Marine protected areas and resilience to sedimentation in the Solomon Islands

B. S. Halpern · K. A. Selkoe · C. White · S. Albert · S. Aswani · M. Lauer

Abstract The ability of marine protected areas (MPAs) to provide protection from indirect stressors, via increased resilience afforded by decreased impact from direct stressors, remains an important and unresolved question about the role MPAs can play in broader conservation and resource management goals. Over a five-year period, we evaluated coral and fish community responses inside and outside three MPAs within the Roviana Lagoon system in Solomon Islands, where sedimentation pressure from upland logging is substantial. We found little evidence that MPAs decrease impact or improve conditions and instead found some potential declines in fish abundance. We also documented modest to high levels of poaching during this period. Where compliance with management is poor, and indirect stressors play a dominant role in determining ecosystem condition, as appears to be the case in Roviana Lagoon, MPAs may provide little management benefit.

Keywords Marine reserves · Sedimentation · Logging · Cumulative impacts · Dominant stressor · Coral triangle

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Introduction

Marine protected areas (MPAs) are being developed and implemented at an increasing pace around the world, driven in part by greater local and regional urgency to protect ocean biodiversity and ecosystems and mitigate the impacts of fishing, as well as by various national and international conventions stipulating such action (e.g., CBD 2010). Evidence is now overwhelming that MPAs can protect species from direct impacts such as fishing and restore populations within MPA boundaries when these stressors are removed (Halpern 2003; Lester et al. 2009). What remains much less clear is whether MPAs are an effective tool for addressing stressors to marine systems that originate outside the boundaries of the MPA, such as land-based point and non-point pollution or climate change. The mechanism for conservation in these cases is not mitigation of the stressor, but instead enhanced resilience to the stressor through improved general condition of the system, as measured, for example, by the abundance and diversity of animals or the cover or condition of foundation species (e.g., Ling et al. 2009).

A number of studies have assessed the potential for MPAs to mitigate indirect stressors by building system resilience, in particular for climate change on coral reefs, with mixed results (McCook et al. 2010; Selig and Bruno 2010; Graham et al. 2011). To date, no studies have evaluated whether MPAs can help mitigate the impacts of

land-based stressors such as sedimentation, even though it is widely recognized as a key stressor to reef ecosystems. The potential for MPAs to build resilience can depend greatly on the types of stressors the system is exposed to (i.e., additive, multiplicative, dominant, and in some cases mitigative; Halpern et al. 2008). For example, if stressors such as climate change or land-based pollution are dominant stressors, altering ecosystems in the same, strong way no matter what other stressors are present, then MPAs are not likely to be effective since MPAs do not directly mitigate these stressors. If instead these stressors act additively or synergistically with other stressors (such as fishing pressures), then MPAs could improve overall resilience to each stressor by decreasing fishing pressure. In the case of sedimentation, MPAs could increase resilience, for example, by building and maintaining abundant populations of herbivorous fish that could keep algal growth in check, allowing corals smothered (temporarily) by sediments a chance to rebound, in turn supporting healthy populations of fish reliant on healthy coral reefs (e.g., Bellwood and Fulton 2008).

In this paper, we examine a system where coral reefs currently experience two key stressors, direct fishing pressure from local villages and indirect impact from sedimentation from upland logging activities. This study focuses on a large lagoon system in New Georgia Island, Western Solomon Islands (Fig. 1). Like most of Melanesia, people of the Solomon Islands manage their resources through a local tenure system that allocates use rights according to various tribal relationships, with boundaries differentially enforced (from very strict to very lax) through various social and cultural norms (Hviding 1996; Ruddle 1998). Although customary practices do not necessarily adhere to the principles of Western conservation, tribal chiefs have the authority and responsibility to manage both land and marine resources for the benefit of the tribe and thus have some incentive to sustain local resources over the long-term. Historically, this has involved decisions about when to close fishing access to reefs and where and how to use land for farming and dwellings (Aswani 1999). More recently, tribal chiefs and elders have also been leasing rights to fisheries or timber, primarily to companies from Malaysia, China, and Japan. Today, the indigenous tenure system is facing economic pressures and opportunities that are resulting in both increased fishing pressure and stressors from land-based runoff. However, if Melanesian tenure systems are provided institutional and economic support that strengthens social mechanisms, regulating access to resources, local chiefs, elders, and their respective tribes can in theory directly manage reef conditions at the local level (Cinner 2005; Aswani et al. 2012) and therefore cease or control threats to ecosystem health.

