Dramatic declines in red abalone populations after opening a "*de facto*" marine reserve to fishing: Testing temporal reserves

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ARTICLE INFO

ABSTRACT

Red abalone (*Haliotis rufescens*) were assessed inside and outside a "*de facto*" reserve before fishing, after 3 and then 6 years of fishing. In just 3 years, there was a 65% decline ($p < 0.001$) in the subtidal and a 78% decline ($p < 0.001$) in the intertidal abalone populations. Size frequency distributions differed significantly following fishing and there was a sharp decrease in the potential egg production (>72% decline). Before fishing began, the intertidal density at the reserve was 86% greater ($p = 0.001$) than at a nearby fished site, however after 3 years of fishing there was no difference ($p = 0.764$). Abalone fishing report cards revealed a 950% increase in local catch once the reserve site was opened, however after just 1.5 years of fishing, catch declined sharply (59%) compared to the previous year. In 3 years, mean abalone catch per hour declined significantly ($p < 0.001$) from 7.01 (SD 6.14) to 2.44 (SD 1.98) as did abalone catch/picker from 2.83 (SD 0.47) to 2.38 (SD 0.92, $p < 0.01$). Estimates of illegal take inside the former reserve were 2.5 times greater than the legal catch. We demonstrate that for areas with high value, slow growing species such as red abalone, temporarily opening reserves may lead to density, size structure and egg production similar to heavily fished areas in just 3 years. These results caution against the use of temporal (rotating) reserves for abalone and emphasize the importance of marine spatial planning.

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1. Introduction

Opening protected areas, formerly private property, may have the unintended consequence of increasing fishing pressure on resources inside these "*de facto*" reserves. The population consequences of fishing newly opened or military areas is poorly understood, since baseline population data are frequently lacking. Opening reserves to fishing allows for a natural experiment to test the consequences of temporary or rotating reserves. Opening reserves temporarily has been proposed for a number of species and locations, however this strategy needs critical evaluation. Little work has been done to quantify how much time is needed between area rotations for species with different life history traits.

Establishing marine reserves has been shown to increase the abundance, size and biomass of populations as well as species diversity (Wallace, 1999; Gell and Roberts, 2003; Halpern, 2003) and the impacts may be long lasting (Halpern and Warner, 2002). Clearly, the life history characteristics of the species in the reserves will have a bearing on the speed of the response to protection as will the intensity of fishing pressure. In the Georges Bank fishery closure, cod fish responded slowly to protection while scallops which are fast growing responded quickly (Murawski et al., 2000).

Life history characteristics such as growth and recruitment rates influence the way populations respond to fishing or reserve status. Recovery rates of biomass inside reserves for example, are variable with some rates tripling after 5 years of no fishing (Roberts, 1995) while others such as tiger grouper (Roberts et al., 2001) and white abalone (Hobday and Tegner, 2001; Butler et al., 2006; Stierhoff et al., 2012), not recovering after 10 years of closure. In one case, limited fishing (1.5 years) eliminated the gains in density acquired over 9 years of protection for large predatory fish in the Philippines (Russ and Alcala, 1996). How successful a species is at recruiting is crucial to subsequent recovery. Animals with slow growth, poor dispersal or reproductive failure at low densities (Allee effects) will recover more slowly (Stoner and Ray-Culp, 2000) than those with fast growth, and regular recruitment rates.

Red abalone (*Haliotis rufescens*) populations in northern California are the basis for an active recreational-only fishery landing an estimated 264,000 abalone (500 mt) per year (Kalvass and Geibel, 2006). The fishery is heavily managed including a prohibition of Scuba gear restricting effort to shallow water (<9 m), daily (3 per day) and yearly bag limits (24 per year), season closures, and a minimum legal size (178 mm). In addition, a network of Marine Protected Areas (MPAs) has been implemented in northern

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California within the range of the red abalone fishery in shallow water (Gleason et al., 2010). Abalone populations are known to be susceptible to localized depletion (Karpov et al., 2000), which could negatively impact the sustainability of the fishery as a whole especially when combined with unknown levels of illegal fishing (Daniels and Floren, 1998). Abalone are now closed to both recreational and commercial fishing in southern California where populations are now less than 5% of baselines estimated during the peak of the fishery (Rogers-Bennett et al., 2002a).

