat Area	2	0.086	5.38	0.018
Age × Habitat	2	0.018	1.16	0.343
Residual	14	0.016		

3.2 Growth

Overall average growth was 36 mm year^{-1} for 1+ age abalone, and 41 mm year^{-1} for 2 + abalone after 9 months grow-out.

3.2.1 Effects of age, density and release mechanism on growth

There was no significant effect of age, density, or release mechanism on growth (Table 8). Following this, the effect of habitat area was investigated.

Table 8. ANOVA results for the effect of age (1+, 2+), density (high, low), and release mechanism (hand, mechanical) on growth of released greenlip abalone (*Haliotis laevigata*) in Flinders Bay, Augusta, Western Australia.

	Growth at 9 months post-release			
	d.f.	**MS**	**F**	**p**
Age	1	1.09	0.02	0.88
Density	1	197	4.18	0.06
Release Mechanism	1	107	2.26	0.16
Age × Density	1	79.9	1.69	0.22
Age × Release	1	18.4	0.39	0.54
Density × Release	1	18.4	0.39	0.54
Age × Density × Release	1	3.89	0.08	0.78
Residual	12	47.2		

3.2.2 Effects of habitat area and age on growth

Once habitat had been accounted for, there was still no significant effect of age and habitat on growth of greenlip abalone (Table 9). This is in contrast to survival, where habitat had a significant effect.

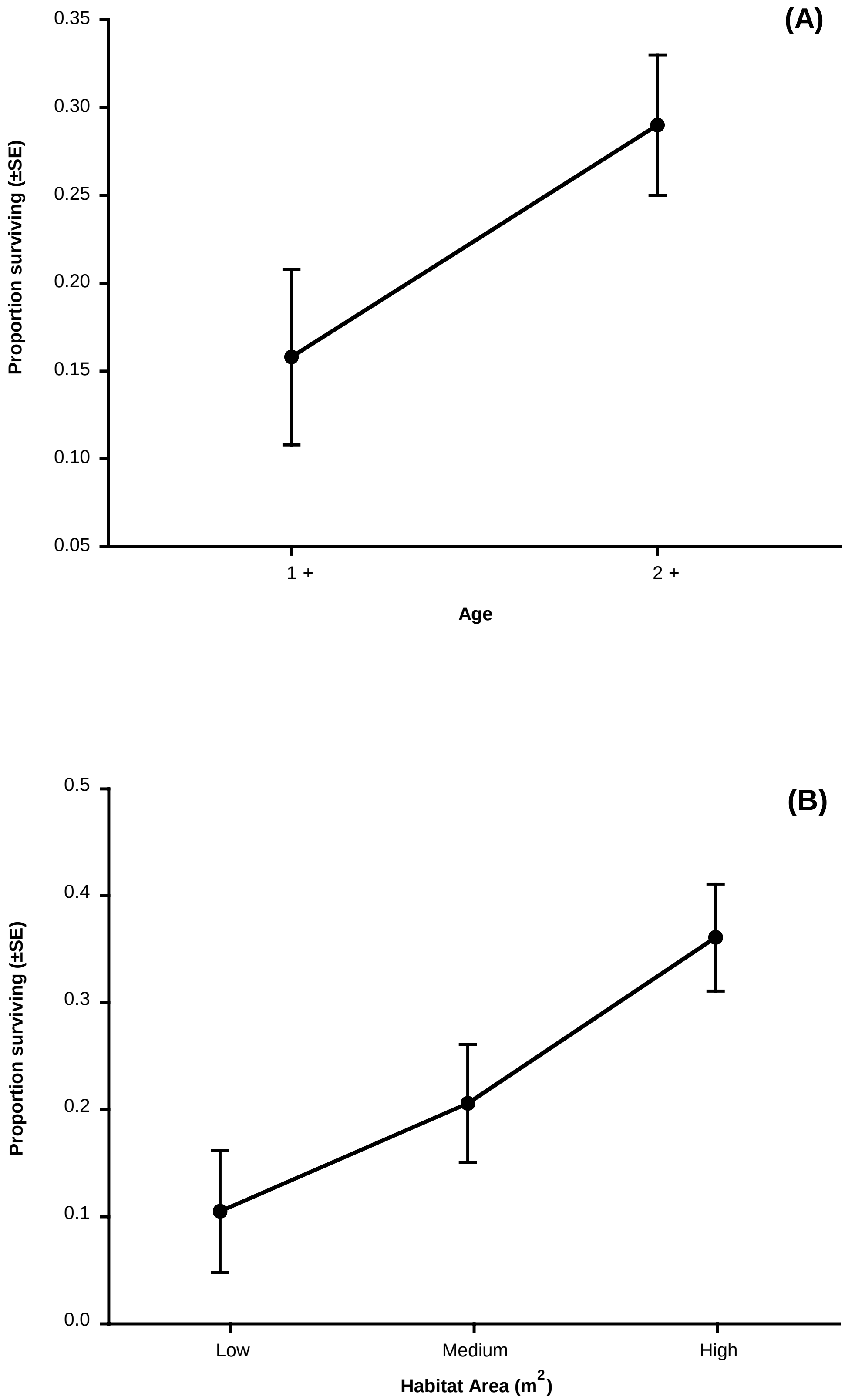


Figure 3. Mean survival (± SE) of seeded *Haliotis laevigata* at different age-at-release (A) and habitat quality (B) treatments. Refer to Table 3 for descriptions of habitat treatments.

Table 9. ANOVA results for the effect of age (1+, 2+), and habitat area (high, intermediate, low) on growth of released greenlip abalone (*Haliotis laevigata*) in Flinders Bay, Augusta.

Variable	Growth at 9 months post-release			
	d.f	MS	F	p
Age	1	17.8	0.37	0.55
Habitat Area	2	112	0.35	0.13
Age × Habitat	2	76.8	1.6	0.23
Residual	14			

3.3 Effect of seeding on population densities of *Haliotis laevigata*.

Baseline comparisons show that, prior to enhancement, densities were significantly lower at the experimental enhancement sites, compared to sites from commercially fished populations (d.f = 124, $t = 7.8$; $p < 0.001$; Figure 4). This indicated that scope existed to increase densities within the experimental sites.

There was a detectable effect of time on mean density of *Haliotis laevigata* (≤ 95 mm shell length) at 9 months post-release (Table 10), but no interaction between time and site. Mean densities of < 95 mm animals had increased five-fold in the 12 months between initial surveys, and the 9 month post-seeding survey (Figure 5). This uniformity of response suggests that enhancement had a real effect.

A comparison of size-frequency of animals on experimental reefs before and after seeding shows clearly the increase in numbers of animals less than 100 mm shell length (Figure 6). Such an increase is not easily explainable in terms of natural recruitment, as it occurs across 2 age classes. In particular, there was no evidence of 2+ abalone (ca. 40 – 70 mm) in the 'before' sample, but good abundance of 3+ abalone (ca. 70 – 100 mm) in the after sample (Figure 6).

Table 10. ANOVA results for the effect of time (Before enhancement, After enhancement [9 mo]), and Site (12 sites) on log (x+1) density of *Haliotis laevigata* (≤ 95 mm shell-length).

			≤ 95 mm	
	d.f	MS	F	p
Time	1	1.50	10.03	0.002
Site	11	0.19	1.28	0.25
Time × Site	11	0.20	1.36	0.21
Residual	72	0.15		

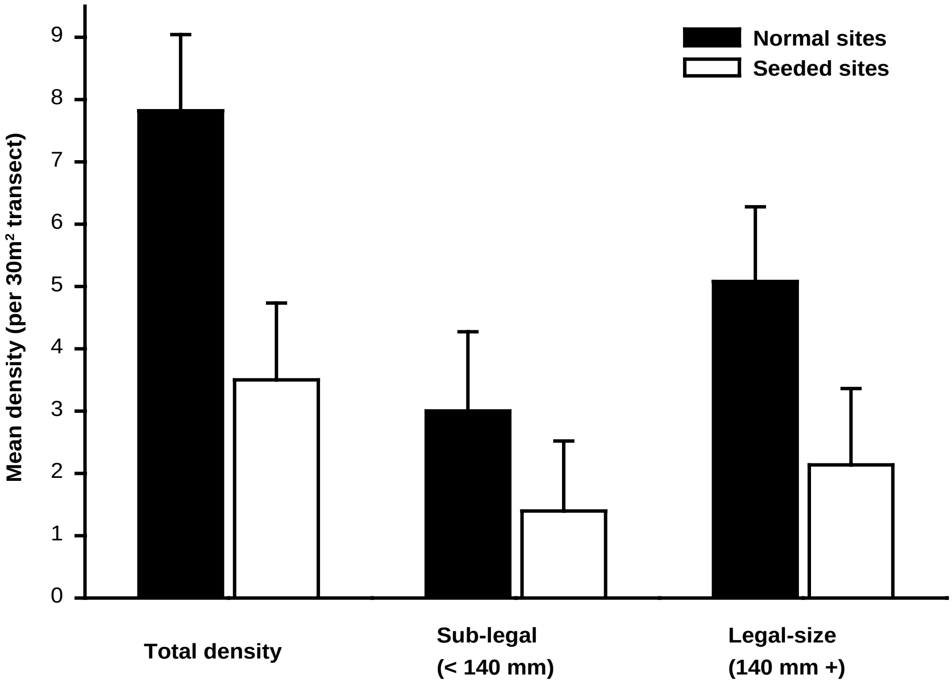


Figure 4. Mean density (± 2 SE) of *Haliotis laevigata* for at experimental sites prior to seeding. Data from commercially fished sites (Normal sites) is provided for comparison.

