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# VIABILITY OF ABALONE (*HALIOTIS IRIS*) STOCK ENHANCEMENT BY RELEASE OF HATCHERY-REARED SEED IN MARLBOROUGH, NEW ZEALAND

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***ABSTRACT*** The total allowable commercial catch from New Zealand's *Haliotis iris* Gmelin 1791 fishery was reduced by 18% between 1999 and 2004. Quota holders have initiated research to assess the viability of stock enhancement by release of hatchery-reared seed. Boulder reefs (1 × 2 × 0.5 m) were constructed by placing natural boulders in wire baskets over sand or bedrock. These reefs allowed accurate census of small abalone during short-term experiments (3–4.5 mo.) examining the effects of seed size [5–25 mm shell length (SL)] and density (25–640 $m^{-2}$ of seafloor) on survival and growth. Survival increased with seed size, but beyond 10 mm the increased survival did not offset the cost of larger seed. Growth and survival of 8–24 mm seed decreased with increasing density, but regressions were nonsignificant ($P = 0.06–0.36$) because of variability among reefs. Densities as high as 300 $m^{-2}$ gave good growth and survival (>40%) over 3 mo. on some reefs. Five natural sites were seeded with 2,600–20,000 juveniles (mean 10–11 mm SL, range 6–19 mm) at an average density of 50 $m^{-2}$ to estimate long-term survival from commercial reseeding. After 17–20 mo, when recovered abalone averaged 47–60 mm SL, survival varied widely among the five sites ranging from 1.7% to 25.1% (average 13.8%). Estimated survival to harvest size of 125 mm SL ranged from 1.3% to 18.6% (average 10.2%) assuming 3 further years of mortality at $M = 0.1$. The two sites with the lowest survival were affected by substrate movement during storms, highlighting the risk of using exposed locations with boulders small enough to be turned for surveys. Survival to harvest averaged 15.2% across the three sites without significant storm damage. Growth averaged 29.5 mm SL year$^{-1}$ across the five sites (range 25–33 mm·year$^{-1}$). A model was used to examine the economic viability of reseeding, assuming that reseeded abalone supplement natural recruits. At a price of NZ$0.32 per 10 mm SL seed, the return on investment was 20% yr$^{-1}$ at 10% survival to harvest, and 30% yr$^{-1}$ at 15% survival. These returns compare favorably with opportunity costs of ~10% yr$^{-1}$, suggesting that reseeding is likely to be economically viable if sites and habitat are carefully selected. Large scale seeding should be accompanied by monitoring to quantify net population increase.

***KEY WORDS:*** abalone, *Haliotis iris*, enhancement, seed size, density, economic analysis

## INTRODUCTION

The New Zealand fishery for *Haliotis iris* Gmelin 1791 is one of the largest remaining abalone fisheries in the world. The fishery has been managed by individual transferable quotas since 1986, and total allowable commercial catch (TACC) remained stable at about 1,250 t·yr$^{-1}$ until 1999 (Sullivan et al. 2005). Since 1999, TACC reductions totaling ~40% have occurred in quota management areas PAU7 (Marlborough) and PAU5B (Stewart Island) (http://www.paua.org.nz/industry_pauamacs.htm), because previous TACCs proved unsustainable. Together, these cuts reduced the nationwide commercial catch by 18% (Sullivan et al. 2005). These catch reductions coincided with a reorganization of New Zealand's national and regional abalone industry bodies (http://www.paua.org.nz/). Under the new structure, various initiatives are being investigated to improve management of the resource (http://www.paua.org.nz/fisheriesmgmttools.htm).

Enhancement of wild stocks by release of hatchery-reared seed is one method by which the yield from the fishery can be improved. This method has been tested in various countries (Ebert 1989, Zhao et al. 1991, McCormick et al. 1994, Davis 1995, Kojima 1995, Sweijd et al. 1998, Tegner 2000, De Waal et al. 2003, Heasman et al. 2004). Japan has practiced massive scale reseeding for decades, with about 30 million seed released annually to support the commercial abalone harvest (Masuda & Tsukamoto 1998). Early research in New Zealand produced very mixed results (Tong et al. 1987, Hooker 1988, Schiel 1992, 1993, Osumi 1999).

