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Biological responses in marine no-take reserves versus partially protected areas

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ABSTRACT: Marine Protected Areas (MPAs) are a common tool for conserving and managing marine and coastal ecosystems. MPAs encompass a range of protection levels, from fully protected no-take reserves to restriction of only particular activities, gear types, user groups, target species, or extraction periods. There is a growing body of scientific evidence supporting the ecological benefits of full reserve protection, but it is more difficult to generalize about the effects of other types of MPAs, in part because they include a range of actual protection levels. However, it is critical to determine whether partial protection and no-take reserves provide similar ecological benefits given potential economic costs of lost fishing grounds in no-take areas, common sociopolitical opposition to full protection, and promotion of partially protected areas as a compromise solution in ocean zoning disputes. Here we synthesize all empirical studies comparing biological measures (biomass, density, species richness, and size of organisms) in no-take marine reserves and adjacent partially protected and unprotected areas across a range of geographic locations worldwide. We demonstrate that while partially protected areas may confer some benefits over open access areas, no-take reserves generally show greater benefits and yield significantly higher densities of organisms within their boundaries relative to partially protected sites nearby.

KEY WORDS: Marine reserves · Marine protected areas · Protection level · Conservation · Ocean zoning

INTRODUCTION

Human activities have broad effects on coastal and oceanic marine systems (Halpern et al. 2008b), often degrading ecosystem services (UNEP 2006), including many fisheries worldwide (Gewin 2004, Worm et al. 2006). These changes have led to calls for more ecosystem-based approaches to marine management, including ocean zoning and the implementation of marine protected areas (Palumbi 2002, Lubchenco et al. 2003, Browman & Stergiou 2004, Crowder et al. 2006, Halpern et al. 2008a). In particular, ocean zoning provides a means to spatially separate incompatible human activities and reduce conflict among user groups (Crowder et al. 2006). However, when attempting to implement a zoning approach or establish a network of MPAs, it is critical to understand the potential ecological consequences of different types of restrictions. There is often a tension between conservationists and extractive user groups regarding the level of protection established, and it is important to evaluate whether this friction is necessary.

No-take marine reserves are often promoted for their ability to offer simple and full protection for marine resources and ecosystems. Numerous syntheses of monitoring studies have documented beneficial effects of reserve protection (Palumbi 2002, Halpern 2003, S. E. Lester unpubl. data), particularly for biomass and density of exploited species within reserve boundaries (Gell & Roberts 2003, Micheli et al. 2004). In addition to

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these demonstrated conservation benefits, there is some theoretical work and more limited empirical evidence that reserves can produce fisheries benefits, either through export of larvae or spillover of adults into unprotected waters (Roberts et al. 2001, Halpern et al. 2004, Hilborn et al. 2004, Goni et al. 2006). Marine reserves are also promoted over partially protected areas for political reasons, such as less complicated regulations and more straightforward enforcement (Bohnsack 2004).

Despite the benefits of marine reserves, prohibiting all extractive activities in certain areas can have socioeconomic costs. Marine reserves often face strong opposition by extractive users, making the process of reserve implementation politically difficult and polarizing. Indeed, even if reserves benefit fisheries, local fishers may be negatively affected by the loss of fishing grounds, at least in the short-term. As a result, MPAs with less restrictive regulations are typically seen as a politically more feasible management strategy and are often advanced as compromise solutions (NRC 2001, Shears et al. 2006). For example, MPAs often allow recreational fishing, subsistence fishing, or fishing with less destructive gear types, depending on the stated management goals.

Partially protected areas have also been shown to produce ecological responses (e.g. Murawski et al. 2000, Blyth-Skyrme et al. 2006, Floeter et al. 2006), although it is difficult to generalize about these effects because empirical results remain scattered throughout the literature. A further challenge is that the intensity and frequency of permitted extractive or destructive activities is a source of variation that is difficult to quantify and thus control for in analyses. We address these challenges here by synthesizing available peer-reviewed data on MPA performance in those locations where there is an adjacent marine reserve. In doing so, we exclude those studies that have looked only at MPA performance, but we gain power by having a controlled, direct comparison to no-take marine reserves. These results can inform decisions on appropriate or necessary level of protection when establishing MPAs in order to meet specified management or conservation goals.

