EXPERIMENTAL ABALONE RANCHING ON ARTIFICIAL REEF IN PORT PHILLIP BAY, VICTORIA

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ABSTRACT Outplanting abalone seed on artificial reef can potentially achieve the dual aim of stock enhancement and habitat improvement. This study examines the feasibility of ranching with hatchery-reared juvenile *Haliotis laevigata* Donovan and *H. rubra* Leach, in northern Port Phillip Bay, Victoria, Australia, and compares growth and survival of outplants on various artificial substrata. The experiments involve seeding 1,440 hatchery-reared juveniles, 10–30 mm size and aged 8–15 mo, at densities of 20–40 m^{-2}, onto concrete and basalt rock artificial reefs. On concrete artificial reefs, the mean survival of *H. laevigata* was 15% after two years, with a mean annual growth rate of 39 mm·yr^{-1}. For *H. rubra*, survival was 9% over three years, and growth rate was 22 mm·yr^{-1}. No significant difference in juvenile survival was detected on noncomplex concrete artificial reef *versus* complex concrete plus basalt rock habitats. Important lessons for ranching and stock enhancement on artificial reefs are discussed.

KEY WORDS: seeding, ranching, hatchery juveniles, stock enhancement, artificial reef, abalone

INTRODUCTION

The greenlip (*Haliotis laevigata* Donovan) and blacklip (*H. rubra* Leach) abalone have high commercial value. Australia's commercial wild-abalone fisheries contribute ~40% of the global abalone catch. In Victoria, *H. rubra* has historically represented 99% of the Victorian catch of the commercial wild-fishery, the remaining 1% being *H. laevigata* (Gorfine & Dixon 2000a).

Ranching, stock enhancement, and aquaculture are strategies used to increase fisheries productivity (Schiel 1992, McCormick et al. 1994, Rogers-Bennett & Pearse 1998, Kent & Drawbridge 1999). Ranching is considered to be at the boundary between capture fisheries and aquaculture. This boundary is becoming less distinct as natural habitats are modified by the introduction of artificial reefs (Bartley 1999a). Outplanting abalone seed on artificial reef can potentially achieve the dual aim of stock enhancement and habitat improvement. It is these principles that form the basis of the investigations conducted in this study.

Whereas commercial incentive is generally the principal stimulus for ranching activities, a combination of factors have fostered interest in abalone ranching and stock enhancement, including: the potential to alleviate pressure on heavily exploited wild fisheries from over-fishing and illegal capture (Schiel 1992, McCormick et al. 1994, Rogers-Bennett & Pearse 1998, Sweijd et al. 1998, Burton & Tegner 2000); the ability of aquaculture to reliably produce seed in quantity (Leber 1999, Seaman & Jensen 2000); advances in concrete artificial reef design (e.g., Mottet 1981, McCormick et al. 1994), and the use of natural quarried rocks to culture abalone (e.g., Morikawa 1999, Dixon et al. 2006). As the world leader in ranching and enhancement, Japan has been the most active, with national programs underpinned by government subsidies established since the 1970s, involving release of millions of hatchery-reared juvenile abalone annually onto artificial and natural reefs (Tanaka 1978, Mottet 1981, Saito 1984, Kojima 1995, Imamura 1999, Matsuoka 1999, Morikawa 1999). Yet, despite such massive investment, seeding has not resulted in an increase in Japanese wild abalone stocks (Seki & Sano 1998), which have continued to decline over time (Masuda & Tsukamoto 1998). Commercial abalone ranching on artificial reef has also been undertaken in Australia on a small scale (e.g., Shepherd et al. 2000) and in China (e.g., Shaodun et al. 1998).

Currently, there are many unresolved issues with ranching and stock enhancement, including: high mortality of juvenile seed (Tegner & Butler 1985, Shepherd et al. 2000); a limited understanding of the environmental parameters that govern growth, recruitment and productivity for a specific ranch site (Bartley 1999a), complex site lease arrangements and security of stock (Bartley 1999b), and the potential for genetic risks and disease to wild abalone populations (Bell 1999, Cross 1999). Releasing hatchery-reared juvenile abalone of mean shell length of 10–30 mm to enhance abalone populations shows the most promise, because hatchery juveniles are robust, sedentary, and can be outplanted with relative ease (McCormick et al. 1994, Shepherd et al. 2000, de Waal & Cook 2001, Heasman et al. 2004, Dixon et al. 2006). Once released into the sea, however, hatchery-reared juveniles often suffer high predation (Tegner & Butler 1989, Heasman et al. 2004), a factor that seriously impedes the viability of ranching and stock enhancement projects.

This study investigated the prospect of commercial abalone ranching in a series of small-scale experiments. The aims of the experiments were to: (1) assess the growth and survival of hatchery-reared juvenile *H. laevigata* and *H. rubra* on artificial reef at the study site to determine the suitability of the site for commercial abalone ranching and (2) compare growth and survival of hatchery-reared juvenile abalone on noncomplex concrete *versus* complex basalt rock artificial reefs at the study site and in on-shore aquaria.