Past work suggests that seed size, seeding density, and site selection are critical variables determining the success of abalone reseeding (Schiel 1993, Mgaya & Mercer 1995, Marsden & Williams 1996, Sweijd et al. 1998, De Waal & Cook 2001). Saito (1984) found that survival increased with increasing seed size in the range 10–50 mm shell length (SL) and suggested that seed size should be varied according to season. Inoue (1976 cited in Masuda 1998) found greater survival in larger size classes but suggested that seed size could be reduced with improved techniques for transferring abalone from hatcheries to the sea. Many studies have used 20–30 mm seed (Zhao et al. 1991, McCormick et al. 1994) but the high cost of abalone seed in New Zealand demands examination of the economic viability of smaller seed sizes.

Heasman et al. (2004) found that average survival increased 3.3 fold when *Haliotis rubra* seed were released in clusters of 100 rather than clusters of 1,000. They noted that densities of wild abalone reduce to 1–3 $m^{-2}$ for 15–30 mm 1+ year olds. This has practical implications for reseeding, because it means that seed need to be released in very low densities of 1–10 $m^{-2}$. This contrasts with some results from other parts of the world where good results have been obtained with seed released at densities of 66 $m^{-2}$ (Schiel 1993) to 200 $m^{-2}$ (La Touché 1993, cited in Mgaya & Mercer 1995).

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In New Zealand, *Haliotis iris* juveniles are nocturnal and cryptic for ~3 y from about 5–70 mm SL. By day, they are found almost exclusively beneath boulders from low water mark to several meters depth. This habitat makes them very vulnerable to the movement of boulders, or the clogging of under-boulder space during storms (e.g., Hooker 1988, Schiel 1993). Small juvenile *Haliotis iris* graze on attached microalgae and seaweed, whereas adults rely primarily on capture of drifting seaweed. The ability to feed on drifting seaweed opens a niche that reduces competition with the numerous generalist grazers abundant in juvenile habitat (Roberts 2003), and is therefore relevant to questions of seed size, carrying capacity, and seeding density. The size at which drift feeding becomes significant in *Haliotis iris* is unknown, but could be as small as 5 mm (Roberts 2003).

The present study addressed key questions relating to stock enhancement by release of hatchery-reared seed in Marlborough, central New Zealand. The objectives were to assess: (1) economically optimum seed size; (2) effects of seeding density; (3) growth and survival of seeded abalone through to 125 mm; and (4) economic viability of abalone reseeding in this area.

## METHODS

### *Study Area and General Approach*

The study was conducted in Tory Channel and adjacent Cook Strait, Marlborough Sounds, New Zealand (Fig. 1). The Marlborough Sounds provides the majority of the abalone catch for quota management area "PAU7," which covers the northern portion of the South Island (http://www.paua.org.nz/industry_pauamacs.htm). The catch for PAU7 fell from 267 t in the 2001/02 fishing year to 156 t in 2003/04 (including TACC cuts plus a voluntary 15% "shelving"). A portion of the shelved TACC has been released for fishing in the 2004/05 and 2005/06 fishing years in response to catch per unit effort data over the first half of the fishing year.

The approach to experimental enhancement was two-pronged. (1) Short-term experiments to examine the effect of seed size and seeding density (Table 1) were conducted on small constructed boulder reefs (see below). These reefs were designed to facilitate accurate census of all survivors. (2) Experiments to estimate what the survival and growth of abalone would be during commercial reseeding used natural boulder shores and released larger numbers of seed at a commercially realistic density (Table 1).

Sixteen constructed boulder reefs were established in Tory Channel. These consisted of a Gabion basket of plastic-coated wire mesh (2 m × 1 m × 0.5 m, L/W/D; ~8 cm square mesh) placed onto bedrock, sand or gravel, and filled with 2–4 layers of natural boulders. Reef tops were ~0–0.5 m below mean low water level, and the boulders they contained were gathered from a similar depth, complete with their epibiota.

Cook Strait and Tory Channel entrance are exposed to southerly swells, which can reach 12 m in the open Strait during extreme storms. Beyond the influence of Cook Strait, Tory Channel is sheltered from swell but receives waves from ferry wakes many times per day. The natural habitat sites used represented the range of wave-exposure in Tory Channel and Cook Strait (Fig. 1, Sites A to E), but were limited to locations with boulders of a size that could be turned for surveys. Constructed boulder reefs were limited to relatively sheltered sites (Fig. 1, Sites 1–16).