Many lagoon reefs were smothered with sediment up to 10 cm deep at the time of our initial surveys in 2005 (Fig. 2), when the MPAs were just 1–5 years old, suggesting that sediment runoff from upland logging had occurred at the same time or before MPA creation. In fact, upland logging has been extensive and ongoing in the region for the last 30 years with most of the upland area (from coast to 400 m elevation) licensed to international logging companies over the last three decades (e.g., Furusawa et al. 2004). Beginning in the 1980s, local tribes agreed to allow forestry concessions to generate income from royalties, and poor logging practices have led to considerable ecological damages from high sedimentation of lagoon reefs (Olsen and Turnbull 1993).

MPAs have been developed and implemented widely throughout Melanesia, including the Solomon Islands, over the past 5–10 years with the aim of better managing and protecting reef fish populations so that they can be more sustainably harvested by local communities. In the New Georgia region alone, over 32 MPAs are now in place (Aswani et al. 2007). These MPAs take on a variety of forms, from partial protection of varying design to full no-take marine reserves. Initial surveys in 2005–2007 showed limited improvements for a few fish taxa in terms of abundance and size distribution (Aswani et al. 2007; Aswani and Sabetian 2010). In 2010, we returned to more carefully evaluate whether or not MPAs, 6–10 years old, were providing ecological benefits in the face of the apparent impacts from sedimentation. The study is intended, in part, to determine the relative roles and potential interactions of sedimentation and fishing pressure (or conversely, MPA protection) in driving coral reef condition.

Methods

Study region

The Western Province of the Solomon Islands is the western-most region of the country and relatively sparsely populated with rural communities and some small urban centers such as Noro and Gizo. The main island, New Georgia Island, is surrounded by three large lagoon systems, including Roviana Lagoon on the southeastern end of the island (Fig. 1). The barrier islands and reefs for these lagoons are punctuated by channels, several of which are deep (>15 m at the barrier) that have been cut by upland streams when sea level was lower. Within the larger boundaries of our applied program (Aswani et al. 2007), thirty-two MPAs have been created within these lagoons in the past 10 years, spanning all lagoon systems in New Georgia, with most MPAs now >5 years old. Unlike