METHODS

Study Site

The study site where seeding experiments were conducted was 15 km southwest of Melbourne in Altona Bay, Port Phillip Bay, Victoria, Australia (Fig. 1). Commercial proponents
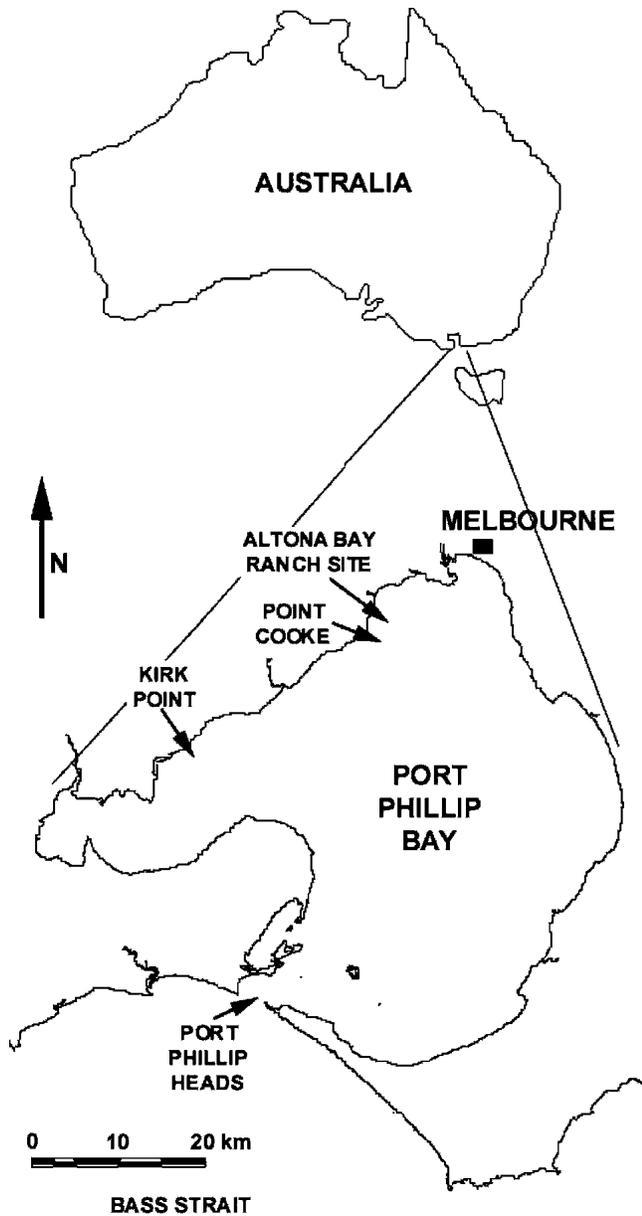
Figure 1. Map showing the location of Altona study site, Port Phillip Bay.

selected the study site based primarily on the fact that a dense population of abalone existed at Point Cook, 2.5 km south of the study site. Water depth at the study site ranged from 2.9 m to 4.8 m, with an average of 3.7 m. Protected from high water currents and wave energies, the site is swept by weak currents (generally <10 cm·sec^{-1}), and wave action was slight (max. modeled wave height $H_{1/3} = 1.2$ m with period $T_{1/3} = 4.5$ sec.). The probability of water currents transporting unattached (i.e., drift) macroalgae (i.e., abalone food) to the site was low. Sedimentation rates were high with a maximum of >1,000 g·m^{-2}·day^{-1} during summer. Water temperature ranged from 9.9°C in July to 23.8°C in January, with salinity averaging 35.5 ppt. The seabed topography at the study site was generally flat, with the natural basalt rocky reef substrate having minimal habitat complexity, consisting of a variable number of small, flat basalt boulders, surrounded by cobbles and sandy patches.

Both the concrete artificial reef and the natural rocky reef provided habitat for a diverse range of flora and fauna, including a low-density wild stock of *H. rubra* of ~1 m^{-2}, a small population of the reef crab *Nectocarcinus integrifrons* at densities of ~1 m^{-2}, which was identified as the key predator of juvenile abalone at the site, and a dense population of the urchin *Heliocidaris erythrogramma* of ~10 m^2, which were more abundant on the natural rocky reef. The pioneer colonizers *Ostrea angasi* and *Balanus trigonus* were the predominant fouling organisms. Cover of crustose coralline algal species was highly spatially variable at about 10% to 25%, which is considerably lower than the cover found in a study of natural reefs 5-km northeast of the site (Daume et al. 1999). Biomass of attached macroalgae (i.e., abalone food) was highly seasonally variable. Competition between species for space on artificial or natural reef was not a factor limiting reef productivity, because 20% to 50% of the reef surfaces was bare at the conclusion of this study (unpublished data).