### *Seed Supply and Handling*

Broodstock from the Marlborough Sounds were spawned by the hydrogen peroxide method (Morse et al. 1977), reared initially on diatoms then weaned onto manufactured feed at ~3–5 mm SL and reared at high stocking density of several thousand per m$^2$. Average water temperature at the hatcheries was similar to that in the reseeding areas, and seed grew at ~1.5 mm per month up to the time of seeding. Seed were cooled to about 10°C, transported in polystyrene bins to a Tory Channel

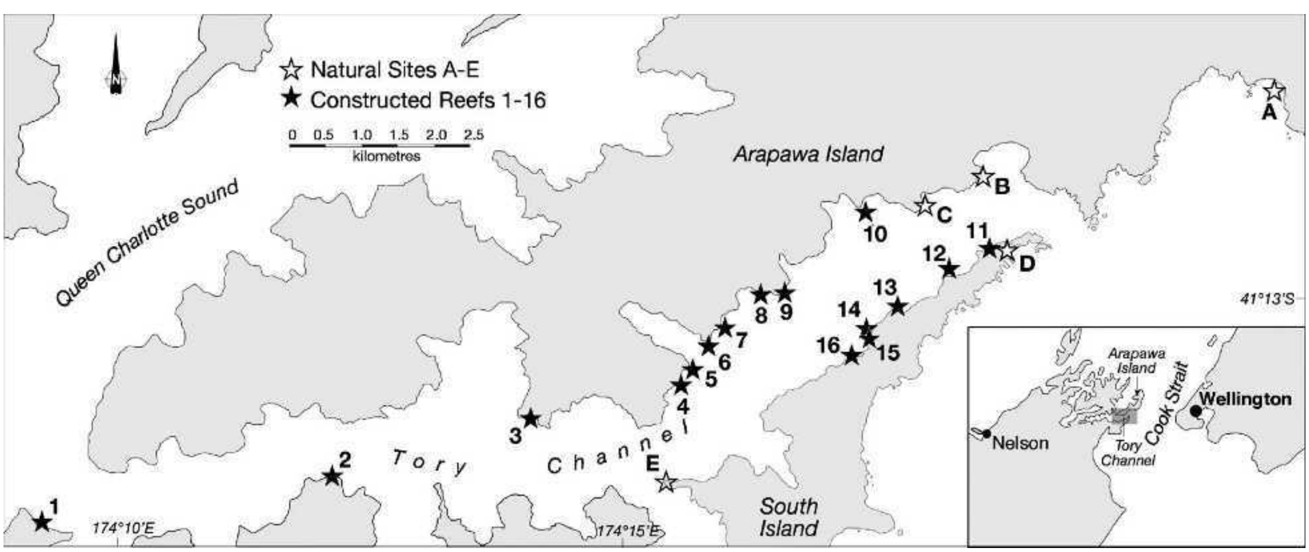


Figure 1. Study sites in Tory Channel and Cook Strait, Marlborough Sounds, New Zealand. Sites 1–16 (black stars) had constructed boulder reefs used for seed size and density trials whereas Sites A to E (white stars) were natural habitat sites used to estimate growth and survival (see Table 1).

**TABLE 1.**

**Details of the abalone growth and survival experiments. Site locations are shown in Figure 1. Seeding density is per square meter of seafloor covered (see Methods).**

| Experiments | Sites Used | Mean Seed Size (mm) | Seeding Density (no. m$^{-2}$) | Release Date | Time at Liberty (months) |
|---|---|---|---|---|---|
| Size class experiments: | | | | | |
| Exp. 1 | 4–7, 11, 14 | 5–20 | 64 | Sept 04 | 3 |
| Exp. 2 | 5, 7, 9, 11, 16 | 5–25 | 64 | Jan 05 | 4.5 |
| Density experiments: | | | | | |
| Exp. 3 | 1–3, 5, 10–13, 15 | 13 | 20–640 | Apr 04 | 3 |
| Exp. 4 | 8, 9, 15, 16 | 17 | 75–600 | Oct 04 | 3 |
| Commercial release experiments: | | | | | |
| Exp. 5A | B, C, E | 10 | 50 | Sept 03 | 20 |
| Exp. 5B | A, D | 11 | 50 | Dec 03 | 17 |

marine farm and placed in temporary holding nets, with shells from adult abalone for attachment and seaweed as food. After several days the abalone seed were transported to study sites on the day of release. Pieces of shell with seed attached were placed amongst boulders by snorkel divers.

Prior to transfer from the hatchery, all abalone seed were fed manufactured feed for a period of months to produce a uniform blue-green shell. This distinctive shell allowed released seed to be distinguished from wild seed in abalone up to 85 mm SL, 20 mo postrelease. It also allowed the size at release to be determined for abalone in Experiments 1 and 2.