In southern California, several large tracks of formerly restricted areas have now been opened including the Hearst Castle (San Simeon, San Luis Obispo County, CA) and the Vandenberg Air Force Base yet few studies exist on impacts to local marine resources. In Puerto Rico, the US Navy opened Vieques Island in 2003 resulting in an increase in Queen conch (*Strombus gigas*) fishing and a decrease in conch populations (Bauer et al., 2008). The challenge for marine conservation will be to manage resources in areas newly opened to the public and determine which resources are highly vulnerable to fishing and which can sustain fishing.

In this paper, we examine the impacts of fishing on red abalone populations inside a former *de facto* reserve (Stornetta Ranch) which was acquired by the Stornetta family in 1917, opened to the public in 2004 and then re-established as a MPA in 2010. Specifically, we examine the resilience of abalone populations inside the reserve to fishing and whether it is possible to detect the impacts of fishing on density, size of fished abalone, recruitment to the fishery, egg production and catch-per-unit-effort (CPUE). We estimate the density, size frequency distribution and egg production in both intertidal and subtidal habitats before, after 3 years and then 6 years later when the site is re-established as an MPA. We collect data from creel surveys (fisher interviews), abalone fishing report cards and telephone surveys of recreational fishers asking about catch, size, fishing effort and incidental mortality. From these fishery data we estimate legal and illegal fishing after the opening of the reserve. We compare what we find inside the former reserve to a neighboring fished site. Finally, we discuss the vulnerability of red abalone populations to fishing in northern California and evaluate the effectiveness of temporal closures for abalone populations.

1.1. Fishing history of reserve and fished site

The Stornetta family has been stewards of the marine resources along their coastal property (38°N, 123°W) since 1917. These resources included red abalone which they managed by restricting public access in addition to following California Department of Fish and Game (CDFG) abalone fishing regulations. Within the portion of the ranch bordering the coastline at Sea Lion Rocks south and east of the Point Arena Lighthouse, the family closely supervised abalone fishing in the intertidal and prohibited diving. Prior to 1991, the family allowed fishing 4–5 days a month during the open season (7 months) when approximately 10–30 invited guests fished for abalone during the low tides only in the intertidal (shore picking). After 1991, access was restricted to 2 days a month during the low tides in April, May, and June and for 1, 2-day fishing period from August through November. Use of weight belts and diving in the subtidal were never allowed (Stornetta family, personal communication).

The ranch was purchased in 2004 by a public-private consortium including the Wildlife Conservation Board, Coastal Conservancy, U.S. Fish and Wildlife, and The Nature Conservancy for approximately $7.7 million dollars and was entrusted to the Bureau of Land Management for oversight. Stornetta Ranch was opened to public access in July 2004 and to abalone fishing in August 2004. In May of 2010, the Stornetta Ranch was incorporated into the newly established Sea Lion Cove State Marine Conservation Area (SMCA) in which the take of marine invertebrates including red abalone is prohibited.

Moat Creek (38°N, 123°W) is a popular abalone fishing site south of Stornetta Ranch, with a similar expansive intertidal bench. Due to the ease of access, this site is visited by hundreds of recreational abalone divers and shore pickers throughout the 7 month abalone season and particularly during spring low tides in April, May and June.

2. Methods

We conducted a multifaceted abalone population assessment of the "*de facto*" reserve at Stornetta Ranch (Fig. 1) prior to the opening of the ranch in the spring of 2004, in 2007 and again in 2010.

Fig. 1. Location of Stornetta Ranch abalone fishing site on California map. The insert photo displays the extent of the subtidal area (light shaded region), and the intertidal area (dark shaded region). The areas of these regions were estimated to be 14,551 m^2 and 119,876 m^2, respectively, using ArcView GIS software.