Concrete and Basalt Rock Artificial Reefs

A single concrete artificial reef structure used for all experiments with dimensions of 1,000 mm length × 300 mm height × 300 mm width, weighing 110 kg, provided a substrate for attachment and shelter for the juveniles (Fig. 2A). The basal area of a single reef was 0.3 m^2 with a total surface area of 1.5 m^2, (cryptic underside area ~0.3 m^2). The reef surface texture was flat, shiny, and extremely hard. A structural design analysis of the concrete artificial reef showed that they were able to withstand the local hydrodynamic forces and were stable on the seabed. Consequently, mortality of abalone through physical disturbance of the artificial reef was assumed to be negligible. The artificial reef design criteria and habitat features (Fig. 2B) included: (1) provision of a large vertical surface area for adult abalone attachment; (2) provision of a small void on the underside of the reefs for juvenile attachment and shelter; (3) upward facing horizontal surfaces for attachment and growth of macroalgae; (4) a sufficient weight to withstand local hydrodynamic forces but light enough to permit underwater manipulation by research divers; (5) a shape permitting compact stacking onto pallets for ease of transport; (6) being nontoxic to the marine environment, and (7) being readily removable in the event of project failure. HollowCore Concrete of Laverton North, Victoria, Australia constructed the artificial reefs using an extruded mould process.

To investigate the effect of increased cryptic habitat on the survival of hatchery juveniles, a layer of new basalt rocks, with similar geology to a natural rocky-reef in Port Phillip Bay, were placed on top of and alongside half of the concrete artificial reef replicates. The basalt rocks were in contact with both the seabed and the concrete reef, providing a complex habitat with crevices for the juveniles. The dimensions of the basalt rock ranged from 0.2 m to 0.45 m diameter (mean 0.35 m), and the surface profile was irregular, with holes ranging from 5–25 mm in diameter and 5–20 mm deep. The concrete and basalt rock artificial reefs were deployed by boat between March and July 2000. Divers moved reef units into discrete experimental groups and aligned all reefs in a north-south orientation. Each replicate and treatment was separated by 10–25 m, and each experiment was separated by at least 100 m. Experimental replicates were randomly interspersed and each replicate was individually marked for identification
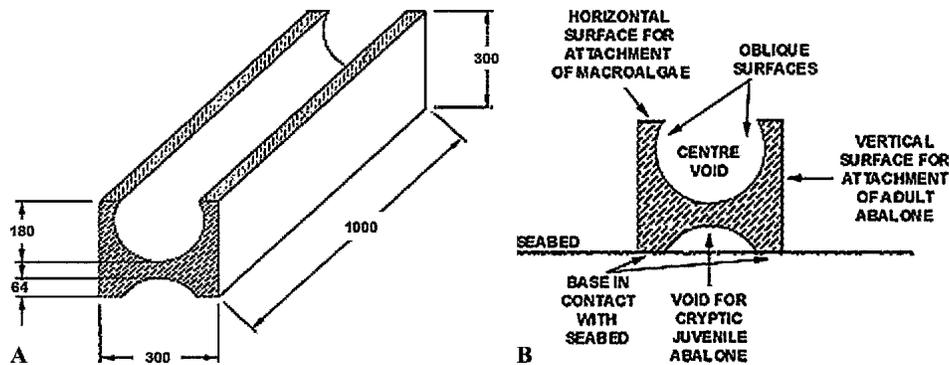
Figure 2. A, Concrete artificial reef design deployed for all experiments. Rendering indicates cut edges. Dimensions (in millimeters) of each reef varied slightly depending on the width of cutting blade and the point of cut. B, Habitat characteristics of the artificial reef design used for all experiments (cross section).

during surveys. The artificial reefs were conditioned in the sea for at least three months prior to stocking with juveniles.

Broodstock

Broodstock necessary to produce *H. rubra* and *H. laevigata* hatchery juveniles for the experiments were captured at Point Cook, 2.5 km south of the study site (Fig. 1), to conserve the genetic integrity of the local wild abalone stocks. Naturally occurring Victorian *H. laevigata* populations are located outside Port Phillip Bay and at Port Phillip Heads; whereas, *H. rubra* are endemic on reefs in Port Phillip Bay (McShane et al. 1986, Gorfine & Dixon 2000b). Nevertheless, in ~2000, commercial abalone divers began to catch small numbers of *H. laevigata* in northern Port Phillip Bay, the first time since the beginning of the fishery in ~1964 (pers. comm. abalone divers). To determine the number of *H. laevigata* in Port Phillip Bay, surveys were conducted on reefs at Kirk Point, Point Cook, and Altona Bay where *H. laevigata* were found sparsely spread in very low numbers. In addition, the *H. laevigata* and *H. rubra* caught on an abalone fishing boat at Point Cook were counted and were found to occur at a ratio of 1 *H. laevigata* to 1,000 *H. rubra*. Based on these observations, and in combination with a survey of *H. rubra* at Point Cook by Gorfine and Dixon (2000a), it was estimated that the northwestern reefs of Port Phillip Bay provided potential habitat for several thousand *H. laevigata* at a low density (unpublished data). These "individuals" were the target broodstock used to produce juvenile *H. laevigata* for the seeding experiments.