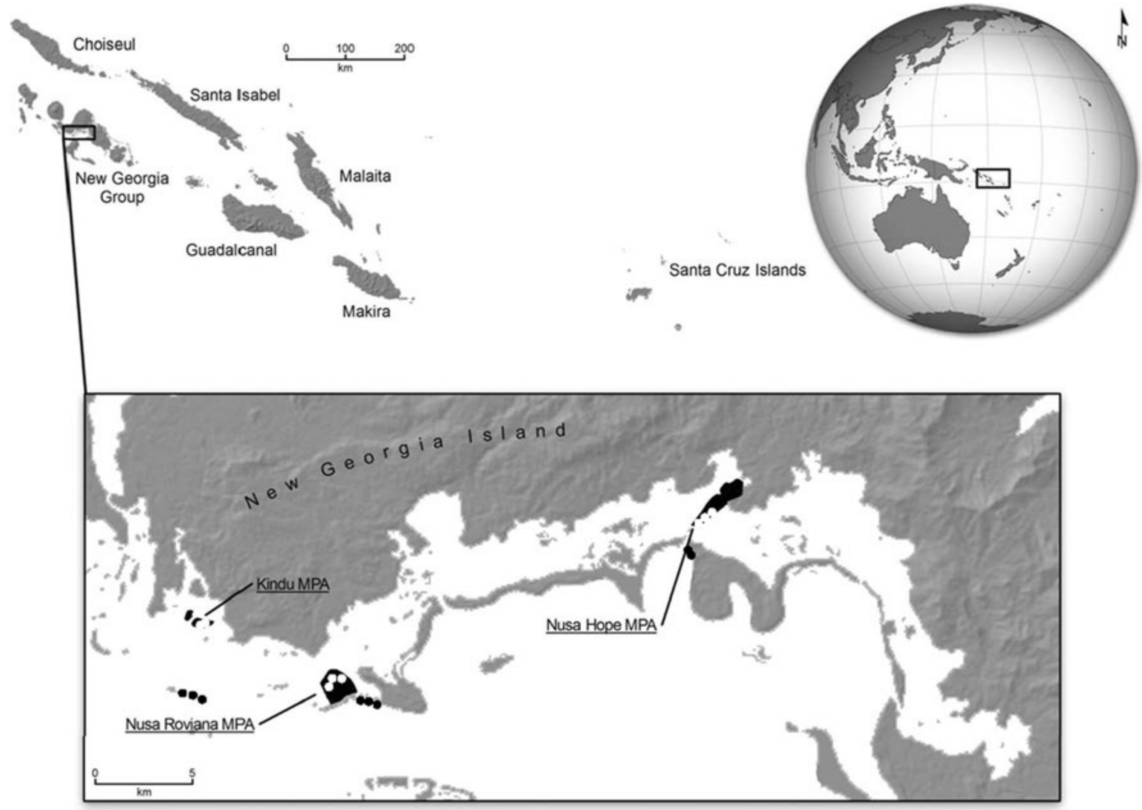

Fig. 1 Map of study system and the location of the MPAs that were surveyed. Survey sites are noted with *black* (outside MPA) or *white* (inside MPA) *dots*. Overlapping dots may not be distinguishable

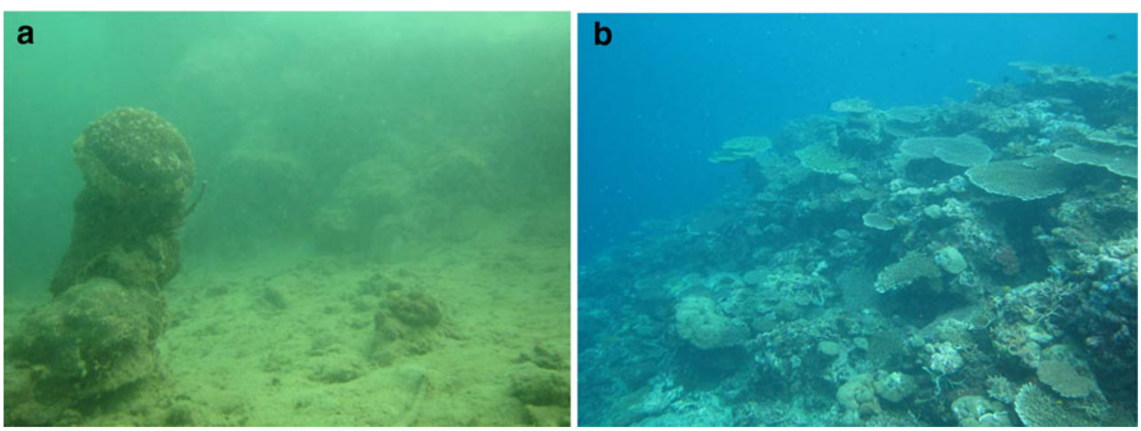

Fig. 2 Reefs **a** inside the Nusa Hope MPA and **b** on the barrier reef just outside the MPA

natural science-driven programs, the MPAs in this network were designed through interdisciplinary natural and social science research, which privileged local tenure institutions and indigenous ecological knowledge. For instance, many reserves were selected through various strategies, including (1) a feasibility study of local customary management (CM) to assess, among other factors, the possibility of implementing marine reserves in the area (Aswani 2005); (2) incorporation of the visual assessments of local photograph interpreters, who identified benthic habitats, resident taxa, and spatio-temporal events of biological significance, into a geographical information system (GIS) database (Aswani and Lauer 2006a); (3) the coupling of indigenous ecological knowledge with marine science to study aspects of life history characteristics of vulnerable species (Aswani and Hamilton 2004); and (4) the inclusion

of fishing time-series data (1994–2004) into GIS to visualize spatial and temporal patterns of human fishing effort and yields (Aswani and Lauer 2006b).