#### *Effect of Seed Size and Density on Short-term Survival and Growth*

In Experiments 1 and 2, the survival of 5, 10, 15, 20, and 25 mm SL abalone (range ±2 mm) was compared over 3 months in the austral spring and 4.5 months in the summer/autumn (Table 1). Twenty-five abalone of each size class were transferred to each replicate reef. In Experiment 1, data from two of the six reefs were amalgamated because of an error in the field, and the 25-mm size class was amalgamated with the 20 mm because of a lack of available 25-mm abalone. At the time of survey, divers systematically searched all substrate in the reef for surviving abalone, removed them from the reef, and measured their shell length at the time of release (from shell color change), and at the time of recovery. The percentage surviving in each size class was calculated. Boulder habitat within 5 m of each reef was also searched for released seed.

To evaluate economically optimal seed size we calculated *relative* survival as follows. For each individual reef, the size class with the highest survival was assigned a value of 1. Each other size class received a value representing its survival on that reef as a proportion of the highest. The relative survival data for each size class were then averaged across the 10 replicate reefs from Experiments 1 and 2 combined, except for the 25-mm size class, which was only available in Experiment 2. A curve was fitted to these data using Curve Expert v1.3. A formula for the cost of seed at various sizes was derived from discussions with New Zealand commercial abalone seed suppliers and represents a base cost of NZ$0.25 per seed at 5 mm SL, increasing at $0.0225 per mm SL thereafter. The "relative cost per survivor" for a given seed size is the seed cost divided by the relative survival.

The constructed boulder reefs were also used to examine the effect of seeding density on short-term survival and growth of seed. In Experiment 3, 13-mm SL seed (range 8–18 mm) were placed on 9 constructed boulder reefs at densities ranging from 50–1,281 seed per reef, and surveyed after 3 mo (April to July 2004). In Experiment 4, 17-mm SL seed (range 10–24 mm) were placed on 4 reefs at densities ranging from 150–1,200 seed per reef, and surveyed after 3 months (October 2004 to January 2005). Abalone density is discussed in terms of the area of seafloor covered by the reef (2 m$^2$ per reef), rather than the total surface area of the boulders placed in the reef. The latter would be between 7 m$^2$ (surface area of rectangular prism 2 × 1 × 0.5 m) and 17 m$^2$ (surface area of 20 cm diameter spheres packed perfectly into the reef).

#### *Estimation of Survival and Growth of Commercially Seeded Abalone*

Five natural boulder shores (sites A to E, Fig. 1) were seeded with 2,600–20,000 abalone (Table 2) in September 2003 (9.9 ± 0.11 mm SL, mean ± 95% CI) or December 2003 (11.4 ± 0.12 mm SL) and surveyed after 17–20 mo (Table 1) by which time reseeds had grown to ~50–60 mm SL. We targeted this size for survival surveys because: (1) detection rates are low for small juvenile abalone in complex boulder habitat (e.g., Shepherd 1998); (2) this size is near the end of the vulnerable under-boulder phase during which mortality rates can be high; (3) the blue/green hatchery shell is still visible at this size allowing released seed to be distinguished from wild abalone, and size at release to be measured; (4) published estimates of natural mortality (Sainsbury 1982, McShane & Naylor 1997) allow extrapolation of survival to harvest size. Growth from 60 mm to 125 mm was assumed to take 3 y, based on the growth curve of Poore (1972).

Areas of continuous boulder habitat were chosen to facilitate survival surveys. The density of abalone was held constant at 50 m$^{-2}$ of seafloor surface. Whole areas of boulder habitat were seeded to minimize the effect of abalone movement on stocking density. Hence the number of abalone per site varied according to the area of boulder habitat available.

Survival at the five natural sites A to E was estimated by counting and measuring paua recovered by one of two methods:

#### Random Quadrats

A rectangular area containing the reseeds was delimited with tape measures, and 50–100 points were marked "blindly" according to a map of randomly generated locations. At each

TABLE 2.