METHODS

We conducted a comprehensive survey of peer-reviewed scientific literature to compile a database of studies documenting and comparing biological effects of fully-protected no-take marine reserves, partially protected marine protected areas (MPAs) and open access areas, all within the same vicinity. Studies must have measured at least 1 of 4 key biological variables (density, biomass/area of organisms, individual organism size, or species richness/area) and must have quantified the variable(s) either (1) inside the reserve, inside the partial protection area and outside the protected areas (open access) after protection was implemented, or (2) in all three areas before and after protection was implemented. The areas referred to in this paper as 'open access' may be subject to some fishing restrictions (e.g. no dynamite fishing), but are less protected than the no-take reserves and partial protection areas. Furthermore, in many of the studies, recreational or subsistence fishing is allowed in the 'partial protection' area (Table 1), while recreational, subsistence and some commercial fishing are allowed in the 'open access' area.

The resulting database contains 20 peer-reviewed scientific publications published between 1977 and 2007 examining 21 protected areas in 11 countries (Table 1). For each study, we extracted quantitative data from text, tables, and figures for the 4 biological variables. Data were extracted at the most aggregated taxonomic level available, even if the level of taxonomic resolution differed within or among studies. If a study reported data for categories of other variables (e.g., by depth, habitat type, or organism size classes), we calculated an un-weighted average of the values reported for these categories to extract a single value for each protection level. If data were collected over time, we used the most recent because they represent the longest duration of protection (for before/after comparisons, this holds for the after data).

To quantify the effects of different levels of protection using comparable metrics across studies, we calculated response ratios for the biological variables as (1) the ratio of inside the no-take reserve to the open access area, (2) the ratio of the partially protected area to the open access area, and (3) the ratio of the no-take reserve to the partially protected area. If the study included before and after protection data, the above three ratios were calculated using the ratios of after versus before for each of the protection levels.

When data were extracted for multiple taxa in a given study, we averaged these response ratios to determine the overall study ratio for all taxa examined, such that study-level ratios can represent from 1 to >100 species depending on the study (Table 1). Two studies (McClanahan & Muthiga 1988, McClanahan et al. 2006) reported data separately for more than 1 of the 3 broad taxonomic groups (fish, invertebrates, algae), and thus we calculated an average for each group first and then averaged these group values to determine the overall ratio. For all analyses, we used log ratios to meet statistical criteria (Hedges et al. 1999) and conducted all statistical tests using JMP 7.0 (SAS Institute).

Table 1. Studies reporting data for adjacent no-take reserves, partially protected areas, and open access areas, including the names of these areas, metrics reported, taxa studied, and the regulations in the partially protected area. Metrics: B, biomass; D, density; R, richness; S, size

No-take reserve	Partially protected area	Open access area	Metrics reported	Taxa studied	Regulations in partially protected area	Source
Tortugas Bank No-take Marine Reserve, USA	Dry Tortugas National Park	Tortugas Bank Fished	D	21 fish species	No commercial fishing; only recreational hook-and-line fishing allowed	Ault et al. (2006)
Tortugas/Fort Jefferson, USA	Sport harvest area between reserve and open access area	Commercial harvest area outside reserve and sport harvest area	D	1 lobster species	No commercial fishing; recreational fishing by skin or SCUBA diving allowed	Davis (1977)
Poor Knights Island Marine Reserve, NZ	Mimiwhangata Marine Park	Cape Brett and Mokohinau Islands	D, S	1 fish species	No commercial fishing; recreational fishing allowed using the following methods: unweighted, single-hook lines, trolling and spearing	Denny & Babcock (2004)
Arquipelago, Brazil	Timbebas/Escalvada/ Pedra Vermelha	Guarapari/ Saco do Anequim	D	135 fish species	Partially protected by distance or park regulations allowing only some fishing gears (e.g. spear, nets, hook-and-line)	Floeter et al. (2006)
Scandola, France	Elbu	Galeria	B, D	17 fish species	Partially protected by distance or park regulations allowing small boats, low-power engines, and traditional fishing methods	Francour (1991)
Scandola, France	Non-integral reserve	Outside reserve	D	3 fish families	Some fishing allowed by permit	Francour (2000)
No-take areas throughout the main Hawaiian islands, USA	Partial protection areas throughout the main Hawaiian islands	Open access areas throughout the main Hawaiian islands	B, D, R	Reef fish assemblage	Allow some fishing methods, varying by area (e.g. hook and line fishing allowed)	Friedlander et al. (2003)
No-take areas throughout the main Hawaiian islands, USA	Partial protection areas throughout the main Hawaiian islands	Open access areas throughout the main Hawaiian islands	B	Reef fish assemblage	Allow some fishing methods, varying by area (e.g. hook and line fishing allowed)	Friedlander et al. (2007)
Invertebrate no-take reserve, Catalina Island, USA	Recreational fishing area, Catalina Island	Commercial and recreational fishing area, Catalina Island	B, D, S	1 lobster species	No commercial fishing; recreational fishing allowed by hand or with hoop nets and with daily bag limit	Iacchei et al. (2005)
Cousin Island, Seychelles	Sainte Anne	Baie Ternay and Curieuse	B	115 fish species	No commercial fishing; subsistence fishing by park residents allowed (~10 fish traps and occasional hand-lines)	Jennings et al. (1996)
Cerbère-Banyuls Marine Reserve, France	Partially protected area (PPA)	Unprotected area (UPA)	D, S	1 urchin species	Commercial fishing only with fixed nets; recreational fishing allowed	Lecchini et al. (2002)