Hatchery-reared Juveniles and Release Methods

During three separate small-scale seeding experiments in the period 2000 to 2003, artificial reefs were stocked with a total of 960 *H. rubra* and 480 *H. laevigata* hatchery-reared juveniles to evaluate abalone ranching at the study site (Table 1). Survival, growth, and habitat preferences of *H. rubra* and *H. laevigata* juveniles on the artificial reefs were evaluated. The age of the juveniles at release was 8–15 mo, and sizes ranged from 10–30 mm. As *H. rubra* and *H. laevigata* from Port Phillip Bay spawned in spring and summer respectively, hatchery-reared juveniles were released at different times onto the artificial reef during seeding experiments.

To minimize handling stress and injury, juveniles were sedated with a benzocaine solution (10% benzocaine diluted in ethanol, 0.5 mL solution per liter of seawater), carefully removed from a poly-vinyl chloride (PVC) substrate, measured and then placed onto large, sun-bleached, clean abalone shells. These provided a good attachment surface during transport and protection from predators after release. Ten juveniles were placed on each shell and shells were bound together to form a "seeding module" stocked with either 20 or 40 juveniles. The seeding modules were placed in mesh bags to prevent escape of the juveniles, and held in an aerated, flow-through seawater

TABLE 1.

Summary of juvenile abalone seeding experiments. Period = date juveniles released onto artificial reef and period of experiment, Temp. = water temperature at release, # Released = number juveniles released for experiment, Age = age of juveniles at release (months), Density = number of juveniles·m^{-2} per reef at release, Shell length = juvenile shell length minimum, maximum and mean (parenthesis) in mm at release, Substrate = Concrete artificial reef (AR) and basalt rock substrates, N = number of replicates.

Experiment	Period	Temp.	# Released	Age	Density	Shell Length (mm)	Substrate	N
H. rubra								
1.	May 2000–May 2003	15°C	360	8	40	10–20 (15.1)	AR	9
2.	Sep. 2002–May 2003	13°C	600	12	20	13–26 (19.1)	AR & basalt rock	15 15
H. laevigata								
3.	May 2001–May 2003	15°C	480	15	20	15–30 (19.2)	AR & basalt rock	6 6

tank for at least seven days for seed to recover from sedation. They were fed red macroalgae and monitored for mortality.

On the day of release, the seeding modules with juveniles firmly attached, were thoroughly drained and packed into chilled, insulated plastic containers. Transport time from the hatchery to release onto artificial reef was 2.5 h. The seeding modules were tied securely to the underside of the artificial reefs, to protect the juveniles against predators and to ensure they could leave the modules and access the void underneath the artificial reef. Juveniles were released during the cooler seasons when water temperatures were 13°C to 15°C. None of the juveniles became detached from the shells during release. Handling mortality was evaluated by monitoring, for seven days in the hatchery, a batch of 50 control juveniles per experiment from the same cohort that was released at the study site. Initial mortality, as distinguished from long-term mortality, was evaluated by collecting empty shells during a diver survey two weeks postrelease. For each experiment, the handling and initial mortalities were added together and deducted from the number of juveniles released.

Juvenile Seeding Experiments

Experiment 1: In May 2000, 360 hatchery juvenile *H. rubra* were released onto nine individual replicate concrete artificial reefs, at a density of 40 juveniles per reef unit (i.e., a density of 40 juveniles·m^{-2}) (Table 1). Experiment 2: In Sept. 2002, 600 hatchery juvenile *H. rubra* were released onto 30 concrete artificial reefs at a density of 20 juveniles per reef unit (Table 1). A habitat constructed of concrete plus basalt rocks was seeded with juveniles to test whether increasing habitat complexity and cryptic spaces would offer greater protection from predators thereby improving survival, compared with the non-complex concrete artificial reef habitats. The treatments in this experiment were: (1) a single concrete artificial reef with no basalt rocks added and (2) addition of ~8 basalt rocks to each concrete artificial reef, to provide alternative cryptic habitat to the juveniles. Each treatment was replicated 15 times by a single artificial reef. Experiment 3: In May 2001, 480 hatchery juvenile *H. laevigata* were released at a density of 20 juveniles per reef unit (Table 1). The concrete and basalt rock treatments in this experiment were the same as those described previously for Experiment 2. Each treatment was replicated six times, each replicate being two concrete units aligned in a row.

Field Surveys

In situ surveys of juvenile growth, survival, and habitat preferences on artificial reef were conducted by divers approximately annually for the duration of each experiment. For Experiment 3, *in situ* surveys were also conducted at two-weeks (survival only) and six-months postrelease. In addition, any natural cobbles or rocky-reef near the experiments was searched within a radius of 5 m from the artificial reef for juveniles <2 y postrelease, and a 10 m radius for juveniles >2 y postrelease. The time allocated during underwater surveys was approximately 10 minutes per square meter of reef substrate. During surveys the juveniles could be identified by the bright green shell from the artificial diet during rearing (Kojima 1995). A final "destructive" survey of all experiments was conducted in May 2003 at the conclusion of the project.