**Survival, growth, and experimental details for "commercial" release experiments (Table 1) conducted at the five natural sites. Errors are 95% confidence intervals. Survival at Sites B and E represent minimum survival based on complete searches of these sites. The percent survival to harvest size of 125 mm shell length assumes 9.5% mortality ($M = 0.1$) per year for 3 y after the survival survey.**

| Site | % Survival May 2005 Survey | % Survival to 125 mm | Size at Survey (mm) | Growth Rate mm $yr^{-1}$ | Number Seeded |
|---|---|---|---|---|---|
| A | 1.7 ± 1.3 | 1.3 | 58.7 ± 9.1 | 33.4 ± 6.4 | 20,000 |
| B | 7.3 | 5.4 | 59.7 ± 1.2 | 29.8 ± 0.7 | 6,524 |
| C | 25.1 ± 12.3 | 18.6 | 60.1 ± 1.9 | 30.1 ± 1.1 | 10,016 |
| D | 18.7 ± 9.63 | 13.9 | 46.9 ± 2.4 | 25.0 ± 1.7 | 5,000 |
| E | 16.2 | 12.0 | 51.8 ± 0.8 | 25.1 ± 0.5 | 2,613 |
| Average of all 5 sites | 13.8 | 10.2 | | | |
| Average of best 4 | 16.8 | 12.5 | | | |
| Average of best 3 | 20.0 | 14.8 | | | |

point, divers searched the substrate within a 0.25 $m^{-2}$ quadrat, recording the shell length of all abalone and distinguishing reseeded abalone from wild juveniles. This method was used at Sites A, C, and D (Fig. 1).

**Complete Survey**

An attempt was made to find all reseeds released at a site, by turning over all boulders and searching crevices. This method gives a minimum estimate of survival, as some survivors are not found. Complete surveys were used on all constructed boulder reefs (Sites 1–16) and at natural sites B and E (Fig. 1). The complete survey method was extremely labor intensive, so was only practical at smaller sites.

In general, reseeded abalone were very easy to distinguish from wild abalone by the blue/green color of the hatchery shell, even at shell lengths of 80 mm. Site B was the only exception, where 144 abalone were of uncertain origin because some natural recruits had similar coloring to hatchery seed. Half of the 144 ambiguous abalone were assumed to be reseeds. An additional 401 seed were unambiguous.

***Evaluation of the Economic Viability of Abalone Reseeding***

A simple model was constructed to examine the economic viability of reseeding in Marlborough. The model allowed the user to vary costs, product values, and biological parameters. Values used in the analysis (Table 3) were sourced as follows: growth and survival to 60 mm SL (present study); growth from 60–125 mm SL (Poore 1972); survival from 60–125 mm (Sainsbury 1982, McShane & Naylor 1997); all other values are estimates from industry participants for mid-2005. The model treated reseeding as if it were a stand-alone business proposition. Economic return was compared with an opportunity cost of 10% per annum for money invested prior to harvest. It did not consider altered asset value through changes in TACC or quota value, nor economic flow-on effects of abalone fishing activity.

## RESULTS

***Effect of Seed Size on Short-term Survival and Growth***

Relative seed survival on constructed boulder reefs increased progressively with seed size, but the greatest gain was between 5 and 10 mm SL, with only small improvement in relative survival for larger seed (Fig. 2). The predicted economically optimal seed size was just below 10 mm (Fig. 2). Absolute seed survival over several months at liberty averaged between 21 ± 6% (mean ± 95% CI, 5 mm seed) and 49 ± 13% (20 mm seed).

***Seeding Density Versus Survival and Growth***

Growth and survival of seed tended to decline with increasing seed density in both experiments, but there was wide variation among reefs (Fig. 3) so these trends were not significant (linear regression $P$ values ranged from 0.06–0.36). Good survival and growth were recorded on reefs seeded with up to 600 abalone (300 per $m^{-2}$ of seafloor) reducing to about half that level with mortality over 3 mo (Fig. 3). Survival and

TABLE 3.

**Values (NZ$ in 2005) used in the model to assess the economic viability of abalone reseeding in Marlborough, New Zealand. Information sources are given in the Methods.**

| Category | Item | Value |
|---|---|---|
| Fixed costs: | Regulatory and administration | $6,500 per seeding run |
| Variable costs: | Seed purchase | $0.20 to $0.60 per seed |
| | Seed holding | $0.01 per seed |
| | Seed deployment | $0.03 per seed |
| | Harvest | $10 per kg landed live-weight |
| Product values: | Meat price | $90 per kg of meat |
| | Shell | $8 per kg of shell |
| Biological parameters: | Survival to harvest | 10 or 15% |
| | Meat recovery | 44% of landed live-weight |
| | Shell recovery | 30% of landed live-weight |
| | Time from seeding to harvest | 5 y |
| | Mean weight at harvest | 300 g |
| | Mortality from survey to harvest | 3 y at $M = 0.1$ |

