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# Evaluating the Effects of Three Forms of Marine Reserve on Northern Abalone Populations in British Columbia, Canada

S. SCOTT WALLACE

Resource Management and Environmental Studies, University of British Columbia, 436E-2206 East Mall, Vancouver, British Columbia V6T 1Z3, Canada, email [sscott@interchange.ubc.ca](mailto:sscott@interchange.ubc.ca)

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**Abstract:** *Marine reserves have been suggested as tools for assisting the management of fisheries by protecting vulnerable marine species from overexploitation. Although there is a theoretical basis for believing that marine reserves may serve as management tools, there are few marine reserves in the world in which to test their effectiveness. My research evaluated three forms of marine reserve on the south coast of Vancouver Island, British Columbia, Canada. I used northern abalone (*Haliotis kamtschatkana*), a severely depleted shellfish in this region, as an indicator of the effectiveness of the reserves. Abalone populations in eight sites receiving different degrees of spatial protection were counted and measured in situ during the spring of 1996 and 1997. In all sites with enforced harvest closures, populations of abalone were greater, and one site with nearly 40 years of protection had on average much larger (older) abalone. Reproductive output, as a function of abundance and size, was also greater in the enforced reserve areas. Larval dispersal from reserves, and hence the benefit to exploited areas, was not formally surveyed. Nevertheless, the results of my study, combined with knowledge of present abalone populations, life history, and regional hydrodynamics, suggest that establishment of reserves is justified in the absence of perfect knowledge of larval dispersal.*

Evaluación del Efecto de Tres Tipos de Reservas Marinas sobre Poblaciones de Abulón del Norte en Columbia Británica, Canadá

**Resumen:** *Se ha sugerido que las reservas marinas son un instrumento para el manejo de pesquerías al proteger de la sobrexplotación a especies marinas vulnerables. Aunque existen bases teóricas para aceptar que las reservas marinas tiene futuro como instrumentos de manejo, existen pocas reservas marinas en el mundo para probar su efectividad. Mi investigación evaluó tres tipos de reserva marina en la costa sur de la Isla Vancouver, Columbia Británica, Canadá. Utilicé el Abulón del Norte (*Haliotis kamtschatkana*), un molusco severamente disminuido, como indicador de la efectividad de las reservas. Las poblaciones de abulón en ocho sitios con diferentes niveles de protección espacial fueron cuantificadas y medidas in situ durante las primaveras de 1996 y 1997. Las poblaciones de abulón fueron mayores en todos los sitios con capturas controladas; un sitio protegido por casi 40 años, en promedio tuvo abulones más grandes (viejos). La reproducción, como una función de la abundancia y la talla, también fue mayor en las áreas protegidas con vigilancia. La dispersión de larvas de las reservas, y por tanto su beneficio para las áreas de explotación, no fue explorada formalmente. Sin embargo, los resultados de este estudio combinados con el conocimiento de las poblaciones actuales de abulón, de sus tablas de vida y de la hidrodinámica regional sugieren que el establecimiento de reservas es justificado ante el desconocimiento de la dispersión de larvas.*

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*Paper submitted March 12, 1998; revised manuscript accepted November 4, 1998.*

## Introduction

The effects of human exploitation of marine ecosystems have reached a crisis level (Roberts 1997a; Pauly et al. 1998). Consequently, managers are searching for alternative ways of managing fisheries and the ecosystems in which they are embedded (Botsford et al. 1997). The concept of "no-take" marine reserves has been gaining popularity as a tool with which to manage fisheries (Schmidt 1997). It has been argued that any successful, long-term fishery is a result of the target species having some form of spatial protection during vulnerable stages of its life cycle (Walters 1996). Typically, spatial protection from human exploitation is unintentional, resulting from natural physical barriers such as depth, currents, and substrate that fishing technologies have been unable to access. Marine reserves, which completely or partially remove human harvest, have only recently been considered as an intentional method of spatial protection to assist in managing habitats and species (Agardy 1997; Allison et al. 1998).

To date, all marine reserves around the world have been established in areas after a history of fisheries exploitation. In these areas, a number of ecosystem changes have occurred, the most obvious and easiest to measure being changes in the abundance and size of target species (Roberts & Polunin 1991; Dugan & Davis 1993; Rowley 1994). One expected benefit is the increase in spawning potential in reserves which, through passive and active out-migration, would replenish nearby exploited areas. This effect would be particularly beneficial for species with broadcast spawning behaviors and small home ranges. Unfortunately, only a few studies have been conducted to evaluate the efficacy of marine reserves for these types of species (Castilla & Durán 1985; Moreno et al. 1986). These studies have indicated, however, that the cessation of human harvest results in dramatic changes in the size and abundance of target species and subsequent changes in the ecological community.