In this paper, we focus on three MPAs that are near underwater stream channels and that have been in place for 6–10 years (Fig. 1), such that they should have had enough time to rebuild fish populations (Halpern and Warner 2002). Sedimentation is pervasive in the lagoons, but particularly high near the stream channels (Fig. 3). One site, Nusa Hope, is in a part of the lagoon that has nearly continuous barrier islands that restrict flow into and out of the lagoon; the other two sites are located at the west end of the lagoon where the barrier reef is exposed only at low tides and so there is greater mixing between the lagoon and outer waters.

The three MPAs have experienced variable levels of enforcement; poaching does occur, particularly in the west end of the lagoon. To manage their MPAs, most MPA villages have established Resource Management Committees (RMC), which are constituted by different village groups including chiefs and elders, church authorities, and women representatives. In recent years, many of these RMCs have functioned intermittently and poorly. Personal observation and communication with local people suggests that Nusa Hope manages their MPA more effectively than Nusa Roviana or Kindu, for two reasons. First, the Nusa Hope area has a territorial-enclosed entitlement model of sea tenure (Aswani 1999), where territorial boundaries are circumscribed, authority over resource areas is centralized, and rights to marine resource areas are regionally recognized. Second, Nusa Hope is socially more cohesive because most of the community adheres to one religious denomination, the Christian Fellowship Church (CFC), and the CFC has a centralized authority that supports and spiritually sanctions the marine management program. In comparison, Nusa Roviana and Kindu have contested and less effective control over marine resource areas as well numerous religious and socio-economic factions and divisions.

Survey methods

Reef fish and corals

We used standard coral reef community underwater visual census survey methods to assess the fish and coral communities at three MPAs and three paired control sites within the lagoon (in 2005 and 2010), and three paired sites just outside the lagoon on the barrier reef (in 2010). Six 30 m by 4 m transects were haphazardly sampled at MPA and control (open to fishing) sites, with all fish >1 cm recorded to family and 5-cm size classes (see Table 1 for list of fish taxa surveyed). Fish of all size classes were surveyed to allow the assessment of changes in size structure of populations and food web structure. Fish taxa were then grouped by major trophic group for analyses (corallivores, farming herbivores, grazing herbivores, invertebrate eaters, planktivores, and predators), with more groups sampled in 2010 than in 2005. Benthic cover was sampled with 1 m^2 quadrants used to record the percent cover of live coral (hard and soft), dead coral, rubble, algal cover, pavement, sponges, and sand; results focus on the first four categories. All sampling was done on reefs 5–10 m in depth and less than 30-degree slope, except in rare cases on the barrier reef sites where slopes occasionally were up to 45 degrees.

Water quality

In July 2010, we surveyed water quality at 110 sites throughout Roviana Lagoon. July is one of the driest months of the year and so water quality during this time is expected to be a 'best-case' condition. At each site, an RBR XR-620 probe was lowered through the water column

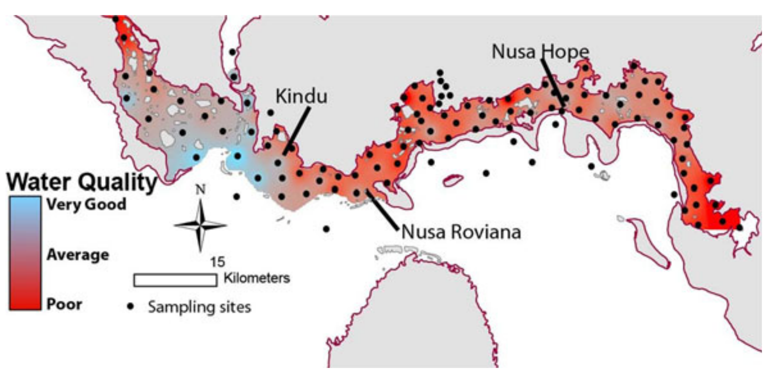

Fig. 3 Sampling sites and modeled water quality for Roviana and Vonavona Lagoons. The water quality index was interpolated from 110 sites throughout the lagoons (shown as *dots* in figure) and combines measures of Chlorophyll *a* fluorescence (phytoplankton), turbidity, and dissolved oxygen levels. Water quality is poor in the eastern areas of Roviana (and surrounding the Nusa Hope study site), but better in the central and eastern parts of the lagoon (adjacent to Nusa Roviana and Kindu)