Table 1 (continued)

No-take reserve	Partially protected area	Open access area	Metrics reported	Taxa studied	Regulations in partially protected area	Source
Las Cruces, Chile	Adjacent semi-protected area	Adjacent open-access area	D, S	1 gastropod species	Open to fishing but access restricted by private property	Manriquez & Castilla (2001)
Malindi Marine National Park, Kenya	Kanamai	Diani	D	1 urchin and the fish community	Partial protection determined by fishing pressure, influenced by proximity to large tourist settlements	McClanahan & Muthiga (1988)
Kisite, Kenya/Tanzania	Tanga, Tanzania	Open access area	B, D, R	Algae, hard and soft coral, urchins, sponges, reef fishes	No dynamite fishing or beach seines and some temporary closures	McClanahan et al. (2006)
Ustica Island Integral Reserve, Italy	Ustica Island General Reserve	Ustica Island Partial Reserve	D, R	161 species (molluscan assemblage)	No commercial fishing; recreational (angling) and subsistence fishing allowed	Milazzo et al. (2000)
Ras Mohammed, Egypt	Sharm-el-Sheikh	Dahab	B, D, S, R	45 fish species	Partial protection determined by accessibility and human population density	Roberts & Polunin (1992)
Platform Gail de facto reserve, USA	Santa Monica Bay	Footprint	D	1 fish family	Closed to commercial fishing activities that use trawls, drag nets, gill nets, and traps, except for a small live-bait fishery that uses lampara nets; also closed to handlines with more than 2 hooks	Schroeder & Love (2002)
Tawharanui Marine Reserve, NZ	Mimiwhangata Marine Park	Tawharanui fished	D	1 lobster species	No commercial fishing; recreational fishing using the following methods allowed: unweighted, single-hook lines, trolling and spearing	Shears et al. (2006)
University of Washington marine research preserves (Shady Cove, Point George, Yellow Island), USA	Marine Protected Areas (Bell Island, Lime Kiln)	Unprotected areas (Cliff Island, Bell Island outside, Lime Kiln outside)	D	1 urchin species	Collection of finfish (not including salmon) prohibited	Tuya et al. (2000)
Punta La Restinga-Mar de Las Calmas, Spain	Buffer zone (ZA)	Neighboring fishing area (AV)	B, D	4 fish species	No commercial fishing; fishing with traditional gears allowed	Tuya et al. (2006)
Isla La Graciosa e islotes del norte de Lanzarote, Spain	Buffer zone (ZA)	Neighboring fishing area (AV)	B, D	4 fish species	No commercial fishing, traps, or underwater gear; fishing with traditional gears (e.g. hook-and-line) and shrimp pots allowed	Tuya et al. (2006)

RESULTS

Partially protected areas (MPAs) may confer some ecological benefits relative to unprotected areas, producing positive but non-significant responses for biomass, density, richness and individual size relative to unprotected areas (Fig. 1) (Partial:open response ratios; *t*-tests, means not significantly different from zero: $p > 0.1$ for all metrics). No-take reserves had larger increases on average relative to unprotected areas than those for partially protected areas (Fig. 1: No-take:open response ratios); these responses were statistically significant for density (*t*-test, means significantly different from zero: $p = 0.015$) and suggestive (though non-significant) for organism size ($p = 0.09$), but not significant for biomass or species richness ($p > 0.1$). Additionally, the reserve effects documented in this dataset are comparable to values in previous more comprehensive analyses of no-take reserves (Halpern 2003; Fig. 1: Halpern ratios).