Juvenile survival was recorded as the number of juveniles per replicate located by the diver on the artificial reefs, plus the natural reef cobbles and boulders within the search area during the allocated search time. Data for the artificial reef and the natural cobbles around it were pooled, because the total number of juveniles surviving if seeded on the reefs was of particular interest to this project. The instantaneous mortality rate, M, was calculated by plotting regressions of natural log number surviving *versus* time in years or months. Growth was measured by the change in mean size of the cohorts released during the period at liberty.

The sighting efficiency of the diver to search for and locate the juveniles during surveys on both substrates was determined by redistributing 50 juveniles found during a final survey evenly onto three concrete reefs, and 50 were evenly distributed on 15 basalt rocks. Then after four days, the juveniles were searched for again. The number of juveniles recovered was divided by the original number released (less any empty shells found) to give an estimate of diver efficiency (Shepherd 1998).

Juvenile Survival in Aquaria on Concrete Reef and Basalt Rock Substrates in the Presence of Nectocarcinus Integrifrons

To examine the survival of hatchery juvenile *H. rubra* in the presence of the predatory reef crab *Nectocarcinus integrifrons*, experiments were conducted in aquaria simulating the concrete and basalt rock reef habitats used during the field experiments. Ten juvenile *H. rubra* were placed into each of the six experimental aquaria (half containing concrete, half basalt rocks) for a total of 12 days: 5 days without crabs plus a further 7 days with crabs. The experiment was repeated twice and juvenile survival on the two substrate types was monitored.

Commercial Requirements of the Proposal and Power Analysis

To be commercially viable, the proponents estimated that juvenile survival would need to be 80% after two weeks, 60% after six months, 40% after one year, and >20% after two and three years (i.e., long-term survival). In addition, the basalt rock treatment would need to yield 10% higher in survival and growth because of additional costs of deploying the rocks. A juvenile growth rate of 20 mm per annum was considered necessary to be commercially viable, in order for the hatchery juveniles (seeded at approximately 20 mm shell length) to reach a harvestable size of 80 mm in three years of ranching. These figures formed the basis of the effect sizes for the power analysis.

RESULTS

For the field experiments, handling mortality ranged from 0% to 2%, and the initial mortality estimates based on collecting empty shells during two-week field survey ranged from 0% to 4%. During field surveys, the efficiency of the diver to search for and locate juveniles of about 40-mm shell length was estimated to be 90% on artificial reef and basalt substrates, and was therefore assumed to be 100% for the analysis. This approach may underestimate survival of juveniles of 40-mm shell length, as only about 90% of juveniles of this size were detected during the surveys. This applies only to Experiment 2, because the juveniles in Experiments 1 and 3 were larger than

40 mm during the final survey (i.e., ~60–100 mm shell length), and it is reasonable to assume that diver efficiency would be about 100%, which is consistent with the analysis of survival. In addition, this approach would not influence the comparison of the substrates.

Concrete Versus Concrete Plus Basalt Rock Artificial Reef

For Experiment 2, juvenile growth and survival on the two reef treatments (i.e., concrete artificial reef *versus* concrete artificial reef plus basalt rock) were analyzed as single factor ANOVAs. For Experiment 3, juvenile growth and survival on the two reef treatments were analyzed as single factor ANCOVAs, with time as a continuous predictor variable (covariate). There was no significant difference in juvenile survival between the concrete and the concrete plus basalt reef habitats for either *H. rubra* (ANOVA, F = 0.150, df = 1,28, $P = 0.701$) or *H. laevigata* (ANCOVA, F = 3.152, df = 1,45, $P = 0.083$) in Experiments 2 and 3 respectively. Experimental power to detect a 10% difference in survival on the substrates was high for *H. laevigata* ($P > 0.80$), but low for *H. rubra* ($P = 0.36$). Power to detect a 20% difference in survival for *H. rubra* was high ($P > 0.80$). Similarly, for the aquaria experiment, there was no significant difference in *H. rubra* survival on the concrete and basalt reef habitats in the presence of crabs (F = 2.142, df = 1,10, $P = 0.174$), although the power to detect a 20% difference in survival in this experiment was low ($P = 0.232$). At the conclusion of the aquaria experiment after 7 days in the presence of crabs, survival (±S.E.) on the concrete was lower (78% ± 7.9%) than on the basalt rock (88% ± 6.5%).