I attempted to evaluate three forms of spatial closure on northern abalone (*Haliotis kamtschatkana* Jonas 1845) in British Columbia, Canada. Many abalone populations throughout the world, including the population I studied, have been harvested to the point of commercial extinction. In the case of the California white abalone (*Haliotis sorensenti*), biological extinction may have already occurred (Davis et al. 1996). Previous work suggests that marine reserves could assist in the recovery and management of abalone populations (Tegner et al. 1992; Tegner 1993).

My research was designed to evaluate three forms of abalone reserve: (1) an unintentional harvest closure resulting from access restrictions enforced by a prison situated on the coast; (2) a provincially managed marine ecological reserve closed to all invertebrate harvest since

1980 and enforced by a full-time lighthouse keeper; and (3) the coast-wide closure of all abalone harvesting since 1990, which on paper makes all British Columbian waters an abalone reserve. Hereafter, these reserves will be referred to as the prison reserve, ecological reserve, and coast-wide reserve, respectively.

A noteworthy characteristic of the prison reserve is that it has been in effect since 1958 when the prison was founded. There has never been a study of an existing marine reserve throughout the period in which over-exploitation of a fishery was occurring. All previous marine reserve studies have taken place in marine equivalents of "forest clearcuts" in which the "succession" was monitored. This form of long-term closure allows the sustainability of the reserve to be evaluated in the context of source-sink relationships.

My objectives were to (1) compare abalone size and abundance among the three forms of reserve and (2) estimate the potential reproductive outputs of abalone in reserve and exploited areas.

## Methods

I conducted abalone surveys in March of 1996 and February of 1997 in the Juan de Fuca Strait off Southern Vancouver Island (Fig. 1). The prison reserve and ecological reserve were compared to six sites in the coast-wide reserve, for a total of eight study areas. Sites used in previous government stock assessment surveys were used for selecting the six sites in the coast-wide reserve. Government survey sites were in turn based on fishermen's logbooks to ensure that survey sites were suitable abalone habitat (Adkins 1996). The coast-wide sites have been heavily harvested by both legal and illegal fisheries. All sites were of sloping bedrock at 3–7 m, with algal coverage dominated by the kelps *Nereocystis luetkeana* and *Laminaria* spp.

All observations and measurements were done in situ by scuba divers. Using calipers, divers measured shell lengths ( $L$ ) to the nearest 0.2 cm and recorded them for all exposed abalone. Data from both years were pooled, and a test of homogeneity of variance, followed by a one-way analysis of variance (ANOVA), was applied to test for significant size differences between all sites. Subsequently, a Bonferroni multiple-range test was used to test for significance between specific sites. In addition, government-conducted size surveys in the study region from 1982, 1985, and 1986 were combined and included in the analysis to provide an alternative data source. These data are from studies designed to determine the average size of exposed abalone (Adkins 1996). Based on a method developed by McShane (1994, 1995), I estimated relative densities with an index of abalone per minute diving (APMD).