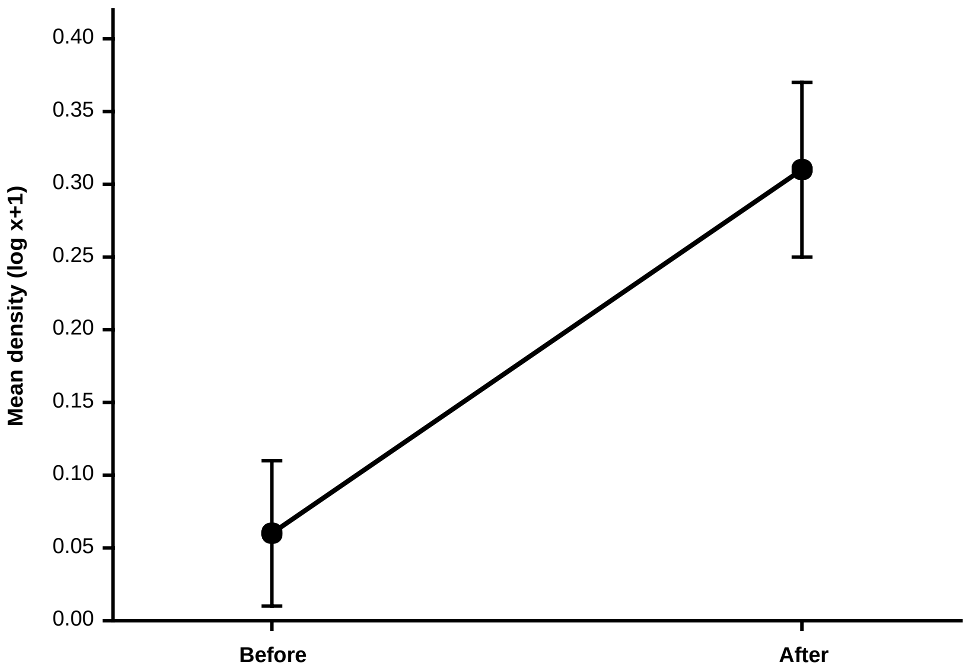


Figure 5. Mean $\log_e$ (x+1) density (± SE) of *Haliotis laevigata* (≤ 95 mm shell-length) before and after (9 months post-release) seeding juveniles at 12 experimental sites (●).

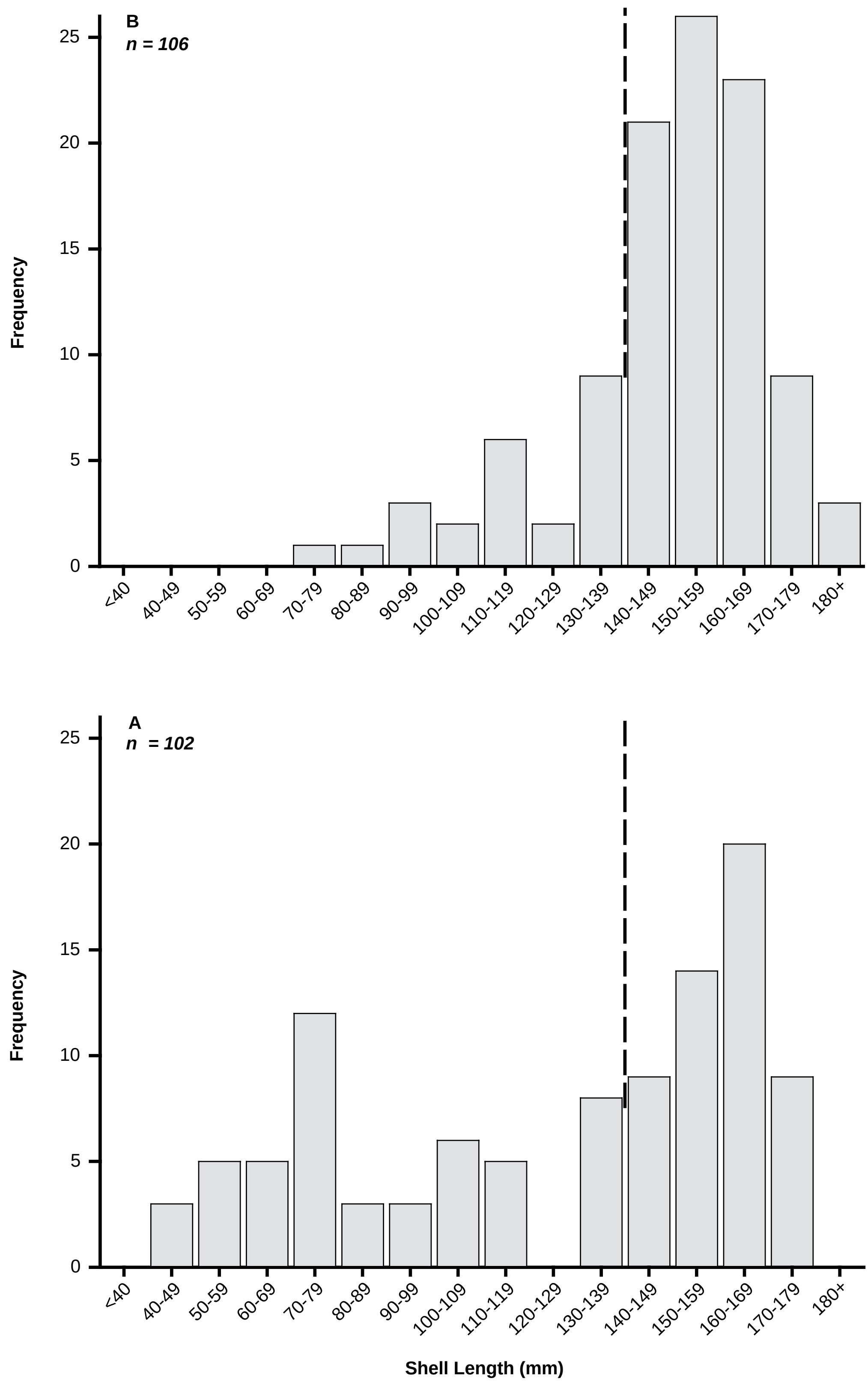


Figure 6. Size-frequency of *Haliotis laevigata* at 12 experimental sites before (B) and after (A) seeding. The dotted line represents the legal minimum length (140 mm).

3.4 Preliminary bio-economic analysis of enhancement

Biological factors identified as important were age of release, habitat area, and natural growth characteristics. These were the main influences on survival, and growth. The economics of stock enhancement were examined for each of those factors. All figures presented on gross income are based on a meat-weight harvest price of $126 per kg (Hart and Fabris, 2005).

3.4.1 Costs of stock enhancement

Total cost of stock enhancement (production + release) was higher for 2+ animals compared to 1+ animals, but reduced with increasing numbers released (Table 11; Figure 7). Maximum efficiency was gained with a release of 500,000 animals, which cost $0.45 per 1+ animals, and $1.08 for 2+ animals.

Table 11. Unit cost (per animal) of enhancement of *Haliotis laevigata* as a function of release age, and numbers released. All costs are based on 5 years depreciation of infrastructure and capital costs (breeding facility), and a release target of 10,000 individuals per vessel per day (Dr Sabine Daume, unpublished data).