Growth on concrete *versus* concrete plus basalt reefs was significantly different for *H. rubra* (F = 10.466, df = 1,28, $P = 0.003$) in Experiment 2, with the annual growth rate estimated to be 5 mm faster on the concrete artificial reef (Table 2). There was no significant difference in growth, however, for *H. laevigata* (F = 0.700, df = 1,33, $P = 0.409$). Experimental power to detect a 10% difference in growth (i.e., 20 mm on concrete compared with 22 mm on basalt per annum) was low ($P = 0.275$) for *H. laevigata* but was high to detect a 20% difference ($P = 0.776$).

Long-term Survival and Growth on Concrete Artificial Reef

Experiment 1: three years after being seeded on concrete artificial reef, mean *H. rubra* juvenile growth was 37 mm in the first year, which then decreased markedly to 15 mm in the second and third years, with mean annual growth being 22 mm·yr^{-1} (Table 2, Expt. 1). *H. rubra* survival was 24% after one year, 11% after two years, and 9% after three years so that mean instantaneous mortality, M ± SE = 0.89 ± 0.10 y^{-1}. Experiment 3: two years after being seeded on concrete artificial reef, mean juvenile *H. laevigata* growth was 41 mm in the first year, and 37 mm in the second year (Table 2, Expt. 3) with mean annual growth being 39 mm·yr^{-1}. *H. laevigata* survival was 17% after one year and 15% after two years, so that mean instantaneous mortality, M ± SE = 0.96 ± 0.15 y^{-1}. Whereas the experiments were conducted over different periods, it is instructive to compare mortality in the first year. Estimates of annual mortality rate (M ± SE) in the first year derived from the survival data for *H. rubra* were 1.47 ± 0.08 y^{-1} and 1.82 ± 0.17 y^{-1} in Experiments 1 and 2 respectively, whereas for *H. laevigata* was 1.83 ± 0.15 y^{-1} in Experiment 3.

DISCUSSION

The seeding modules made from clean abalone shell provided a suitable method of transporting the juveniles to the study site, and the results suggest that handling mortality was very low. The juveniles, firmly attached inside the shells, were protected from physical injury during handling. Using a natural material such as shell for seeding has the advantage over other artificial seeding devices (e.g., McCormick et al. 1994, Goodsell et al. 2006) that it does not introduce litter into the environment, particularly for commercial ranching with ongoing seeding operations. Within 10 min of attaching the seeding modules to the underside of the artificial reef, however, the crab *N. integrifrons* began to forage near the modules. Several days later, many crabs were near the modules, with several small crabs sheltering inside the modules. McCormick et al. (1994) reported high juvenile mortality occurring within several hours of seeding juveniles, and Tegner and Butler (1989) suggested that the mucus produced by juvenile seed during handling may initially attract predators. Furthermore, rearing of hatchery juveniles in an artificial environment may cause them to express poor behavioral responses (Bell 1999), such as failure to take adequate shelter to avoid predators (Schiel & Welden 1987), which may also influence survival rates. It thus seems likely that the juvenile seed were attracting *N. integrifrons*.

TABLE 2.

Summary of survival and growth of abalone seeding experiments. Duration = duration of experiment, Substrate = Concrete artificial reef (AR) and basalt rock substrates, Shell length = shell length of juveniles at conclusion of experiment in mm showing minimum, maximum with mean ±SE in parenthesis, Growth = mean annual growth rate ± standard error, %Surv. = % survival averaged over the duration of the experiment, M = annual instantaneous mortality ± standard error.

Experiment	Duration	Substrate	Shell Length	Growth.yr-1	% Surv.	M
H. rubra						
1.	3 y	AR	55–104 (80.0 ± 1.89)	22 ± 0.63	9%	0.89 ± 0.10
2.	8 mo	AR	21–58 (37.4 ± 0.66)	*27 ± 1.00	32%	1.82 ± 0.17
		AR & basalt rock	24–51 (33.9 ± 0.55)	*22 ± 0.82	35%	1.77 ± 0.21
H. laevigata						
3.	2 y	AR	80–117 (97.1 ± 1.33)	39 ± 0.66	15%	0.96 ± 0.15
		AR & basalt rock	84–108 (96.7 ± 1.06)	39 ± 0.53	15%	0.92 ± 0.12

* Growth for *H. rubra* in Experiment 2 after 8 mo was extrapolated to estimate annual growth rate.

Generally, the probability of recovering small empty seed shells is very low, because they are hard to find (Tegner & Butler 1989), and crabs may crush them (Mower & Shepherd 1988); hence collecting empty shells gives at best a crude estimate of minimum mortality (McCormick et al. 1994). Hence, in this study, despite thoroughly searching for empty shells two weeks post seeding, initial mortality is likely to be underestimated. During the field surveys, empty juvenile shells, usually recovered within one meter from the release point, had distinctive chips at their edges, or were partially or totally crushed; the shells recovered resembled the shells damaged by *N. integrifrons* during the aquaria experiment. Because no other significant juvenile abalone predators were identified at the study site, *N. integrifrons* was inferred to be responsible for the damaged shells and mortality of the juveniles. Crabs are well known predators of abalone, particularly of juveniles (Tegner & Butler 1985, Schiel & Welden 1987, Mower & Shepherd 1988, Shaodun et al. 1998, Konishi & Uki 2002). To reduce mortality, fishing or trapping of predators such as crabs, octopus, fish, seastars, and lobsters prior to seeding with juveniles is often undertaken as part of ranching and enhancement programs (Kojima 1995, Shaodun et al. 1998, Bartley 1999a). Tegner and Butler (1989) suggested that predator trapping for abalone enhancement exercises must be continuous to greatly improve seed survival, but this would add to the cost of abalone seeding operations.