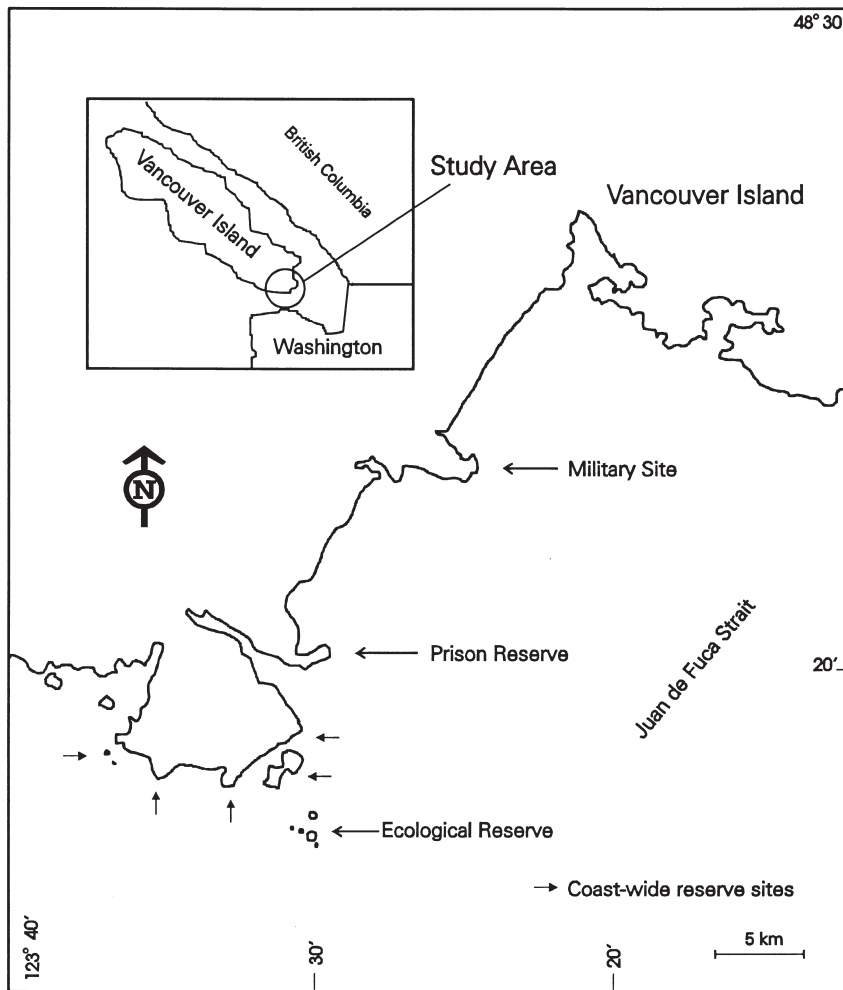


Figure 1. Northern abalone survey sites along the southern coast of Vancouver Island.

Potential reproductive output of the sites was estimated by first converting length ( $L$ ) to whole weight ( $W$ ) in grams:  $W = 0.0001 \times L^{3.034}$  (Breen & Adkins 1982). Fecundity ( $f$ ) was then estimated by using Breen's (1986) egg-per-recruit model fitted for northern abalone:  $f = 0.0065W - 0.098$ , where  $f$  is fecundity in millions of eggs. Relative reproductive output was calculated by multiplying the APMD in each site by the mean fecundity of abalone in each study site.

## Results

The abundance of abalone in the study sites varied, as indicated by the APMD (Table 1). Five of the six coast-wide reserve sites surveyed had insufficient abalone to provide the necessary sample size ( $n = 30$ ) for statistical comparisons. This in itself is significant. One exploited site had sufficient abalone, however, and in fact it had higher densities than the two reserve areas (Table 1).

Table 1. Comparison of abalone abundance and size based on data from three forms of marine reserve and a historical government study.

| Location              | Number of abalone (n) | Effort (min.) | APMD <sup>a</sup> (n/min.) | Average size/range (mm)     | >130 mm (%) |
|-----------------------|-----------------------|---------------|----------------------------|-----------------------------|-------------|
| Prison reserve        | 211                   | 275           | 0.77                       | 115.6 (62-154) <sup>b</sup> | 26.5        |
| Ecological reserve    | 241                   | 345           | 0.70                       | 99.7 (40-148)               | 8.8         |
| Military site         | 163                   | 134           | 1.22                       | 100.4 (40-152)              | 6.1         |
| Government data       | 298                   | na            | —                          | 98.1 (50-142)               | 3.4         |
| Five coast-wide sites | 9                     | 173           | 0.05                       | 109.4 (72-127) <sup>c</sup> | 0           |

<sup>a</sup>Abalone per minute diving.

<sup>b</sup>Significant Bonferroni test,  $p < 0.01$ .

<sup>c</sup>Not used in statistical analysis because only sites with 30 or more abalone were considered.

For this reason I treated this site as an experimental unit separate from the coast-wide closure sites. This site is located on military land, and I refer to it as the military site.

Because abundances were too low in most coast-wide reserve sites to conduct statistical comparisons, size comparisons were made only among the prison reserve, the ecological reserve, the military site, and government data. Abalone sizes differed significantly among the four sources (ANOVA,  $p < 0.01$ ), with the prison reserve abalone significantly larger (16 mm) on average than those at the other three sites (Bonferroni test,  $p < 0.01$ ; Table 1).