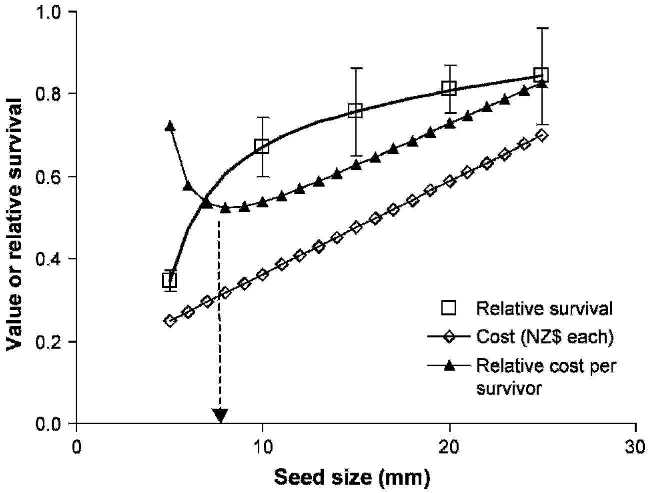


**Figure 2. Estimate of economically optimal abalone seed size (arrow) based on the combination of seed cost and seed survival data. The thick line fitted to the relative survival data is $y = 0.712 + 0.006x - 9.91/x^2$ ($r^2 = 0.9998$) and each plotted point on this curve is the mean (±SE) of 10 reefs from Experiments 1 and 2. See Table 1 for experimental details.**

growth rates were both higher in Experiment 4 (spring/summer) than Experiment 3 (autumn/winter).

Movement of seeded abalone off constructed boulder reefs appeared to be low, with the number of survivors found within 5 m beyond reefs averaging only 4.8% of the number of survivors found on reefs. The number of emigrants did not relate to seeding density. Wild abalone and potential predators moved onto the constructed boulder reefs, implying that they offered suitable habitat.

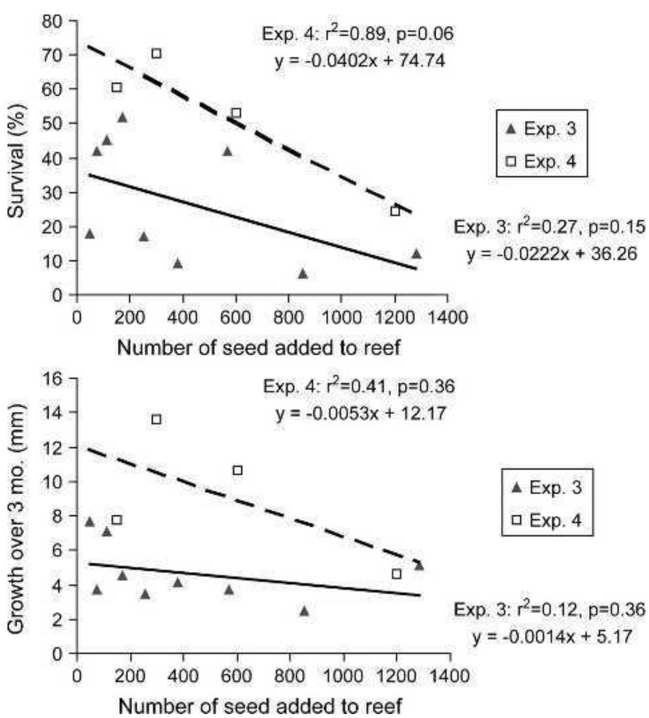


**Figure 3. Survival (top) and growth increment (bottom) versus seeding density for abalone released onto constructed boulder reefs after 3 mo at liberty in autumn/winter (Experiment 3) and spring/summer (Experiment 4). See Table 1 for experimental details.**

### *Survival and Growth of Seeded Abalone Through to 125 mm*

Survival and growth of abalone released at the five natural sites seeded at commercial scale is shown in Table 2. Survival to harvest ranged from 1.3% to 18.6%. The worst survival was at Site A, which was very exposed to southerly swell. Two extreme storms occurred 1–2 mo after seeding in January and February 2004, generating peak southerly swell heights of 10 and 12 m in open Cook Strait waters. The boulder seabed at Site A was massively disturbed by these storms (D. Baker, pers. comm.). Site B also yielded low survival. At the time of the survival survey, it was noted that some of the under-boulder space present at the time of seeding had become clogged with sand and gravel. Gravel from slips clogged small stretches of boulder habitat at Site C, but some excellent habitat remained, and survival and growth were good (Table 2). Site D appeared to avoid significant storm damage because of protection by headlands, and gave very good survival. Survival was relatively good at Site E, which was sheltered from southerly swell but subject to frequent wash from ferry traffic, as were sites B and C.