Costs	Number Released		
	100,000	500,000	1,000,000
Production cost per animal (1+ age)	1.24	0.39	0.39
Production cost per animal (2+ age)	2.33	1.02	1.00
Cost of release (per animal)	0.07	0.06	0.06
Total cost per animal (1+)	1.31	0.45	0.45
Total cost per animal (2+)	2.40	1.08	1.06

3.4.2 Survival schedule

The estimated survival schedule calculated for seeded animals from the two different age classes is given in Figure 8. Data for proportion surviving (**Ps**) in the 1st year of release were from the medium and high quality habitat reefs (**Ps**: 1+ = 0.16; 2+ = 0.32). Animals assumed to be subject to a natural mortality (M) of 0.25 (22% per year) following the initial year of release until they enter the fishery.

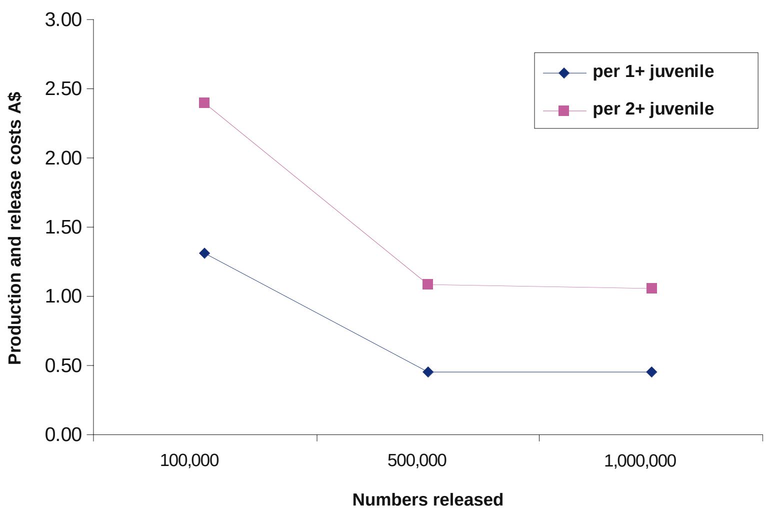


Figure 7. Trends in cost per animal for an enhancement program of *Haliotis laevigata* as a function of age at release (1+; 2+), and numbers released. All costs are based on 5 years depreciation of infrastructure and capital costs, and a release target of 10,000 individuals per vessel per day.

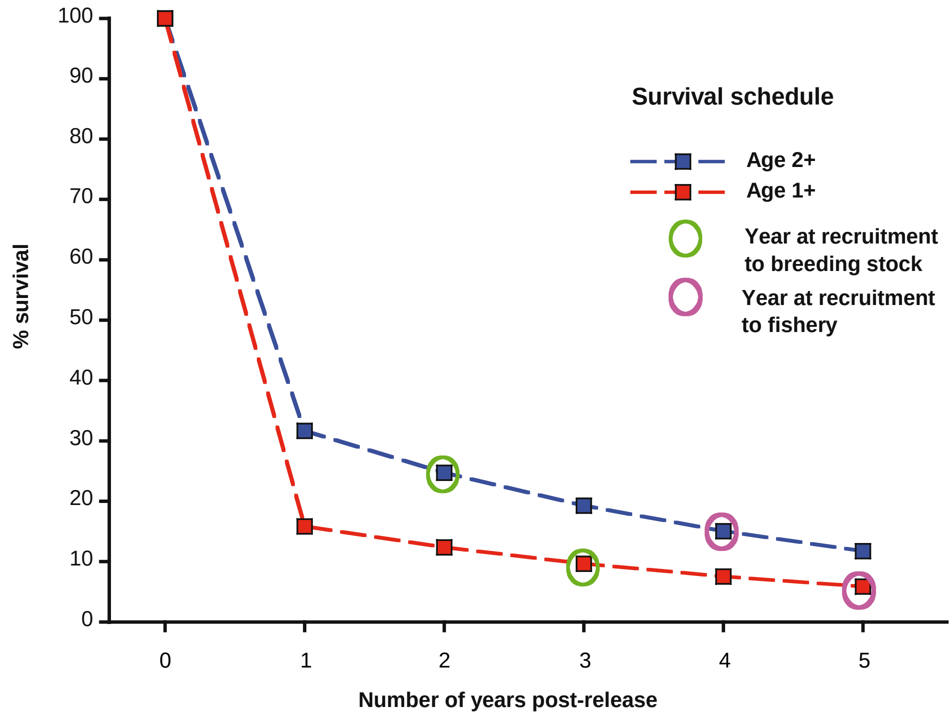


Figure 8. Survival schedule of *Haliotis laevigata* released at two different ages. Animals assumed to be subject to a natural mortality (M) of 0.25 (22% per year) following the initial year of release, and are harvested at 5 years post-release (1+ animals), and 4 years post-release (2+ animals).

3.5 Optimal enhancement scenarios

The enhancement scenarios make three key assumptions. First, that a breeding facility designed specifically for stock enhancement is operating. Such a facility would apply genetic diversity and disease management protocols to ensure genetic integrity and health of wild stocks is maintained. Second, that an established distribution process is in place. This process is likely to include a detailed habitat map of abalone producing reefs and release sites, a purpose-built vessel, innovative laboratory technology for loading of abalone into release modules, and novel methods for distribution of abalone from the ocean surface to the habitat. Third, there are no density-dependent effects of seeding, as maximum target releases are well within natural variation of recruitment.

3.5.1 All genetic zones

Using the estimates of production costs (Table 11) and the breeding stock enhancement targets (Table 12), the annual cost of the enhancement program for greenlip abalone in all genetic zones in Western Australia was $1.1 million for 1+ animals, and $1.2 million for 2+ animals. Such a program would result in an annual release of 2.5 million 1+ animals, or 1 million 2+ animals (Table 12).

Assuming the enhanced stock are caught as part of the wild fishing catch, and can expect a return of $126 / kg meat weight, about 13 tonnes of extra production is required for a break-even point on enhancement costs of both 1+ and 2+ released animals (Figure 9).

Estimated survival of 1+ animals at the year they become vulnerable to the fishery (4 years post release) is 5.8% (Figure 9). Harvest of all of these animals would result in an increased catch of 36 t and a gross income of $3.2 million (Figure 9).

Estimated survival of 2+ animals at the year they become vulnerable to the fishery (3 years post release) is 15.2% (Figure 9). Harvest of all of these animals would result in a gross income of $3.0 million (Figure 9).

3.5.2 Selected genetic zones

3.5.2.1 Cape Bouvard to Windy Harbour (Augusta Region)

An annual enhancement program would cost $232,000 to release 554,000 × 1+ animals (Table 12). This would require about 3 tonne (meat weight) of extra production per annum for a break-even point on enhancement costs (Figure 10).

Estimated survival of 1+ animals at the year they become vulnerable to the fishery (4 years post-release) is 5.8% (Figure 10). Harvest of these animals would result in a gross income of $1.0 million (Figure 10).

Estimated survival of 2+ animals at the year they become vulnerable to the fishery (3 years post-release) is 15.2% (Figure 10). Harvest of these animals would result in a gross income of $0.8 million (Figure 10).

3.5.2.2 Windy Harbour to Hopetoun (Windy / Albany Region)

An annual enhancement program would cost $165,000 to release 199,000 × 1+ animals (Table 12). This would require about 1.8 tonne (meat weight) of extra production for a break-even point on enhancement costs (Figure 11).

Estimated survival of 1+ animals at the year they become vulnerable to the fishery (4 years post-release) is 5.8% (Figure 11). Harvest of these animals would result in a gross income of $0.18 million (Figure 11).

Estimated survival of 2+ animals at the year they become vulnerable to the fishery (3 years post-release) is 15.2% (Figure 11). Harvest of these animals would result in a gross income of $0.15 million (Figure 11).