Relative frequency distributions of shell length indicated differences in size structure at the sites (Fig. 2). The abalone population at the prison site had a large proportion of abalone  $>130$  mm (Table 1), whereas the proportion of abalone  $<100$  mm in the prison reserve was lower than in the other three study sites (Fig. 2).

The prison reserve showed the highest reproductive output per abalone simply as a function of average size (Table 2). When relative abundance (APMD, Table 1) was factored into the fecundity equation, however, the military site was the most productive.

## Discussion

In 1990, due to low stock abundance, all abalone harvesting was closed in British Columbia, making the entire coast an abalone reserve. My research evaluated the effects of three types of reserves: a coast-wide closure, an unintentional long-term closure, and an intentional ecological reserve.

The high black-market value of abalone (up to CDN \$100/kg) encourages a considerable illegal harvest in British Columbia. In the study region alone, more than

20 poaching convictions have been made since 1990, demonstrating that the coast-wide reserve is being violated (Adkins 1996). My results indicate that only closed areas that completely restrict harvest result in significant changes to local abalone populations.

The most noteworthy result in this study was the low abundance of abalone in five of the six coast-wide reserve sites. With the exception of the military site, the abundance of abalone in the coast-wide reserve areas was too low for statistical comparisons. Prior to my study, the military site was considered a representative coast-wide closure site, but it now appears that this site may also receive unintentional protection from illegal harvest. This site is adjacent to land owned by the Department of National Defence, there is a light station on the adjacent land which is occasionally occupied, and during most days there is military presence on the land. Also, according to nautical charts, the waters around the military site are restricted-access. Because there are no obvious biophysical differences between sites (sea otters, disease, substrate type), and given the current levels of indiscriminate illegal harvest, it is highly unlikely that the abalone populations in the military site can be attributed to anything other than unintentional protection. If this is true, it provides a strong case for the role of reserves in reestablishing populations, given adequate enforcement.

I intended to measure a minimum of 30 abalone at each study site in order to use size (age) as an indicator of harvest pressure. Only the three areas receiving some form of additional protection had sufficient abalone to allow this measurement. The prison reserve, perhaps as a function of a 39-year closure, had significantly larger abalone than the other two sites.

Northern abalone growth rates depend on water temperature and availability of food types (Paul et al. 1977). Temperature is the same throughout the study area

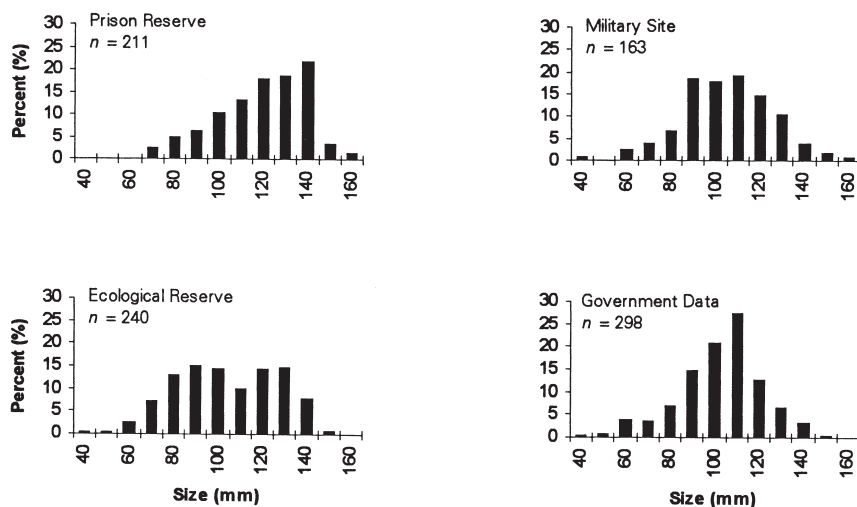


Figure 2. Frequency distributions of abalone in survey sites and government data representing percentage of abalone in each size class.