The survey components focused on red abalone and consisted of separate subtidal, intertidal and creel surveys. Intertidal surveys of red abalone at Moat Creek, a nearby fished site were also conducted.

2.1. Subtidal and intertidal surveys

In the spring of 2004, the Humboldt State University (HSU) Scientific Diving class, was commissioned by CDFG, to assist with subtidal surveys for abalone along 30×2 m (60 m^2) band transects examining red abalone abundance and size data. Subsequent subtidal band transect surveys of the same area were completed in September of 2007 and 2010 by CDFG. Transects were located offshore just to the east of Sea Lion Rocks and north of the isthmus bridge in the light gray shaded area of Fig. 1.

Similarly, intertidal surveys of Stornetta Ranch during minus tide series were conducted by CDFG in the spring of 2004, in the fall/winter of 2007/2008 (2007) and 2010/2011 (2010) using the same methodology as the subtidal transects (see Fig. 1, dark gray area). Intertidal emergent transect surveys were also completed at a fished site Moat Creek in spring 2004 and spring 2008.

Subtidal densities of red abalone populations were also enumerated at a reserve and four fished sites along the Mendocino county coast using the same methods as the Stornetta survey. These four sites were surveyed between 2009 and 2011.

Comparisons of red abalone density at sites in Mendocino were analyzed with the Kruskal–Wallis multiple comparisons test using Matlab R2006. The size distribution of each survey was grouped into 5 mm size classes and compared using the Kolmogorov–Smirnov Two-Sample Test.

2.2. Egg production estimates

We determined densities for females in 25 mm sizes classes starting at 100 mm, with the third size class ending at 178 mm, (minimum legal size) and the following class comprising of 179–200 mm as per (Rogers-Bennett and Leaf, 2006). Female red abalone in northern California mature at >100 mm (Rogers-Bennett et al., 2004). These densities were calculated by taking half the measured red abalone in each size class, since there is a 50/50 sex ratio (Rogers-Bennett et al., 2004) and multiplying by the density of the cumulative surveys in either the subtidal or intertidal areas. This fraction density was then multiplied by either the total subtidal or the total intertidal area calculated using ArcView (light and dark gray areas, respectively) in Fig. 1 and summed for 2004, 2007 and 2010.

Egg production was averaged for each size class using egg count data from female red abalone collected from northern California (see methods, Rogers-Bennett et al., 2002b). Using the Table Curve2 Dv.5.01 program, a best-fit power function curve was determined for the graph of egg count versus shell size. Egg counts for each size class were calculated using the median size of each size class. The number of female red abalone for each size class for the entire area was then multiplied by this egg count estimate. The egg counts were then totaled producing an estimated total potential egg production estimate for the area in 2004, 2007 and 2010.

2.3. Fisher surveys

Creel surveys (field interviews) of recreational abalone fishers were conducted at Stornetta Ranch in 2004 and 2007 during spring minus tides. Fishers take their catch from the intertidal and subtidal areas of the site. By 2010, the site was closed to fishing so no fisher surveys were conducted. Surveys encompass two consecutive weekday–weekend days during daylight minus tides with

samplers on site one-half hour before low tide through 3 h after low tide.

Survey information collected included fishing mode, i.e. shore picker (looking in the intertidal) or diver (using masks and fins), site access mode (shore or boat), number of fishers per group, number of abalone taken, total time spent searching for abalone, number of undersized abalone returned, condition of abalone, and fishing location information. Interviewers measured and examined abalone for cuts and shell damage. The take per picker day, take per hour, and returns per picker day was determined. The expected incidental fishing mortality due to cut damage and the annual average incidental fishing mortality was calculated.

Incidental mortality was calculated using the following algorithm:

Abalone Returned/Trip $*$ ((Medium Cuts/2) + (Heavy Cuts)/Number Examined).

Fig. 2. Comparisons of red abalone density between (a) Stornetta subtidal surveys conducted in 2004, white bars, 2007, light gray bars and 2010, dark gray bars and (b) Stornetta intertidal surveys conducted in 2004, white bars, 2007–08, light gray bars and 2010–11, dark gray bars and (c) Moat Creek intertidal surveys conducted in 2004, white bars, and 2008, light gray bars, no 2010 data.