To control for potential differences among study locations and species sampled, we conducted pairwise comparisons of full versus partial protection areas. We found that no-take areas had higher biomass, density, species richness and individual organism size on average relative to partially protected areas (Fig. 2). This difference was statistically significant only for density ($p = 0.02$ for density, $0.1 < p < 0.9$ for biomass, species richness and organism size), although it should be noted that organism size and species richness had very low sample sizes ($n = 5$, $n = 4$, respectively).

DISCUSSION

While partially protected areas may result in higher values of ecological metrics than open access areas, no-take reserves generally produced greater increases and yielded significantly higher densities of organisms within their boundaries relative to partially protected sites nearby. These results suggest that no-take reserves have advantages over less protected areas and may therefore represent a preferable management strategy, depending on management goals and social, economic and political constraints. Although the effect of no-take protection relative to partial protection was only significant for density, this is also the biological measure for which we had the most data. The no-take:open ratios from our synthesis are within the same range as those of Halpern's (2003) more comprehensive analysis of no-take reserves, and there is a remarkable similarity between studies for density, organism size and species richness. This suggests that the reserves in our dataset are a representative sub-

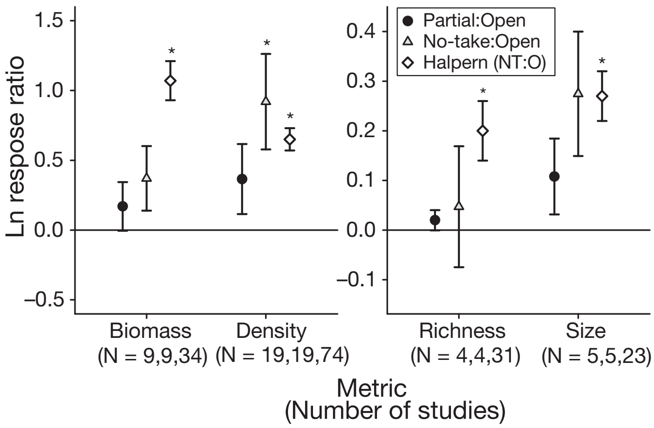

Fig. 1. Response ratios of overall study means (± SE) for partially protected areas compared to open access areas (●), for no-take reserves compared to open access areas from this synthesis (△), and for no-take reserves compared to open access areas from the comprehensive synthesis of Halpern (2003) (◇). *: mean significantly different from zero (*t*-test, $p < 0.05$). Sample size for each ratio is shown in parentheses following the sequence in the plot. Response ratios (RR) from Halpern (2003) were converted from logRR to lnRR to match the transformation used in this synthesis

sample and we should be able to detect an effect of partial protection, at least for density, if such an effect exists.

It is important to note that there is considerable variability in the documented effects of no-take versus partial protection, likely resulting from various factors that could not be accounted for in our analyses due to lack of information or insufficient data, including duration of protection, MPA/reserve size, habitat type and qual-

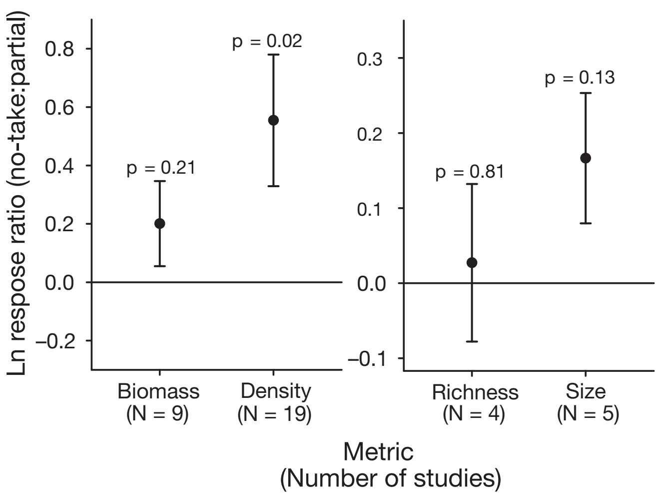

Fig. 2. Response ratios of overall study means (± SE) for no-take reserves and partially protected areas. p-values indicate the results of *t*-tests (testing for means significantly different from zero)

ity, and enforcement and compliance. Additionally, given the limited amount of data available, we aggregated across all taxa and thus were not able to control for specific taxon traits, such as trophic level or whether or not taxa are exploited. Thus, there is a critical need for more empirical studies documenting biological effects in adjacent open access, partially protected, and no-take areas; these studies should be conducted in a variety of locations and habitat types worldwide and focus on a range of taxa. Ideally such studies would also collect data prior to protection to avoid confounding effects of protection when MPAs are sited in 'better' areas.