**Table 2.** Relative fecundity of abalone in study sites based on abalone per minute diving (APMD) and mean fecundity.

| Location              | Mean fecundity ( $10^6$ eggs/abalone) | Relative fecundity (APMD $\times$ mean fecundity) |
|-----------------------|---------------------------------------|---|
| Prison reserve        | 1.19                                  | 0.91  |
| Ecological reserve    | 0.78                                  | 0.55  |
| Military site         | 0.77                                  | 0.94  |
| Five coast-wide sites | 0.90                                  | 0.05  |

(Thomson 1981). Food availability is a function of dominant macro-algal type. All areas selected were covered by similar macro-algae, *Nereocystis luetkeana* and *Laminaria* spp., which eliminates dominant food type as a variable. Breen (1980) showed that abalone inhabiting substrates dominated by *Pterygophora californica* had the slowest growth rates, whereas *Macrocystis integrifolia* had the fastest and *N. luetkeana* was in between. Algal coverage was surveyed in previous government studies and was reexamined in this study to ensure that the areas had not changed. Variables affecting abalone growth rates are unlikely to be a factor contributing to the significant differences observed between sites.

Over one-quarter (26.5%) of the abalone at the prison reserve were larger than 130 mm. On a conservative growth curve, abalone that are 130 mm in length are on average over 30 years old (Breen 1980). The large size of abalone at the prison reserve appears to be a function of restricted harvest over a long period (39 years), whereas the military site (8 years) and ecological reserve (18 years), having been closed for shorter periods, had smaller abalone on average.

It is widely accepted that size and abundance of target species increases in reserve areas (Roberts & Polunin 1991; Rowley 1994). The question concerning most fisheries managers is the ability of reserves to export larvae while sustaining the internal population (Roberts 1997b). Fecundity as simply a function of body size and abundance was shown to be greater in the enforced reserve areas than in the coast-wide sites (Table 2). I did not conduct surveys to assess the fate of exported larvae, nor did I specifically look for recruitment into the sites, but I did find differences in age-frequency distributions between the study sites (Fig. 2). For example, only 32% of the prison-reserve abalone population was <100 mm, whereas in the ecological reserve and military site 57% and 53% of the respective populations were new recruits. A number of combined factors potentially contribute to patterns of abalone recruitment, settlement, and survival (McShane 1992), including regional hydrodynamics (McShane & Smith 1991), stock size (Prince et al. 1988), coastal topography (Shepherd et al. 1992), and substrate composition (McShane & Smith 1988). Teasing out the physical processes responsible for recruitment patterns between source and sink populations was beyond the scope of my study, and, as Roberts (1998) re-

cently argued, perhaps should not be an immediate goal for marine reserve science.

In British Columbia, approximately 0.01% of coastal habitat is formally designated as no-take marine reserve. The most important scientific information that can be contributed at the moment is evidence that areas closed to human harvest show ecological changes attributable to this exclusion. In terrestrial conservation, refuges were initially established to decrease human-caused mortality to vulnerable hunted animals. If terrestrial conservation were to have been primarily concerned about the fate of seeds from trees in refuges, there would perhaps be fewer terrestrial protected areas. Justification of marine reserves exists without knowledge of the precise extent of larval dispersal outside the boundaries.

In the region of my study, for example, abalone were once found in greater abundance (Breen 1986). Results from my research indicate that areas that receive protection support larger and more abundant abalone. Abalone are known to be broadcast aggregate spawners requiring high densities to ensure fertilization (Clavier 1992). The study region is influenced by strong tidal currents with daily maximum ebb and flood currents of 1.8 m/second and 1.5 m/second, respectively, indicating that the larvae will be transported away from their natal site, potentially replenishing depleted areas (Thomson 1981). From a practical management perspective, there is enough information available to warrant implementation of marine reserves.

Justifying marine reserves on a species-by-species basis does provide needed evidence at a regional level, but spatially managing single species has limitations comparable to other forms of single-species management. Ecosystem benefits thought to emerge with the creation of marine reserves will be considerably more difficult to evaluate with quantitative studies. Designing reserves to account for scientific uncertainty while including ecosystem dynamics may be best accomplished according to scientific principles of biogeographic representation, replication, and network design (Ballantine 1997). These principles should underlie the science of marine reserves. Regional case studies such as the one I describe here are useful to decision-making institutions because they provide evidence in support of the fundamental objectives of marine reserves. In political jurisdictions with no reserves, unintentional closures resulting from either

natural or human-created barriers provide an alternative method of evaluating the potential of marine reserves.

## Acknowledgments

This project was supported by the Mountain Equipment Co-op environment fund, British Columbia, Canada. I thank D. Lacroix, who provided many hours of volunteer field assistance. This project would not have been possible without the field support of boats and diving equipment from Lester B. Pearson College of the Pacific, Victoria, Canada. Special thanks to Jane Watson who provided the idea.

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