Table 1
Subtidal red abalone (*Haliotis rufescens*) populations at Stornetta.

	2004	2007	2010
Area surveyed (m^2)	1380	1980	1620
Number of abalone	1805	894	539
Abalone (m^2) (SD)	1.28	0.45	0.33
	(0.61)	(0.35)	(0.32)
Mean size mm (SD)	172	168	166
	(28)	(26)	(29)
Range (mm)	45–230	40–217	80–221
Change in density compared with 2004 baseline year sampled (%)	–	–65%[a]	–74%[a]

[a] *p*-Value < 0.001.

First, we estimate the number that each fisher returned to the ocean while fishing, then we multiply by the number of abalone with medium cuts/2, as half of those with medium cuts are expected to die, while all those with heavy cuts will die. Abalone have no blood clotting mechanism so heavy cuts leads to death. The size distribution of the 2004 and 2007 creel surveys was compared using the Kolmogorov–Smirnov Two-Sample Test. CPUE data were compared using the Mann–Whitney Rank Sum test.

Since 2001, CDFG has implemented the abalone report card to gather abalone catch information, including catch location, take per fisher per year. Abalone fishers are required to report catch, site, day and time for each abalone taken. The abalone report card return rate has averaged around 30% and the returned cards are sampled at random.

A telephone survey of abalone report card purchasers was implemented in 2002 to gather catch and effort information from a random sample. This survey asks questions pertaining to abalone fishing activities and is combined with catch and effort data from returned report cards to provide an unbiased estimate of the overall abalone catch.

2.4. Estimates of illegal catch

An estimate of red abalone removed by illegal take (poaching was made) at the former reserve site from 2004 to 2007. To estimate illegal take, the population prior to fishing was compared with the population 3.5 years later while taking into account losses due to fishing, incidental mortality and natural mortality.

First, the initial 2004 and final 2007 populations were determined at the former reserve site using an ArcView map of the area to estimate the subtidal and intertidal areas (see Fig. 1). We multiplied the area by the survey densities of abalone in the subtidal and intertidal then added these together, for a total number of red abalone in the area. Since the report card location is for the entire Point Arena area (reserve plus non-reserve), we distinguish between reserve and non-reserve catch. To do this, we estimated fishing mortality (FM), subtracting the average catch from the

previous year (before the reserve was fished) to determine catch outside the reserve. Incidental fishing mortality (IM) is a percent of the total catch and the incidental mortality percentages is determined from direct observation of a portion of the catch during the creel interviews. Natural mortality (NM) was estimated using published mortality estimates for northern California at a reserve site of $M = 0.05$ year^{-1} (Leaf et al., 2006). The number of abalone lost to NM, was calculated from a modified abundance (mA), of red abalone not including abalone that were fished, lost to incidental mortality and taken illegally during the year using the following equation (Breen, 1986):

$$mA * (1 - e^{(-0.05)}) \tag{1}$$

A constant illegal take estimate, P, was assumed per year from 2005 to 2007 (in 2004 half this value was used since the site was closed for the half the year). The initial and final abundance numbers are known, A_{2004} and A_{2007}, however the year's in between are estimated, eA_{2005} and eA_{2006} and eA_{2007}. The following year's abundance, is determined using a step-wise process using Eqs. (2)–(5) as the following years abundance must take into account a number of sources of mortality (FM, NM and IM) occurring within the year:

$$A_{2004} - FM_{2004} - IM_{2004} - P/2 - NM_{2004} = eA_{2005}(NM_{2004}$$
$$= (A_{2004} - FM_{2004} - IM_{2004} - P/2)(1 - e^{-0.05})) \tag{2}$$

$$eA_{2005} - FM_{2005} - IM_{2005} - P - NM_{2005} = eA_{2006}(NM_{2005}$$
$$= (A_{2005} - FM_{2005} - IM_{2005} - P)(1 - e^{-0.05})) \tag{3}$$

$$eA_{2006} - FM_{2006} - IM_{2006} - P - NM_{2006} = eA_{2007}(NM_{2006}$$
$$= (A_{2006} - FM_{2006} - IM_{2006} - P)(1 - e^{-0.05})) \tag{4}$$

$$eA_{2007} - FM_{2007} - IM_{2007} - P - NM_{2007} \approx A_{2007}(NM_{2007}$$
$$= (A_{2007} - FM_{2007} - IM_{2007} - P)(1 - e^{-0.05})) \tag{5}$$