3.5.2.3 Hopetoun to Pt Culver.

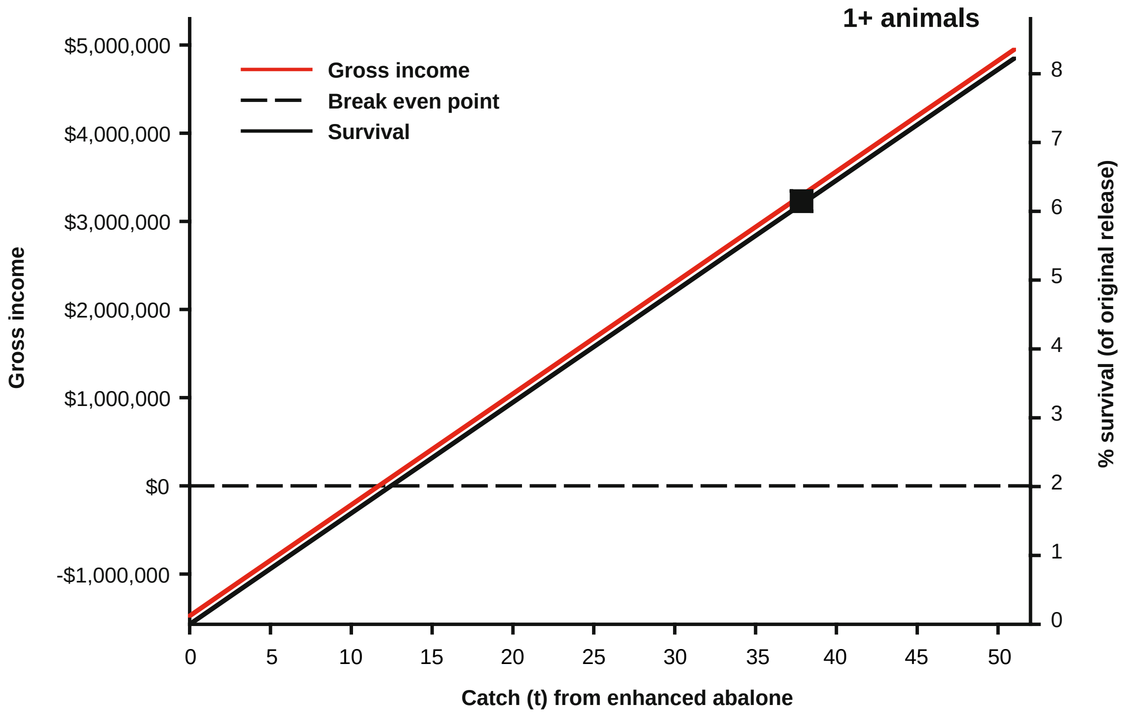
An annual enhancement program would cost $753,000 to release 1,793,000 × 1+ animals (Table 12). This would require about 8 tonnes (meat weight) of extra production for a break-even point on enhancement costs (Figure 12).

Estimated survival of 1+ animals at the year they become vulnerable to the fishery (4 years post-release) is 5.8% (Figure 12). Harvest of these animals would result in a gross income of $2 million (Figure 12).

Estimated survival of 2+ animals at the year they become vulnerable to the fishery (3 years post-release) is 15.2% (Figure 12). Harvest of these animals would result in a gross income of $2.2 million (Figure 12).

Table 12. Maximum breeding stock enhancement (BE_i), numbers to be released (NR_i1+ = 1+ age; NR_i2+ = 2+ age), and respective costs for an annual program within the three main genetic zones of the Western Australian *Haliotis laevigata* fishery. Target release numbers (NR_i) based on a survival estimate of 9.7% for 1+ animals and 24.7% for 2+ animals for the year of entry to breeding stock (Figure 8).

Genetic Zone	BE_i	NR_i(1+)	NR_i(2+)	1+ Cost	2+ Cost
Cape Bouvard to Windy Harbour	53,000	554,000	216,000	$232,000	$362,000
Windy Harbour to Hopetoun	19,000	199,000	78,000	$165,000	$181,000
Hopetoun to Pt Culver	173,000	1,793,000	699,000	$753,000	$699,000
TOTALS	245,000	2,536,000	993,000		
Annual enhancement costs ($AUD)				$1,151,000	$1,242,000



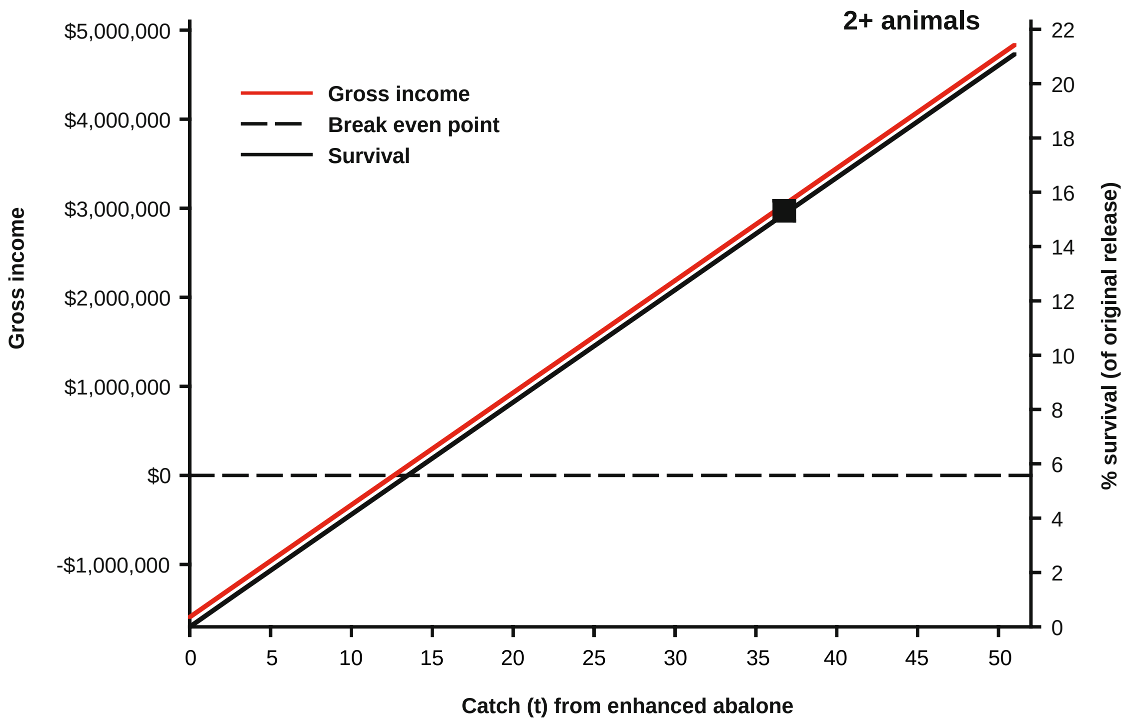
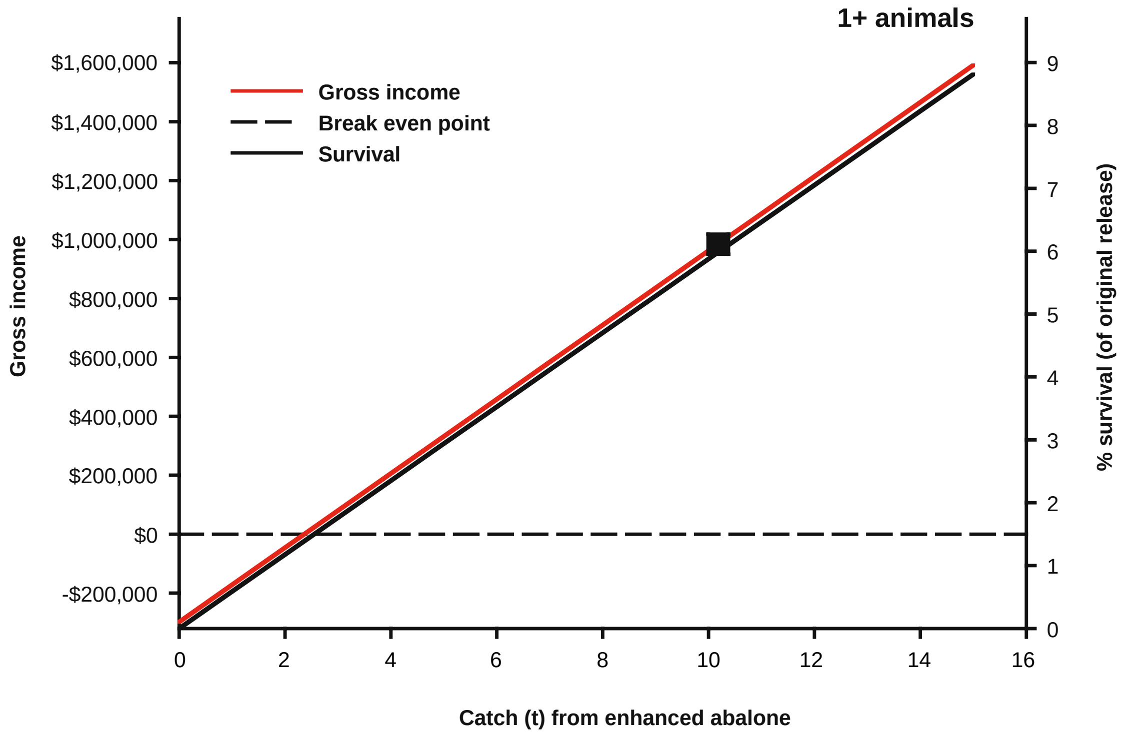


Figure 9. The gross income ($AUD) of an annual *statewide* enhancement programme for *Haliotis laevigata*, as a function of % survival (of the original number released – see Table 12) and commercial catch (in meat weight tonnes) derived from that programme. Current landed value of this species is $126 / kg meat weight. ■ = Expected survival/income at harvest, based on the Figure 8 survival schedule, and average meat weight of 190 grams.