Surviving seed were concentrated on boulders with large spaces beneath them, usually around low tide mark at Sites B, C, D, and E. Far fewer seed remained in the deeper part of the area over which they were released at these sites. Lateral movement of seed was limited to <30 m from the boundaries of the seeded area, despite continuous rocky shoreline.

Average growth rate (which included two summers in the 17–20 mo period) ranged from 25–33 mm year$^{-1}$ across the five sites (Table 2). Average growth rate was slowest at Sites D and E where there was a high density of recruits on very shallow rocks that lacked significant seaweed growth.

### *Economic Viability of Abalone Reseeding*

Predicted economic returns from reseeding for various combinations of seed price and seed survival are set out in Table 4. A seed size of 10 mm is assumed based on Figure 2. Seed prices of (1) NZ$0.40, (2) $0.32, (3) $0.20, and (4) $0.60 represent: (1) current seed price for 10 mm SL abalone; (2) current price possible for large and long-term seed supply contracts; (3) a possible future seed price if large abalone hatcheries become established in New Zealand; and (4) a possible future seed price if costs rose substantially, rather than falling as expected. Survival rates of 10, 12.5, and 15% represent the average survival to harvest from: (1) all five natural sites; (2) the best four natural sites; (3) the best three natural sites, respectively (Table 2). These scenarios are relevant because commercial reseeding would not need to select sites with small boulders suitable for scientific surveys, so one would hope to avoid storm-prone sites such Site A and B of the present study. Economic returns over the 5 years from release to harvest varied 7% to 41% per annum for the scenarios examined, with most returns comparing favorably with the opportunity cost of ~10% per annum. Seed purchase price, seed survival and meat sale price were major determinants of economic returns. Meat recovery and weight at harvest had a direct influence on profitability but are less likely to vary widely. Shell sales accounted for only ~10% of income, so had a small influence on profitability.

**TABLE 4.**

**Estimated economic returns from reseeding in Tory Channel or Cook Strait, Marlborough. Results are based on parameter values in Table 3. The interest per annum (p.a.) represents the return on investment as a compounding interest rate. Opportunity cost is ~10% p.a.**

| Seed Cost (NZ$) | Survival to Harvest | Return on Investment | "Interest" p.a. |
|---|---|---|---|
| 0.60 | 10% | 41% | 7% |
| 0.60 | 12.5% | 76% | 12% |
| 0.60 | 15% | 111% | 16% |
| 0.40 | 10% | 103% | 15% |
| 0.40 | 12.5% | 154% | 21% |
| 0.40 | 15% | 205% | 25% |
| 0.32 | 10% | 148% | 20% |
| 0.32 | 12.5% | 209% | 25% |
| 0.32 | 15% | 271% | 30% |
| 0.20 | 10% | 267% | 30% |
| 0.20 | 12.5% | 359% | 36% |
| 0.20 | 15% | 450% | 41% |

## DISCUSSION

Abalone reseeding in the study area appears to be economically viable, with returns higher than the opportunity cost of ~10% per annum for most of the scenarios examined. The model applies to geographic areas that have rapid growth to harvest size over five years. Many other locations in Marlborough and elsewhere in New Zealand have slower growth and will need to account for increased opportunity cost and cumulative mortality over the longer period until return on investment.

Survival was strongly site dependent at the five natural sites studied. An understanding of the factors that dictate this variability among sites will be critical to optimizing economic returns. In the present study, the two natural sites with the lowest survival were affected by substrate movement during storms, highlighting the risk of sites in storm-exposed locations with boulders small enough to be turned for surveys. Most of the Cook Strait coastline of Marlborough contains much larger boulders, which are less prone to storm damage, but also impossible to move for quantitative surveys.

Larger seed showed higher survival as expected (Zhao et al. 1991, Masuda & Tsukamoto 1998) but the increased cost of larger seed more than offset the higher survival for seed >10 mm SL. The predicted optimal seed size of ~10 mm is smaller than used in many previous experiments and Japanese commercial reseeding (reviewed by McCormick et al. 1994, Roberts 2003) but consistent with some of Schiel's (1993) results and with Heasman et al.'s (2004) conclusion that 5–15 mm seed are most cost-effective. If excess abalone seed production capacity develops in New Zealand, as it has in some other abalone farming countries, larger seed may become more financially attractive.