The poaching estimate, P, can be determined by iteration when Eq. (5) equals the known abundance for 2007, with abundance capturing all of the mortality FM, NM and IM for the year. We then multiplied this yearly poaching estimate, P, by 3.5 years to determine poaching over the survey period (2004–2007).

3. Results

3.1. Subtidal and intertidal surveys

The 2004 subtidal baseline survey density of red abalone at Stornetta Ranch, was 1.28 abalone/m^2 (SD 0.61). In 2007, abalone density declined to 0.45 red abalone/m^2 (SD 0.35) and in 2010 declined further to 0.33 abalone/ m^2 (SD 0.32) (Fig. 2, Table 1). This 65% decrease between 2004 and 2007 is a significant decline

Table 2
Intertidal red abalone (*Haliotis rufescens*) populations at Stornetta and Moat Creek.

	Stornetta			Moat Creek	
	2004	2007	2010	2004	2008
Area surveyed (m^2)	2160	2040	2100	1200	1320
Number of abalone	1320	273	352	100	112
Abalone (m^2) (SD)	0.61 (0.82)	0.13 (0.20)	0.17 (0.22)	0.08 (0.12)	0.09 (0.13)
Mean size mm (SD)	143 (36)	129 (33)	135 (35)	135 (34)	152 (32)
Range (mm)	25–225	8–216	7–229	55–193	20–213
Change in density compared with 2004 baseline year sampled (%)[a]	–	–78[a]	–72[b]	–	2 (ns)[c]

[a] *p* < 0.001.
[b] *p* < 0.01.
[c] Not significant (ns).

($p < 0.001$) as is the 72% decline from the 2004 to 2010 surveys ($p < 0.001$).

The intertidal baseline surveys at Stornetta Ranch conducted during the spring of 2004 revealed an average density of 0.61 red abalone/m^2 (SD 0.82) which in 2007 fell to 0.13 red abalone/m^2 (SD 0.2), a 78% significant decrease ($p < 0.001$). In 2010, abalone densities had risen slightly to 0.17 red abalone/m^2 (SD 0.2) in 2007 however this increase was not significant ($p = 0.190$).

Fig. 3. Comparisons of red abalone size frequency distribution in 25 mm increments of red abalone per square meter (a) Stornetta subtidal surveys conducted in 2004, white bars, 2007–08, light gray bars and 2010, dark gray bars and (b) Stornetta intertidal surveys conducted in 2004, white bars, 2007–08, dark gray bars and 2010–11, light gray bars and (c) Moat Creek intertidal surveys conducted in 2004, white bars, and 2008, light gray bars. Dashed line in each graph denotes lower limit of legal sized abalone, 178 mm.

Comparing 2010 with the baseline in 2004 was a significant decline of 72% (p < 0.002) (Fig. 2, Table 2).

The neighboring fished site, Moat Creek, the intertidal was surveyed in June 2004 and April 2008. The intertidal density in 2004 was 0.08 red abalone/m^2 (SD 0.12) while the 2008 surveys, yielded a very similar density of 0.09 red abalone/m^2. The densities are not significantly different (SD 0.13, p = 0.742) (Fig. 2, Table 2) between years.

Comparing intertidal densities at the former reserve site and the intertidal at Moat Creek, we found significantly different densities of abalone between the sites during the 2004 sampling year. Not surprisingly, the density at the reserve site of 0.61 red abalone/m^2 was far greater (86%) than the fished sited site at 0.08 red abalone/m^2 (p < 0.001). In 2007, 3.5 years after the reserve site was opened, the density at the former reserve site of 0.13 red abalone/m^2 was slightly greater than the density at Moat Creek in 2008 of 0.08 red abalone/m^2, but the difference was not significant (p = 0.764).