Diver efficiency of 90% on both substrates for abalone of 40 mm shell length was higher than that found in Shepherd (1998) of less than 60% for up to 50 mm shell length. This difference is attributable to the different habitat characteristics of the substrates searched. In this study, the reef habitats were noncomplex, with minimal cryptic spaces and were surrounded by small cobbles, shell matter, and sand, whereas in Shepherd (1998) the reef habitat was complex layers of boulders, with abundant cryptic spaces not clearly visible to divers.

Concrete Versus Concrete Plus Basalt Rock Artificial Reef

Increasing available cryptic habitat by placing basalt rocks alongside and on top of the artificial reefs did not result in increased survival of juveniles in the field experiments. This was verified in the aquaria experiments where despite the differences in the substrates (i.e., flat, smooth, noncomplex concrete surfaces *versus* the irregular, cryptic, basalt surfaces), juvenile survival in the presence of *N. integrifrons* was similar. *N. integrifrons* also sheltered in crevices among the basalt rock, in both the field and aquaria experiments, probably nullifying any extra protection provided by this habitat to the juvenile abalone. The experiments showed that *N. integrifrons* was well adapted to survive on the basalt rock and the concrete substrates, leaving little doubt that the dextrous crabs are able to lever the juveniles off the substrate or crush the shells. The reason for the slower growth of *H. rubra* on the basalt rock than on concrete may be increased competition for food from urchins, which had a higher density on natural basalt than on the concrete artificial reefs at the study site (unpublished data). There was no difference in growth on the substrates, however, for *H. laevigata*. Whereas no basalt rocks were lost during storms, wave forces caused movement of smaller rocks, possibly injuring the juveniles attached to the underside, or causing them to move to a more stable substrate. Schiel (1992) reported that movement of rocks was responsible for mortality of hatchery juveniles, and

Mottet (1981) reported that placement of light rocks should be avoided in places of strong current or high wave activity.

Long-term Survival and Growth on Concrete Artificial Reef

The survival rates in this study were about average for *H. laevigata* and for *H. rubra* as compared with previous studies of juvenile seeding onto artificial and natural reef (reviewed in McCormick et al. 1994 and Shepherd 1998). The fact that survival was similar and growth for *H. laevigata* was greater than that of *H. rubra* was surprising, because the study site has not historically had a *H. laevigata* population. In South Africa, Sweijd et al. (1998) found that *H. midae* hatchery seed survived outside their natural geographic range. It appears that ranching of abalone by seeding with juveniles is not necessarily confined to areas where natural abalone populations occur or once occurred.

Releasing juvenile *H. rubra* at a higher density of 40 m^{-2} in Experiment 1 did not yield higher survival compared with a lower density of 20 m^{-2} in Experiment 2 (Table 2). Although Experiments 1 and 2 were not conducted simultaneously, the findings suggest that juvenile survival rates were converging to become similar after one year because of the effects of density dependent mortality. In addition, as the density of wild *H. rubra* at the site was ~1 m^{-2} on artificial and natural reef, it is possible that seeding with densities of 20 m^{-2} was still too high. These findings for *H. rubra* are consistent with similar studies by Heasman et al. (2004) and Shepherd et al. (2000). Heasman et al. (2004) reported that releasing *H. rubra* onto natural reef at lower densities (i.e., releasing batches of 100 juveniles instead of batches of 1,000) increased survival from 3.8% to 12.5%. Similarly, in a study of *H. rubra* seeding in Tasmania, Australia, Shepherd et al. (2000) found that survival for various seed densities of 10, 20, 30, and 40 m^{-2} was lowest for the highest density. They attributed the lower survival to increased predation or weakening of abalone because of increased competition between the higher density seed. Therefore, lower release densities could have advantages in terms of survival rates, although out-planting costs may be higher.

H. laevigata had a faster growth rate (39 mm·yr^{-1} as compared with 22 mm·yr^{-1} for *H. rubra*), which showed promise for commercial ranching. In a recent study of seeding in South Australia, growth of hatchery juvenile *H. laevigata* on constructed (natural) boulder habitats was also reported to be ~40 mm per annum (McAvaney et al. 2004). For *H. rubra*, the growth of 22 mm per annum rate recorded in the present study is comparable with the findings of other similar studies of juvenile *H. rubra* (e.g., Day & Leorke 1986, Shepherd et al. 2000; Heasman et al. 2004).