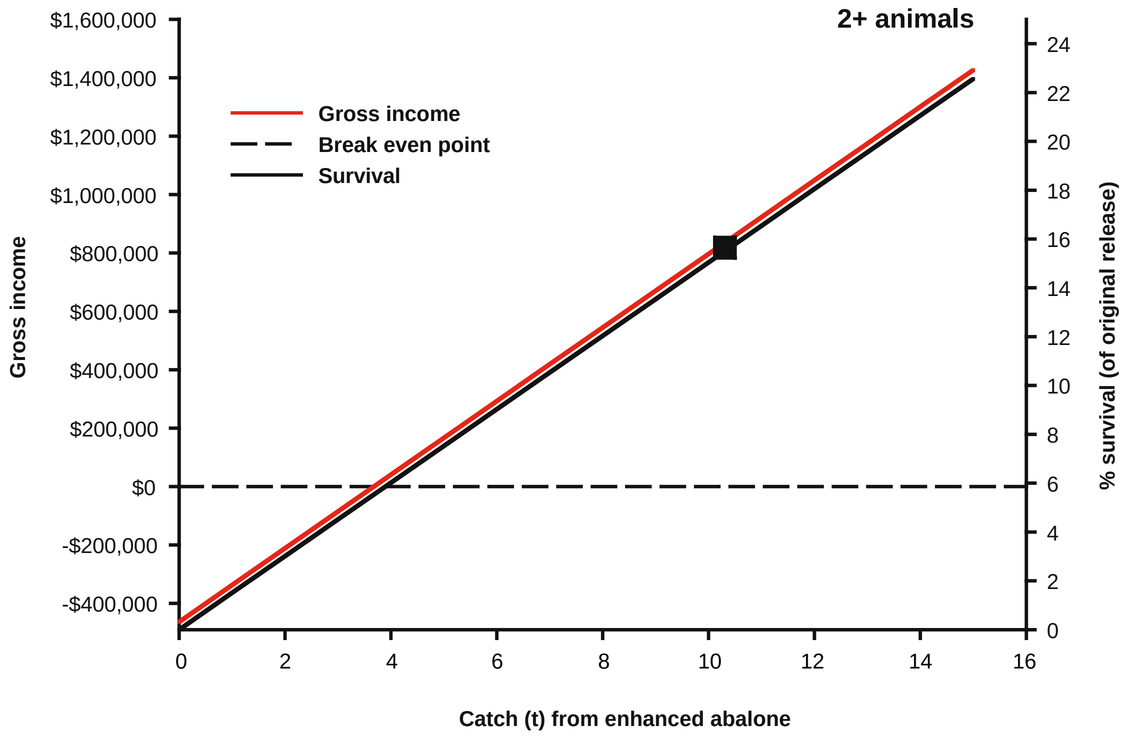
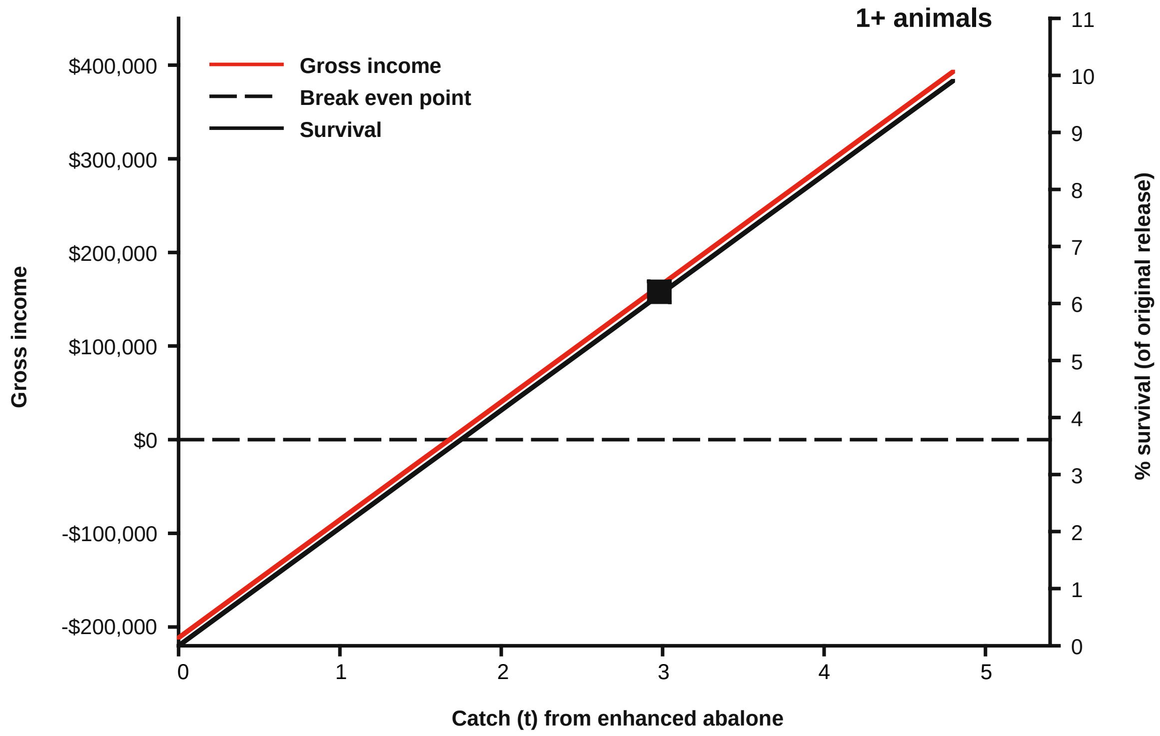


Figure 10. The gross income ($AUD) of an annual *Augusta* region enhancement programme for *Haliotis laevigata*, as a function of % survival (of the original number released – see Table 12) and commercial catch (in meat weight tonnes) derived from that programme. Current landed value of this species is $126 / kg meat weight. ■ = Expected survival/ income at harvest, based on the Figure 8 survival schedule, and average meat weight of 240 grams.



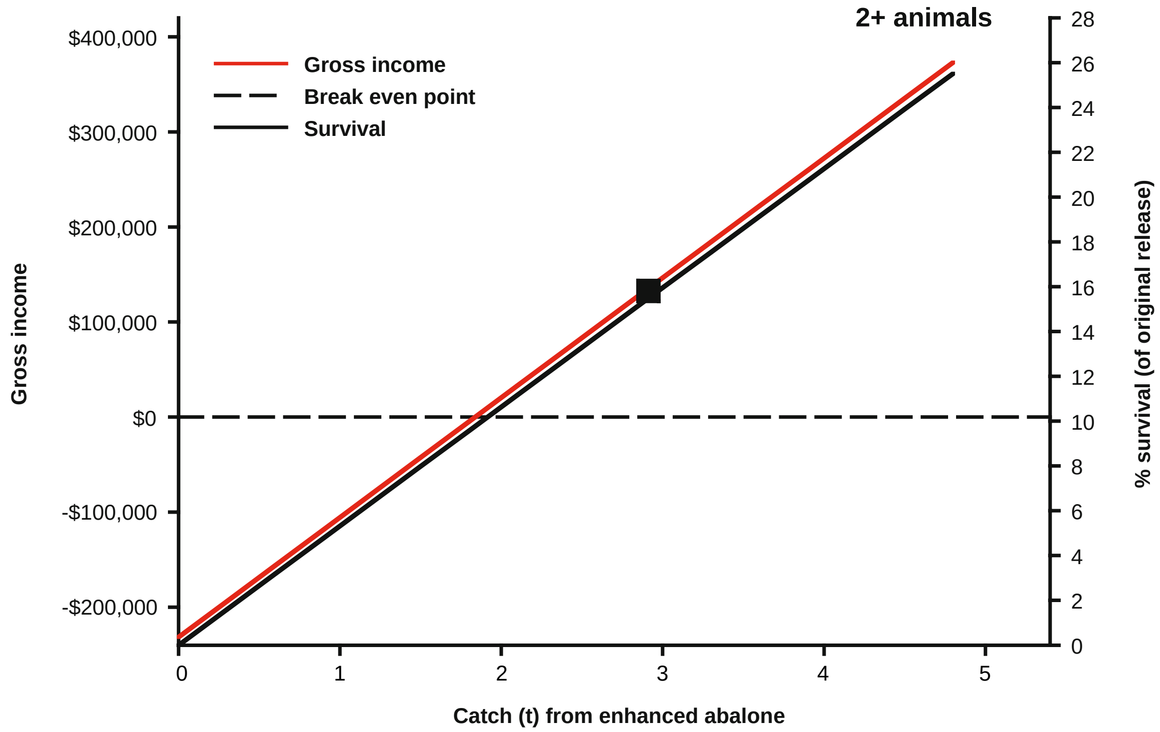


Figure 11. The gross income ($AUD) of a *Windy Harbour / Albany* region enhancement programme for *Haliotis laevigata*, as a function of % survival (of the original number released – see Table 12) and commercial catch (in meat weight tonnes) derived from that programme. Current landed value of this species is $126 / kg meat weight. ■ = Expected survival/ income at harvest, based on the Figure 8 survival schedule, and average meat weight of 190 grams.