Size distributions for both the baseline surveys at the former reserve in both the subtidal and intertidal revealed significant differences between surveys completed 3 and 6 years later (K–S two sample test $D > D_{0.01}$ for all). In contrast, the size distributions between the 2007 and 2010 surveys were no longer significantly different (p > 0.05). Densities for legal size classes (>178 mm) were reduced and densities of sub-legal size classes also declined indicating poaching of small abalone (Fig. 3).

The density of red abalone at the former reserve site in 2004 of 1.28 red abalone/m^2 is the highest red abalone density measured in the Mendocino County sites in northern California. This site was significantly higher than both the Van Damme (VD) and Todd's Point (TP) sites which are popular fishing sites (Fig. 4). Stornetta was higher but was not significantly higher than the other reserve site Point Cabrillo Reserve (PCR) which had a density of 0.79 abalone/m^2 (SD 0.84) measured in 2003 (Fig. 4).

3.2. Egg production estimates

There were large declines in potential egg production estimates from 2004 to 2007 and again in 2010. The percent decline in total estimated potential egg production of all size classes totaled 72% from 2004 to 2007 and 78% between 2004 and 2010 (Fig. 5) The percent decline between sub-legal size classes between the

Fig. 4. A box plot of the density of red abalone in the subtidal in the 2004 Stornetta survey (prior to fishing) with standard deviations showing Stornetta with the highest density observed compared to other fished sites and Point Cabrillo reserve site. Sites are listed from north to south along the Mendocino coast. + indicates outliers.

baseline and 2007 and 2010 was 63% and 71%, respectively, while the percent decline between legal size classes was 75% and 80%, respectively.

3.3. Fisher surveys

During the August 2004 creel survey at Stornetta Ranch, 114 abalone fishers were interviewed and 303 legal size abalone were measured with a mean size of 204 mm (SD 11.86). The April and June 2007 creel surveys contacted 224 abalone fishers and measured 493 abalone revealing a 192 mm mean size (SD 9.54), (Fig. 6). Size frequency results revealed a significant decline in abalone shell length in the catch between the 2004 and 2007 surveys (p < 0.0001). No interviews were conducted in 2010 due to the establishment of the site as an MPA.

In 2004, the mean abalone take per hour of 7.01 (SD 6.14) and the 2007 take per hour of 2.44 (SD 3.78) were found to be significantly different between years (p < 0.001). In 2004, the mean abalone take per picker was 2.83 (SD 0.47), and in 2007 it was 2.38 (SD 0.92), a significant decline (p = 0.011).

Incidental fishing mortality estimates the number of abalone picked and then returned that later die from fishing wounds. The combined incidental fishing mortality for 2004 and 2007 was 0.02, or 2% of the abalone taken at this site. Based on the estimated take for 2004 (partial fishing year) of 4223 abalone, the number of abalone that suffered incidental fishing mortality was 84, this number increased to 151 in 2007 based on the estimated catch of 7558. Using the same incidental fishing mortality for 2005 and 2006 (full fishing years), we estimate incidental mortality of 312 and 370 abalone, respectively.

We estimate catch at Stornetta Ranch at Sea Lion Cove, by subtracting the baseline non-Sea Lion Cove fishing years from the total catch since report cards and telephone surveys do not specifically pinpoint Stornetta catch. The Point Arena Lighthouse site on the abalone report card encompasses the former reserve site. Catch estimates for this larger area increased dramatically when the small reserve was opened to public fishing in August of 2004. The baseline estimated catch in 2002 and 2003, prior to opening to fishing pressure, was 1673 and 1574 abalone per year, respectively. In 2004, when the reserve was opened to fishing for 4 months from August to November, the catch estimate increased to 4223. During the next 2 years, in which the reserve was open for the whole season (7 months), the catch estimates rose further to 15,602 for 2005 and 18,511 for 2006. This is a 950% increase in catch from the baseline 2 year pre-opening average to the 2 year post-opening average of the reserve to fishing. In 2007, the catch dropped dramatically to 7558 a 59% decrease from the 2006 catch (Fig. 7). In 2008 catch estimates fell again to 3768 abalone while 2009 estimates were 5420 abalone.