The relationship between seed density and seed survival and growth showed negative trends but these were clouded by the high degree of variation among reefs. Some poor results on constructed reefs were associated with the use of soft boulders, clogging of boulders by gravel, or lack of seaweed growth. In other cases the variation was unexplained and may relate to transient predators. For example, conger eels *Conger verreauxi* Kaup 1856 were occasionally found sheltering in reefs during surveys (Keys 2005).

The density experiments demonstrated that good seed growth and survival could be obtained at relatively high densities of up to 300 seed $m^{-2}$ of boulder reef. This contrasts with *Haliotis rubra* in New South Wales, where carrying capacity of coralline habitat limits the density of recruits to 1–3 $m^{-2}$ at 15–30 mm SL, and where the recommended seeding density for 5–15 mm seed is 1–10 $m^{-2}$ (Heasman et al. 2004). The high densities tolerated by *Haliotis iris* support the contention of an early transition to drift feeding (Roberts 2003) but may also relate to differences in seaweed availability or foraging behavior.

Ideal natural habitat can contain ~50 $m^{-2}$ *Haliotis iris* juveniles at 40–100 mm SL (Schiel 1993, R. Roberts unpubl.) and similar concentrations of 40–80 mm released abalone were found in the present study. This represents a grazing biomass many times higher than we placed on our constructed boulder reefs. These concentrations of large *Haliotis iris* juveniles generally occur around low tide mark on rocks without substantial seaweed growth. In such cases, drift seaweed is likely the predominant food supply although foraging to access deeper seaweeds is also possible. We noted some reduction in growth rate of abalone at high densities on both constructed boulder reefs (Fig. 3) and where abalone became highly aggregated in natural habitats (Table 2, Sites D and E).

The predominant factor explaining the observed aggregation of large juveniles (40–80 mm SL) appeared to be the availability of dark spaces sufficiently large to accommodate abalone of this size. Such space is more common around the low tide mark than in deeper water where sand, gravel, and fouling organisms often limit under-boulder space. The availability of under-boulder space for large juveniles is potentially a limiting resource for *Haliotis iris* and should be considered as a secondary factor in site selection for reseeding. It is, however, not an absolute requirement—large juveniles will occupy the flanks of boulders if under-boulder space becomes unavailable.

The logistics of producing significant tonnages from abalone reseeding deserve consideration. If 12.5% of released seed survive to a harvest weight of 300 g, then ~267,000 seed need to be released to yield 10 tons of abalone at harvest. At a seeding density of 50 seed per $m^2$ per year, this requires 5,340 $m^2$ of seafloor to be seeded. In much of Marlborough, ideal reseeding habitat is limited to a strip only ~2 m wide. In such areas each 10 tons of harvest requires seed to be spread along about 2.7 km of coastline. The length of Marlborough Sounds coastline that appears suitable for reseeding is in the order of 20–60 km. Based on figures mentioned earlier, this provides adequate habitat to produce between 70 and 220 tons of abalone per year, which is significant in terms of the commercial abalone catch in Marlborough (180 tons in PAU7 in 2005–2006) and New Zealand (~1,050 tons).

Whereas large scale reseeding appears spatially possible, the issue of carrying capacity is unresolved. Natural recruitment of *Haliotis iris* remains strong in many areas of Marlborough and reseeding would be futile if released abalone simply displaced natural recruits because of limited carrying capacity. To avoid strong density-dependent effects, seed should be released at a size above that at which the key density-dependent bottlenecks occur

(Hilborn 1998). The bottlenecks determining population size are poorly understood for abalone. Roberts (2003) suggests that competition for food in the early juvenile phase may be a critical bottleneck for abalone. The ability to catch drift algae develops at 5–10 mm SL in some abalone species, easing the abalone's competition with surface-grazing invertebrates (Roberts 2003). The growth rates documented in the present study were good, suggesting that competition for food is unlikely to have strongly affected survival of seed, or displaced natural recruits.

Our economic projections assume that surviving seed supplement the existing abalone population rather than displacing natural recruits, but net population increase was not quantified. The ultimate test of reseeding success will be to enhance several stretches of coastline, and compare their yield before and after enhancement with that of several control areas. Those data can then contribute to a comparison of the cost-benefit ratio of the range of measures that are being investigated for abalone management (e.g., http://www.paua.org.nz/fisheriesmgmttools.htm). Release of hatchery reared seed should not be seen as a replacement for good fishery management but as part of a suite of potential management tools.

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