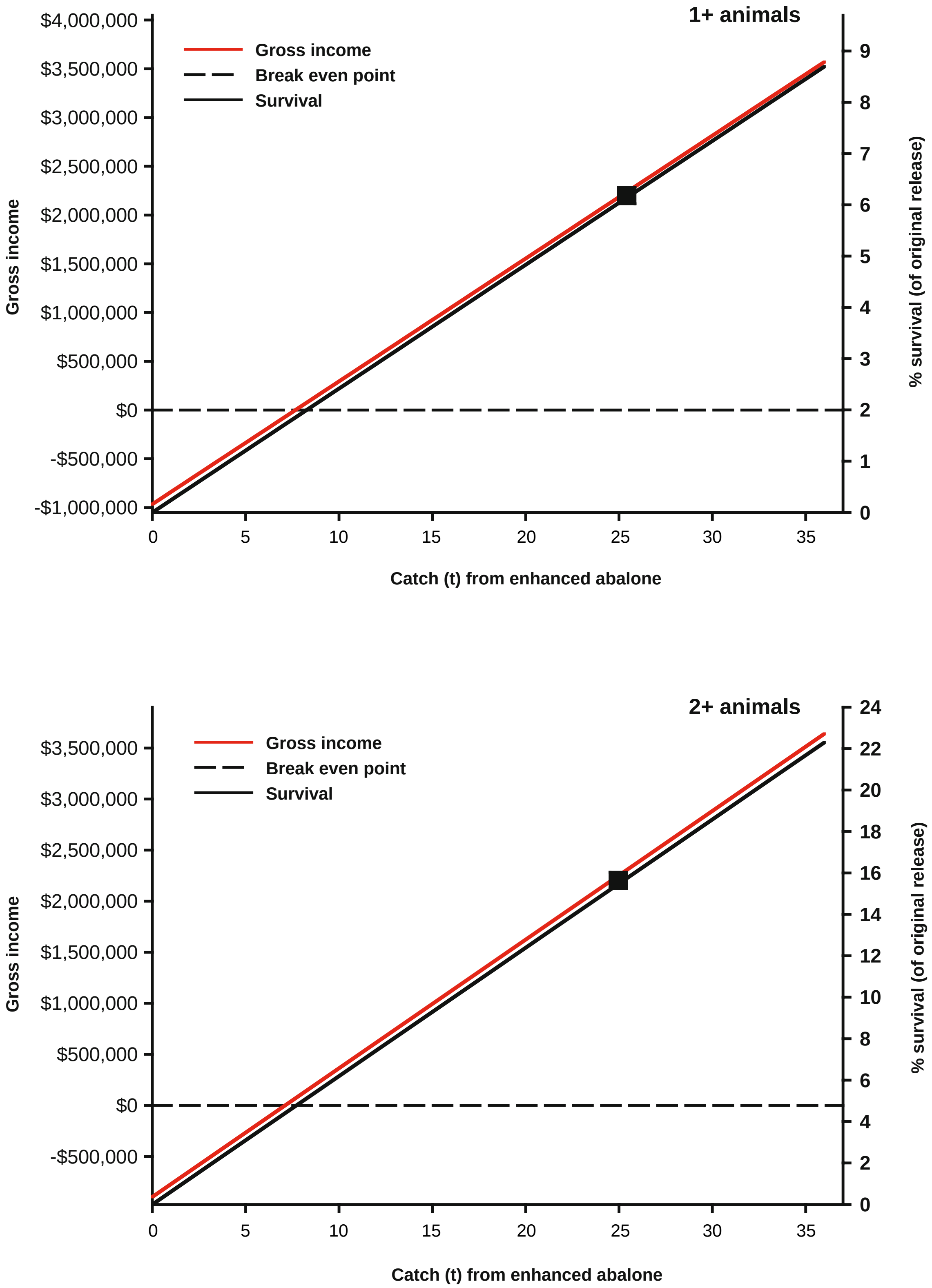


Figure 12. The gross income ($AUD) of a *Hopetoun to Pt Culver* enhancement programme for *Haliotis laevigata*, as a function of % survival (of the original number released – see Table 12) and commercial catch (in meat weight tonnes) derived from that programme. Current landed value of this species is $126 / kg meat weight. ■ = Expected survival/ income at harvest, based on the Figure 8 survival schedule, and average meat weight of 180 grams.

4 Proposal for a test case of commercial enhancement

4.1 Introduction

Based on the results of this study, a test case for commercial enhancement could be carried out at a site with the appropriate attributes. A good site is the Flinders Bay region of Augusta, however other sites with similar features could also be considered. Flinders Bay is the region where this pilot research has been carried out, and where there is a known history of commercial catch, as well as incidences of illegal fishing that have reduced some of the abalone producing reefs to low levels. It is also a contained embayment that is likely to be self-recruiting, and consequently, any effects of enhancement on current and future recruitment are likely to be contained within the system. This will make it easier to determine whether stock enhancement has worked.

Additionally, samples of genetic diversity of existing stocks in this area have already been taken (Elliot and Conod, 2001), and can thus provide a baseline against which future stock diversity can be compared.

4.2 Objective and Parameters

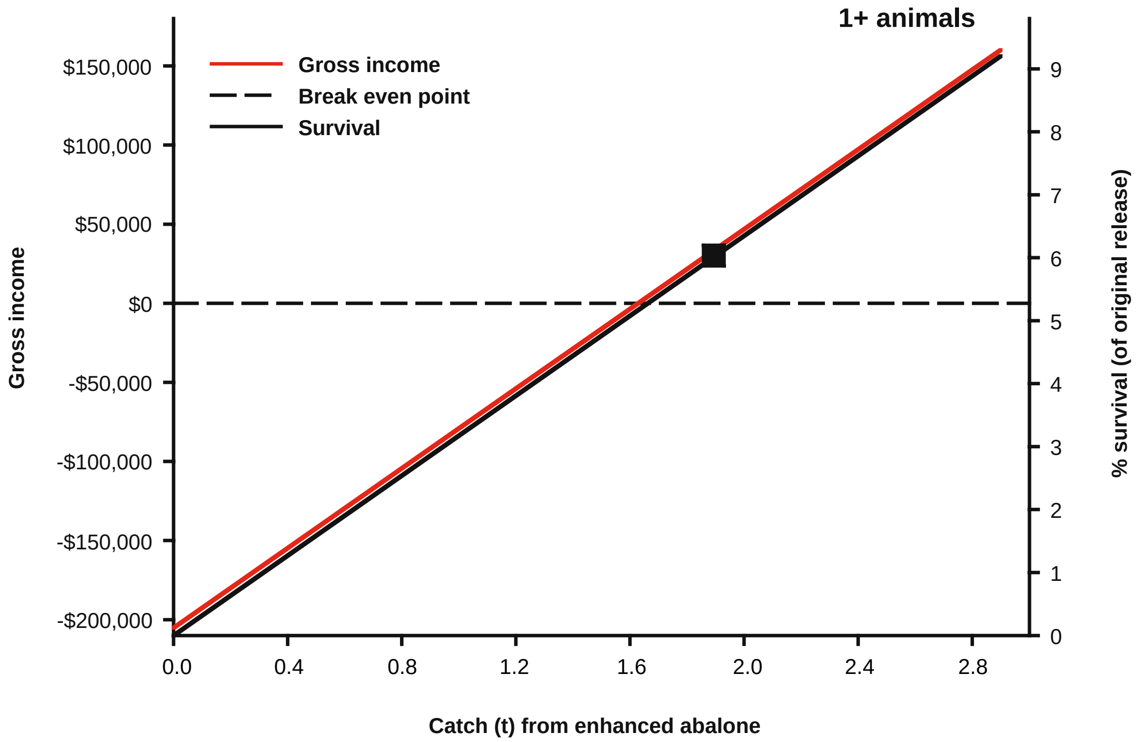
The overall objective of this test enhancement programme is to measure the potential of stock enhancement as a fisheries management tool. It is estimated this will require 7 years, beginning with spawning of selected wild broodstock, and ending with the completion of 5 successive released cohorts. Five successive years of annual releases is the time-span required so that the effects of enhancement can be gauged within the highly variable recruitment within abalone populations.