3.4. Estimates of illegal catch

Illegal catch between the baseline surveys and the 2007 surveys was estimated by determining total abundance prior to fishing then subtracting all the known estimated mortalities. The 2004 and 2007 subtidal and intertidal densities multiplied by the estimated corresponding areas yielded a total red abalone population of 255,589 in 2004 and 79,732 in 2007 a difference of 175,857 abalone. Fishing estimates at the reserve were calculated for the years between 2004 and 2007 to be 39,367 red abalone. The incidental mortality rate calculated from creel surveys was 787 abalone, approximately 2% of the catch. This only accounts for a total of 40,154 of the loss. Using these numbers on a per year basis we estimated the number of illegally taken abalone to be 104,984 over the 3.5 years of fishing while 30,718 abalone were lost to natural mortality over this time period.

Fig. 5. (a) Estimate of the number of female red abalone in the calculated subtidal and intertidal area of Fig. 1 for the following size classes: 100–125 mm, 126–150 mm, 151–178 mm, 179–200 mm, 201–225 mm in 2004, white bars, 2007–08, black bars and 2010, gray bars. (b) Total potential egg production estimates calculated from the number of female red abalone in Fig. 5a for the following size classes: 100–125 mm, 126–150 mm, 151–178 mm, 179–200 mm, 201–225 mm in 2004, white bars, 2007–08, light gray bars and 2010, dark gray bars.

4. Discussion

Opening private lands had unintended consequences for valuable abalone resources within the former "*de facto*" reserve. We found that this former reserve, with its long history of protection, allowed for the build up of a uniquely dense population of red abalone. This dense population was quickly depleted once the area was fished. We also found evidence that densities of sub-legal size classes (<178 mm) decreased dramatically, suggesting that illegal take contributed to the population decline at this site.

This study demonstrates that benthic marine invertebrates, such as red abalone, are particularly vulnerable to fishing and that densities, sizes and egg production can be significantly depleted in just 3 years. In this case, densities declined in both the subtidal (65%) and intertidal (78%) areas. After 3 years of fishing, the density inside the former reserve site was not significantly different from a neighboring heavily fished site despite an initial difference of 86%. Fishery dependent measures such as abalone taken per hour

(CPUE) were sensitive to fishing and decreased from 7 to 2.4 while the time to locate legal-sized abalone increased nearly three fold. Finally, catch dropped after just 1.5 years of fishing, decreasing precipitously between 2006 and 2007 (59% drop) indicative of the speed of depletion in the local stock.

The density in the subtidal habitats at the reserve site dropped from the highest measured in northern California, 1.28/m^2 down to 0.45/m^2 in 3 years. Similarly, density in the intertidal dropped from 0.6/m^2 to 0.13/m^2 in the same time period. After just 3 years, the density in the intertidal was below the Minimum Viable Population (MVP) size proposed for abalone of 0.3/m^2 (Shepherd and Brown, 1993) and below the density set in the ARMP of 0.2/m^2 (ARMP, 2005). Broadcast spawning marine invertebrates such as abalone are susceptible to Allee effects such that they require high densities and close proximity for successful external fertilization. Field experiments have demonstrated that greenlip abalone (*Haliotis laevigata*) must be within 2.5 m of each other for successful external fertilization (Babcock and Keesing, 1999). At the baseline

Fig. 6. Percent of legal-sized red abalone fished from 175 to 205 mm in 5 mm increments by recreational shore pickers and divers during two consecutive weekday–weekend daylight minus tides in 2004, white bars, and in 2007, light gray bars.