Evaluation of Altona Site for Commercial Ranching

An economic model by Sweijd et al. (1998) based on cost of seed production to produce 1 t of abalone ranched on natural reef, suggested that long-term survival of seed of >15% is desirable for commercial ranching in South Africa. In the present study of ranching on concrete artificial reef, long-term survival of >20% was considered by the proponent to be necessary to achieve commercial viability for a ranching operation in Port Phillip Bay, based on an initial cost of AUD$0.50 per juvenile. The experimental results showed that, under the project framework provided by the proponent, the

survival rate of hatchery juvenile *H. rubra* and *H. laevigata* of 10–30 mm shell length on artificial reef was only marginally viable at the site. On both substrata and for both species, growth rates exceeded the commercial requirement of 20 $mm \cdot yr^{-1}$. Long-term survival rates for both species, however, were lower than the commercial requirement of 20% after two and three years. High initial juvenile mortality, caused by predation (density = 1 $crab/m^2$ on artificial and natural reef) and high sedimentation rate (max. > 1,000 $g \cdot m^{-2} \cdot day^{-1}$ during summer), were the key factors contributing to poor juvenile survival. In addition, the algae identified at the site were not those species usually preferred by *H. rubra* or *H. laevigata* (Sanders 1981, Fleming 1991, Shepherd & Steinberg 1992). Nevertheless, this study has demonstrated the potential at suitable sites to alleviate fishing pressure on *H. laevigata* by enhancing wild populations in Victoria, which have suffered collapse from over-fishing (Gorfine & Dixon 2000a).

As yet, the commercial viability of unsubsidized abalone out-planting remains unproven (McCormick et al. 1994), although projects, which have undertaken prerelease surveys to identify suitable habitat (e.g., de Waal & Cook 2001, Dixon et al. 2006) and those, which have removed predators (e.g., Shaodun et al. 1998) have demonstrated increased juvenile survival and commercial viability. Many factors determine the productivity of abalone habitat, such as food supply, substrate availability, hydrodynamics, and predator and competitor populations. Hence, few areas may be suitable for stock enhancement and ranching of abalone (Shepherd et al. 2000). The Altona site proved to be marginally viable for ranching, and this situation is likely to be applicable to many other sites, including the Aquaculture Zones in Victoria identified by government as being possible abalone ranching sites; e.g., Bates Point Aquaculture Zone (Environment Conservation Council 2000).

Critical Evaluation of Artificial Reef Design

The concrete artificial reef used in this study was designed and manufactured using an extruded process developed for prefabricated building products, which is potentially cheaper than conventional moulding processes (Mr. Peter Healy, HollowCore Concrete, pers. comm. 2001), and may facilitate the production of artificial reefs in the future. The flat concrete surfaces of the artificial reef were smooth at a scale of <1 mm. Such a surface provides poor microhabitat for shelter of small juvenile abalone (2–5 mm shell length) from predators. Studies in Japan have indicated that surface irregularity is the most important aspect of the shape for artificial reef, with abalone preferring irregular surfaces (Grove & Sonu 1985). Commercially manufactured artificial reefs, such as Reef Balls, are prepared by a roughening process during manufacture to provide microhabitat for small juveniles and to enhance settlement of larvae (Reef Ball 2005). Chojnacki (2000) reported

that concrete with a roughened surface, presumably at a scale of 1–10 mm, was a superior surface for larval settlement of *Mytilus edulis* and *Balanus improvisus* compared with smooth surfaces. Evaluation of the performance of smooth *versus* roughened artificial reef as substrate for settling veligers was not undertaken in this study. Nevertheless, water currents passing over the smooth concrete surfaces would have laminar flow, lessening the chance of larval settlement, compared with a more turbulent regimen over a rough surface. A roughened reef surface with rugosity at a scale of 10–20 mm also has the additional advantage of being able to "snag" drifting algae for abalone food. Hence, the design of the reefs used in this study could have been considerably improved by roughening the surfaces during manufacture.

The artificial reef design in this study did not incorporate crevices underneath the reefs to protect cryptic juveniles from predators, which may have contributed to juvenile mortality. In fact, the cavity under the artificial reefs, designed specifically to provide protection for juvenile abalone, was too simplistic because it also provided habitat for predators such as *N. integrifrons* and the seastar *Coscinasterias muricata*. The artificial reef design could therefore be improved by incorporating crevice habitat to protect cryptic juveniles from predators, as detailed in McCormick et al. (1994) and Mottet (1981). The height and the vertical surfaces of the artificial reef were satisfactory for attachment of adult *H. rubra* and *H. laevigata*, as demonstrated by the colonization of the reefs by wild adult *H. rubra* at a density of approximately one adult m^{-2}. The reefs may have been significantly improved, however, if they had provided a greater upward-facing horizontal surface area for attachment and growth of macroalgae.

In conclusion, this study highlights the wisdom of undertaking a thorough scientific evaluation of the intended site before proceeding with commercial abalone ranching.

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