We did not find significant ecological effects of partially protected areas relative to open access areas. A more complete synthesis of the studies that have examined only effects of partially protected MPAs relative to open access areas could help refine our understanding of the potential for MPAs to provide management and conservation benefits; a key challenge would be accounting for and controlling likely drivers of differences in MPA performance (e.g. the range and intensity of activities permitted within the MPA as well as differences in habitat, geography and species composition). Almost certainly, the amount of protection provided to species of interest within MPAs (e.g. fishery species) will greatly influence MPA performance relative to no-take marine reserves. Indeed, it is not surprising that we failed to document significant ecological effects of partially protected MPAs given that most of the studies we reviewed reported results for species targeted (although often by different fishing methods) in both open access and partially protected areas. Some species, particularly those heavily targeted by both commercial and recreational fishers, may be protected only by no-take reserves. Our focus here on studies that examined both MPAs and no-take reserves does not eliminate these challenges, but allowed us to directly compare these management options and helped minimize the potential for factors such as habitat type, species composition, or geography to influence the results.

Many partially protected areas, including those in this study, frequently exclude commercial fishing but allow recreational and/or subsistence fishing (Table 1). There is a widely held perception that recreational fishing does not have a substantial impact on marine ecosystems. For example, a recent poll prepared for the American Sportfishing Association reported that 64 % of Californians think that recreational fishing is a 'not serious' threat to marine ecosystems (FRC 2007). However, there is a growing body of evidence indicating that recreational fishing can constitute a significant portion of the regional catch for some species (Schroeder & Love 2002, Coleman et al. 2004, Cooke & Cowx 2004), and the lack of an MPA effect in our analyses on species that remain targeted by recreational fisheries further supports this evidence. Schroeder & Love (2002) examined 20 yr of landings data for nearshore fisheries species in California and found that for 16 of 17 species, recreational angling was the primary source of fishing mortality. Even catch-and-release fisheries can have dramatic effects on longer-lived species due to relatively small increases in mortality incurred post-hooking (Schroeder & Love 2002). Additionally, recreational fishing can have ecosystem-level effects similar to those from commercial fishing (Cooke & Cowx 2004, 2006); in some cases, recreational fishing can have even larger impacts because of a greater focus on higher trophic levels (Coleman et al. 2004) and shallower nearshore environments (Cooke & Cowx 2004).

One potential reason for smaller ecological effects in MPAs is that in some cases fishing effort becomes concentrated in partially protected areas relative to open access areas because of a perception among fishers that MPAs are likely to have more or larger fish due to the exclusion of commercial fishing (Denny & Babcock 2004, Shears et al. 2006). Likewise, rotational closures also often experience high levels of fishing that counteract the benefits of temporary protection (Murawski et al. 2005). For example, a study investigating rotational management in Hawaii found that fish biomass increased during closed periods, but not enough to compensate for the reduction in biomass during open periods (Williams et al. 2006).

MPA and reserve designation requires a balance of ecological, political, economic and social goals. Thus, regardless of the larger ecological responses in no-take reserves relative to partially protected areas, human needs will require MPA networks to allow a mix of protection levels and restrictions to accommodate multiple objectives, human activities and stakeholder groups. Additionally, partial protection can be used to exclude activities that are deemed too destructive (such as benthic trawl commercial fishing) despite potentially increasing fishing pressure for some species. It is important, however, for policy makers and managers to be aware of the ecological cost of conferring lower levels of protection in MPAs so that management decisions can be fairly evaluated by their ability to meet stated goals. Furthermore, there are numerous other advantages of no-take protection over partial protection not tested here (Schroeder & Love 2002, Bohnsack 2004). For example, reserves may provide control areas for fisheries-independent stock assessments and for teasing apart natural versus anthropogenic changes to marine ecosystems. Additionally, reserves can enhance various non-extractive uses such as recreation and tourism, many of which can provide economic benefits (Bhat 2003, Brander et al. 2007). Determining the appropriate level of protection for different areas of the ocean requires a careful balancing of conservation and management priorities, and analyses like those presented here can help inform this decision-making process.

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