Fig. 7. Estimates of recreational abalone catch taken from Point Arena Lighthouse, on CA red abalone punch card and telephone surveys. Arrow denotes that fishing opened in August 2004. Black bars for the subsequent years after Stornetta Ranch opened to fishing are the average of the 2002 and 2003 catch estimates so that white bars indicate catch increase. Black triangles on z-axis denote subtidal density from surveys.

intertidal density of 0.61/m², abalone with a fairly even distribution could be within 2.5 m of another abalone, however, at densities below 0.2/m² abalone may be too far apart for successful fertilization.

Density and size frequency differences in the reserve before and after opening of the site to fishing translated into dramatic declines (drop of 72%) in estimates of egg production in just 3 years. Egg per recruit (EPR) models have been used to examine the relative impacts of fishing regulations on egg production (Tegner et al., 1989; Breen, 1992). An analysis of an EPR model for the southern California abalone fishery indicated that during the failed fishery the existing regulations maintained 48% of the egg production. Despite this level of protection by the existing regulations (e.g. size limits), populations collapsed under fishing pressure by the 1980–1990s (Tegner et al., 1989). This suggests that drops greater than 48% of egg production, such as those at the former Stornetta reserve (currently at 22% of the initial egg production) may have serious implications for local recruitment and recovery. Egg per recruit models have been used to set reference points for red abalone management in northern California and suggested minimum egg production targets range from 60% to 70% (Leaf et al., 2008) which was clearly exceeded at the former Stornetta reserve site. Sublegal adult abalone have been shown to be critical to population dynamics of population model projections further impacting sustainability (Rogers-Bennett and Leaf, 2006). Slow-growing, long-lived marine animals in general have low potential for recovery as has been seen with generalized demographic models which address the potential benefits of MPAs (Gerber and Heppell, 2004).

Illegal take is notoriously difficult to estimate, yet we know it is rampant in the recreational red abalone fishery in northern California. Careful tracking of the reserve (Stornetta Ranch) before and after fishing allowed us the unique opportunity to make estimates of the impacts of fishing as well as illegal fishing. In this case, we estimate illegal catch at 104,984 which is more than double the legal fishery catch estimate of 39,367 over 3.5 years of fishing. The size frequency distribution also shows that sublegal size classes declined as much as legal sizes suggesting illegal take of sublegal size classes. Former estimates of illegal take in this fishery are much lower (Daniels and Floren, 1998), however estimates of illegal take in the South African abalone fishery also exceed legal catch

estimates (Tarr, 2000). Modeling the impacts of poaching in rock-fish (also slow growing) showed that the positive impacts of MPAs for yield were negated with poaching of 15% per year in a model fishery (Sethi and Hilborn, 2007). High abalone densities built up over decades, ease of access (no steep cliff), protected location (in the lee of Sea Lion Rocks), wide intertidal bench and shallow subtidal area averaging less than 15 ft (5 m) combined into a perfect storm resulting in sharp declines in abalone density once the site was opened.

In 1999, the Marine Life Protection Act (MLPA) mandated the CDFG to build a network of MPAs in California (Gleason et al., 2010). In May 2010, the former reserve site, Stornetta Ranch, was incorporated into the Sea Lion Cove SMCA and is now designated as a reserve specifically excluding abalone fishing. The MPA was established as part of the north coast MPA process in California as mandated by the MLPA legislation. The final survey of Stornetta Ranch in 2010, now Sea Lion Cove SMCA, revealed a slight, but not significant, increase in intertidal abalone density. These data are now part of a baseline survey to compare with future surveys that will monitor the potential recovery of the abalone population. The recovery of lobster has been quantified in New Zealand where recovery rates were 4–9% per year inside reserves (Kelly et al., 2000).

Our data caution against the use of marine reserves for abalone which are opened to fishing periodically such as within rotating (Polacheck, 1990) or temporary reserves (Bullock et al., 2000). For long-lives species such as abalone, with high black market values, temporarily opening reserves for 1.5 years can wipe out gains in density acquired over decades of closure. In California and around the world, the marine conservation challenge will be to maintain sustainable marine resources as public access increases in formerly inaccessible sections of the coast including private and military areas.

Acknowledgements

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