4.2.1 Enhancement program

Based on the methodology developed in this study, the maximum annual breeding stock enhancement target for Flinders Bay is 13,200 animals (Table 13). This corresponds to an annual release of 137,000 × 1+ animals, or 53,000 × 2+ animals (Table 13). This enhancement program would require about 1.2 – 1.6 tonnes (meat weight) of extra annual production for a break-even point on enhancement costs (Figure 13).

Table 13. Breeding stock enhancement target (BE_i), maximum numbers to be released (NR_i1+ = 1+ age; NR_i2+ = 2+ age), and respective costs for an annual enhancement program within Flinders Bay of the Western Australian *Haliotis laevigata* fishery. Due to the small numbers released, unit costs (per animal) have been extrapolated from Figure 7 to be \$3.00 per 2+ animal, and \$1.50 per 1+ animal.

Genetic Zone	BE_i	NR_i(1+)	NR_i(2+)	1+ Cost	2+ Cost
Flinders Bay	13,200	137,000	53,000	$205,000	$160,000
Annual enhancement costs ($AUD)				$205,000	$160,000



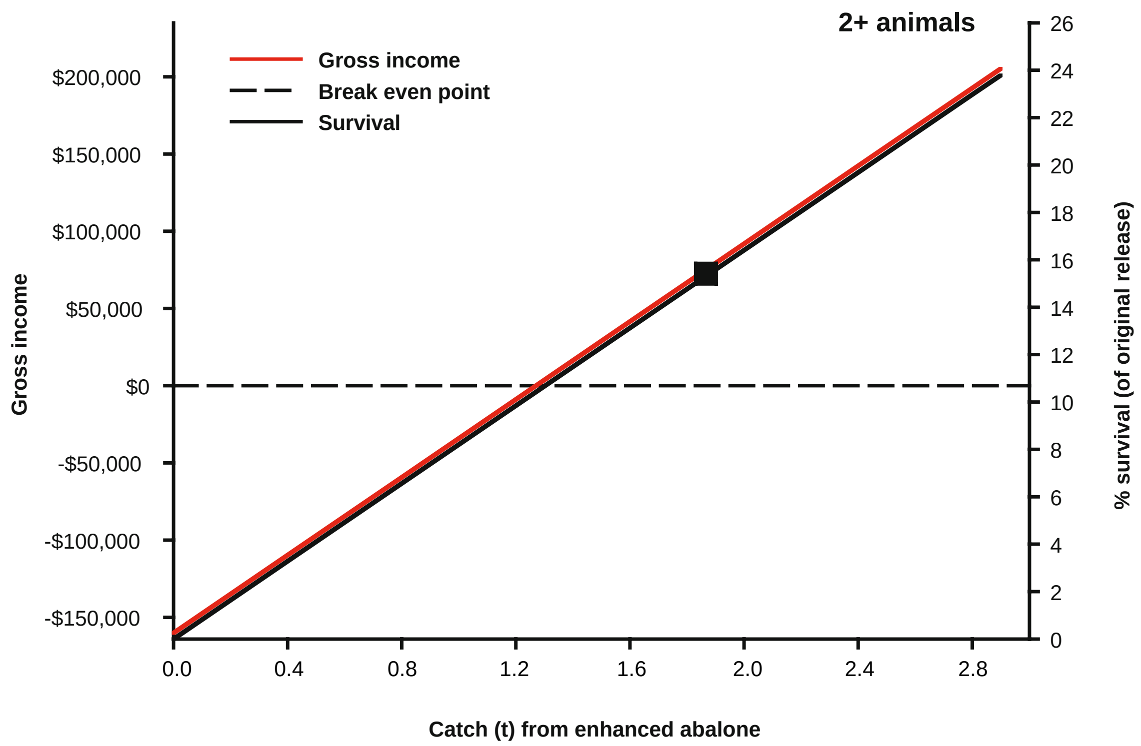


Figure 13. Gross income ($AUD) of the proposed *Flinders Bay* enhancement programme for Haliotis laevigata, as a function of % survival (of the original number released – see Table 13) and commercial catch (in meat weight tonnes) derived from that programme. Current landed value of this species is $126 / kg meat weight. ■ = Expected survival/ income at harvest, based on the Figure 8 survival schedule, and average meat weight of 230 grams.

Estimated survival of 1+ animals at the year they recruit to the fishery (5 years post-release) is 5.8% (Figure 13). Harvest of these animals would result in a gross income of $30,000 (Figure 13).

Estimated survival of 2+ animals at the year they become vulnerable to the fishery (4 years post-release) is 15.2% (Figure 13). Harvest of these animals would result in a gross income of $80,000 (Figure 13).

The economics of the test enhancement program in Flinders Bay show that a break-even point in investment is the most likely scenario, given the small-scale nature of the study.

4.2.2 Sampling program

Stock densities, environmental variables, and genetic diversity would be monitored annually at 40 survey sites within Flinders Bay. These survey sites have already been created, and provide 2 – 4 years of baseline information against which future changes can be compared. The overall effect of enhancement shall be examined within a BACI (Before After Control Impact) sampling program.

4.2.3 Targets

The biological targets for the enhancement program are:

1. an increase in stock densities of 20 – 40% for the age classes enhanced
2. an increase of 1.5 – 2 tonnes in the 5 year average catch and / or a 20 – 40% increase in commercial fishery catch rates. The current seven year (2000-2006) average catch from this area is 4.0 tonnes (meat weight).
3. no statistical change in existing genetic diversity within Flinders Bay *Haliotis laevigata* stocks
4. no statistical changes in the predicted response of relevant environmental parameters. These are the percentage cover of algal classes (green- Chlorophyta, red- Rhodophyta, brown- Phaeophyta) and the density of co-occurring key invertebrate species (the red sea urchin - *Heliocidaris erythrogamma*, the abalone *Haliotis scalaris* and the marine snail *Scutus antipodes*).

The success of the enhancement program can be gauged against these proposed targets.

5 Discussion

5.1 Survival and growth

Survival differed significantly between age-classes, but only after the quality of habitat had been taken into account. Otherwise no significant differences could be found between age, density at release, or release mechanism. This clearly shows that targeted habitat releases are essential to understanding and maximising the success of greenlip abalone reseeding. Growth however, was unaffected by habitat or age in this experiment, although there are differences within wild stocks that affect the economics of enhancement. For example, there is a higher average size of animal in the Augusta genetic zone (Cape Bouvard to Windy Harbour) compared to the Hopetoun to Pt Culver zone, and production per seeding animals is higher.

5.2 Effect on natural population densities

Overall densities at seeded sites were significantly lower than non-seeded sites subject to commercial fishing. However, mean densities 95 mm had increased five-fold in the 12 months between initial surveys, and the 9 month post-seeding survey, suggesting that enhancement had a positive effect on natural stock densities.

5.3 Preliminary bio-economic analysis

From the scenarios investigated, there were two main results.

1. Costs of an enhancement program using 1+ or 2+ animals are similar.
2. Survival was different, however gross income were similar, between 2+ and 1+ released animals.

5.4 Broodstock enhancement scenarios

The broodstock enhancement scenarios showed that 1 million 2+ releases are needed to achieve maximum allowable enhancement to the broodstock at a statewide scale, however 2.5 million × 1+ animals are required for the same production or income. Both these release amounts will ensure existing genetic diversity is maintained.

From a cost-benefit analysis, 2+ and 1+ releases were similar in economic performance. The choice is a larger breeding program and a smaller enhancement program, in which case, 2+ releases are preferred. Alternatively, a smaller breeding program, and a larger release program, in which case, 1+ releases will be suitable. The choice of these will depend on the overall extent of the stock enhancement programme.

5.5 Proposal test case for commercial enhancement

The proposal test case for Flinders Bay indicated that the biological and environmental targets for enhancement could be satisfactorily completed. Only 137,000 1+, or 53,000 2+ released animals would be required on an annual basis for the broodstock enhancement targets to be met. Existing monitoring data on stock densities, environmental parameters, and genetic diversity will enable the implementation of a responsible approach to stock enhancement in the test case.

5.6 Breeding programs to support stock enhancement in *Haliotis laevigata*

Stock enhancement as a wild fisheries management tool requires a breeding program that supports the long-term maintenance of a wild stock in its natural state. In this sense, it is a fundamentally different activity from aquaculture for commercial purposes, which is designed to artificially enhance specific aspects of the target animal that maximise consumer and producer benefits, i.e., to remove the wild stock from its natural state. Practically, a breeding program for stock enhancement will require strategies that meet the twin objectives of maintenance of genetic diversity, and minimisation of disease and environmental impact. These include, but are not restricted to the following:

- Identification of wild stock units
- Rotational selection of broodstock (e.g. broodstock replenished annually using a schedule that ensures genetic diversity is maintained)
- Comprehensive disease management
- Explicit spatial and temporal enhancement targets

The ultimate program is likely to involve Government (Department of Fisheries) expertise for the broodstock management, spawning, and disease-testing activities to ensure the broader ecosystem is not adversely affected. However, the grow-out and enhancement phases could be undertaken by commercial ventures.

5.7 General points and cautionary notes

- The study was a preliminary analysis and conclusions need to be verified with a stronger experimental design before large-scale enhancement could be justified or implemented on an economic basis, assuming all other criteria are met (e.g. genetic management, disease-testing).
- A new and important result was that rearing animals for an extra year in the hatchery (i.e 2+ releases) had a similar economic performance to earlier releases, under the targeted enhancement scenarios. This is because the 2+ animals have twice the initial survival rate, require half the numbers to be released, and grow into the breeding stock within 2 years compared to 3 years for 1+ animals. Generally, large-scale releases at a young age (e.g. 0+, 1+) have been recommended (see Heasman, 2006).
- The importance of habitat to survival must be considered at the micro-scale at which it varies.
- This assessment assumed that releases could take place in habitat that was under utilised by existing abalone, and hence density-dependent effects on mortality and growth were minimal. It is also assumed that increased fishing mortality will counter density-dependent effects. Any potential benefits of increasing the breeding stock have not been evaluated.
- Enhancement into the natural habitat could only be practically implemented as an activity that is integrated into the wild-stock management, for example, by assigning ITQs commensurate with the level of re-seeding undertaken by them, and the known probability of survival and growth. Such decisions however, would need to work within the existing suite of performance indicators currently used to manage the wild stock fishery.

5.8 Conclusions and recommendations

- The study examined the likelihood and limitations of stock enhancement of greenlip abalone in Western Australia on a biological and economic basis.
- A larger experiment is required to critically investigate the effect of habitat on survival, and supply robust estimates of growth and survival to optimise the bio-economic analyses.
- Quantification of habitat type across the wild stocks is essential to optimise targeting of enhancement into preferred habitats.
- A detailed survey of existing genetic diversity within wild stocks is needed to provide baseline data against which future genetic surveys can be assessed.
- If undertaken, a stock enhancement programme should commit fully to examining its potential as a fisheries management tool. This is estimated to require 7 years, starting with spawning of selected wild broodstock, and ending with the completion of 5 successive released cohorts. A proposal for a test case for commercial enhancement has been developed and includes appropriate biological targets against which the success of the proposal can be gauged.

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7 References

Babcock, R. and Keesing, J.K. (1999). Fertilisation biology of the abalone *Haliotis laevigata*: Laboratory and field studies. *Canadian Journal of Fisheries and Aquatic Science.* 56: 1668-1678.

Bell, J.D., Rothlisberg, P.C., Munro, J.L., Loneragan, N.R., Nash, W.J., Ward, R.D. and Andrew, N.L. (2006). Stock enhancement of marine invertebrate fisheries. *Advances in Marine Biology*. 49.

Blankenship, H.L. and Leber, K.M. (1997). A responsible approach to marine stock enhancement. *American Fisheries Society Symposium.* 15: 167-175.

Borg, J. (2002). Reseeding of grazing gastropods and bivalves into the marine environment in Western Australia. Fisheries Management Paper 162. Department of Fisheries, Western Australia.

Caputi, N., Penn, J.W., Joll, L.M. and Chubb, C.F. (1998). Stock recruitment-environment relationships for invertebrate species of Western Australia. *Canadian Special Publications in Fisheries and Aquatic Science.* 125: 247 – 255.

Daume, S., Brand-Gardner, S. and Woelkerling, W. J. (1999). Preferential settlement of abalone larvae: diatom films vs. non-geniculate coralline red algae. *Aquaculture.* 174: 243-254.

Dixon, C.D., Day, R.W., Huchette, S.M.H. and Shepherd, S. (2006). Successful seeding of hatchery-produced juvenile greenlip abalone to restore wild stocks. *Fisheries Research*. 78: 179-185.

Dixon, C.D., Gorfine, H.K., Officer, R.A. and Sporcic, M. (1998). Dispersal of tagged blacklip abalone, *Haliotis rubra*: Implications for stock assessment. *Journal of Shellfish Research.* 17(3): 881-887.

Doherty, P.J. (1999). Recruitment limitation is the theoretical basis for stock enhancement in marine populations. *Stock enhancement and Sea Ranching* (Howell, B.R., Moksness, E. and Svasand, T. eds), pp. 9-21. Fishing News Books, Blackwell, Oxford.

Elliot, N. and Conod, N. (2001). Microsatellite analysis of Western Australian and Tasmanian greenlip abalone (*Haliotis laevigata*). Unpublished Report to Fisheries Western Australia. CSIRO Division of Marine Research.

Evans, B., Bartlett, J., Sweijd, N., Cook, P. and Elliot, N.G. (2004). Loss of genetic variation at microsatellite loci in hatchery produced abalone in Australia (*Haliotis rubra*) and South Africa (*Haliotis midae*). *Aquaculture*. 233: 109-127.

Hart, A. and Fabris, F. 2006. Greenlip and Brownlip Abalone Managed Fishery status report. In: *State of the Fisheries Report 2005/06*, eds W.J. Fletcher and F. Head, Department of Fisheries, Western Australia, pp. 192-195.

Heasman, M.P. (2006). In pursuit of cost-effective fisheries enhancement of New South Wales blacklip abalone, *Haliotis rubra* (Leach) fishery. *Journal of Shellfish Research.* 25 (1): 211 – 224.

Kojima, H. (1995). Evaluation of abalone stock enhancement through the release of hatchery-reared seeds. *Marine and Freshwater Research*. 46:689-695.

Littay, M. and De Silva, S. (2001). Reproductive performance indices based on physical characteristics of female blacklip abalone *Haliotis rubra* L. *Journal of Shellfish Research.* 20(2): 673-677.

Masuda, R. and Tsukamoto, K. (1998). Stock enhancement in Japan: review and perspective. *Bulletin of Marine Science*. 62: 337-358.

Moloney, B.W., Lenanton, R., Jackson, G. and Norriss, J. (2003). Stock enhancement as a fisheries management tool. *Reviews in Fish Biology and Fisheries*. 13: 409-432.

Olsen, E.M., Heino, M., Lilly, G.R, Morgan, M.J., Brattey, J., Ernande, B. and Dieckmann, U., (2004). Maturation trends indicative of rapid evolution preceded the collapse of northern cod. *Nature.* 428. 932-935.

Prince, J. (2004). The decline of global abalone (genus *Haliotis*) production in the late twentieth century. Chapter 31 in Leber, K.M., Kitada, S., Blankenship, H.L., Svasand, T. (eds). Stock enhancement and sea ranching developments. Pitfalls and Opportunities. pp. 427-443.

Shepherd, S.A. (1990). Studies on Southern Australian Abalone (genus *Haliotis*). XII. Long-term recruitment and mortality dynamics of an unfished population. *Australian Journal of Marine and Freshwater Research.* 41: 475-492.

Shepherd, S. A. and Daume, S. (1996). Ecology and survival of juvenile abalone in a crustose coralline habitat in South Australia. In: Watannabe, Y., Yamashita, Y. and Oozeki, Y. (eds). Proceedings of an international workshop – survival strategies in early life stages. pp. 297-312. A.A. Balkema, Rotterdam, The Netherlands.

Ward, R.D. (2006). The importance of identifying spatial population structure in restocking and stock enhancement programmes. *Fisheries Research.* 80(1): 9 – 18.

Wells, F.E. and Mulvay, P. (1995). Good and bad fishing areas for *Haliotis laevigata*: A comparison of population parameters. *Marine and Freshwater Research.* 46, 591-598.

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