Table 1 Families of fish seen in underwater visual census transects across all sites

Acanthuridae
Balistidae
Caesionidae
Carangidae
Chaetodontidae
Dasyatidae
Ephippidae
Haemulidae
Holocentridae
Labridae
Lethrinidae
Lutjanidae
Mugilidae
Mullidae
Nemipteridae
Pempheridae
Pomacanthidae
Pomacentridae
Scaridae
Scombridae
Serranidae
Siganidae
Sphyraenidae
Tetradontidae

to sample dissolved oxygen, chlorophyll fluorescence and turbidity once every 3 s, yielding water quality data approximately every 5 cm between the surface and the benthos. A water quality index for each site was developed using a sum of the normalized data for dissolved oxygen, chlorophyll fluorescence and turbidity, with high index values indicating poor water quality (high turbidity, high chlorophyll fluorescence, and low dissolved oxygen). We then interpolated water quality index values across the rest of the Lagoon using Arc GIS 10. We note that turbidity is an imperfect proxy for sedimentation rates.

Analytical methods

Because the physical setting for the three reserves varied, we analyzed each MPA and adjacent unprotected and barrier reef sites separately using ANOVA and then used a paired *t* test to compare overall effects of MPAs versus unprotected sites.

Results

There were few significant differences in coral reef condition between MPAs and fished sites within the lagoon either within or between survey years, while barrier reef sites had significantly more live coral and less rubble on average in the surveys conducted in 2010 (Fig. 4). These patterns generally held at each site, except that Kindu MPA had significantly more dead coral and less algal cover in 2010 than 2005 and Nusa Roviana MPA and barrier sites had significantly different dead coral and algal cover from the lagoon fished site (Fig. 4).

Results for fish communities were more varied. Trophic group abundances across all sites were not significantly different between MPAs and fished lagoon sites in 2005 or 2010, except for planktivorous fishes in 2010 (Fig. 5c, d); this latter result was due to large schools of Caesionidae passing through a few transects. At specific sites, there were few significant differences, except significantly more predators and corallivores in the Nusa Roviana MPA compared to the open site in 2005 but not in 2010, significantly more planktivores in Kindu and Nusa Hope MPAs compared to open sites, and more invertebrate eaters and farming herbivores on the Nusa Hope barrier site compared to the two lagoon sites in 2010 (Fig. 5a, b). Similarly, there were few differences in the average sizes of individuals within trophic groups in either year, except for the significantly larger predators within MPAs in 2005, a result that did not persist in 2010 (Fig. 6c, d). Predator size results in 2005 were driven by significantly larger fish in the Kindu and Nusa Hope MPAs (Fig. 6a). Few other significant differences existed among any of the MPA, fished, or barrier sites at any of the three locations (Fig. 6a, b).

Discussion

Resilience has two components, resistance and recovery time, that influence the degree to which a system experiences long-term consequences of a stressor's impact (Folke 2006). Sedimentation on the coral reefs within Roviana Lagoon had begun at least at the time of MPA creation, if not before, and so the potential resilience that MPAs could have provided the reefs was primarily through improving recovery time rather than greater resistance to the initial impact. Results show strong differences in coral reef condition between lagoon and barrier sites (in 2010), with few significant differences between MPA and fished sites within the lagoon for coral health or fish abundance and size in either 2005 or 2010. Furthermore, coral reef health showed signs of getting worse over time, while fish abundance and size remain largely unaffected by MPA protection over time and show some signs of decline.

There are two likely explanations for these patterns. First, fishing pressure within MPAs (via poaching) could be sufficient enough to remove benefits from protection and

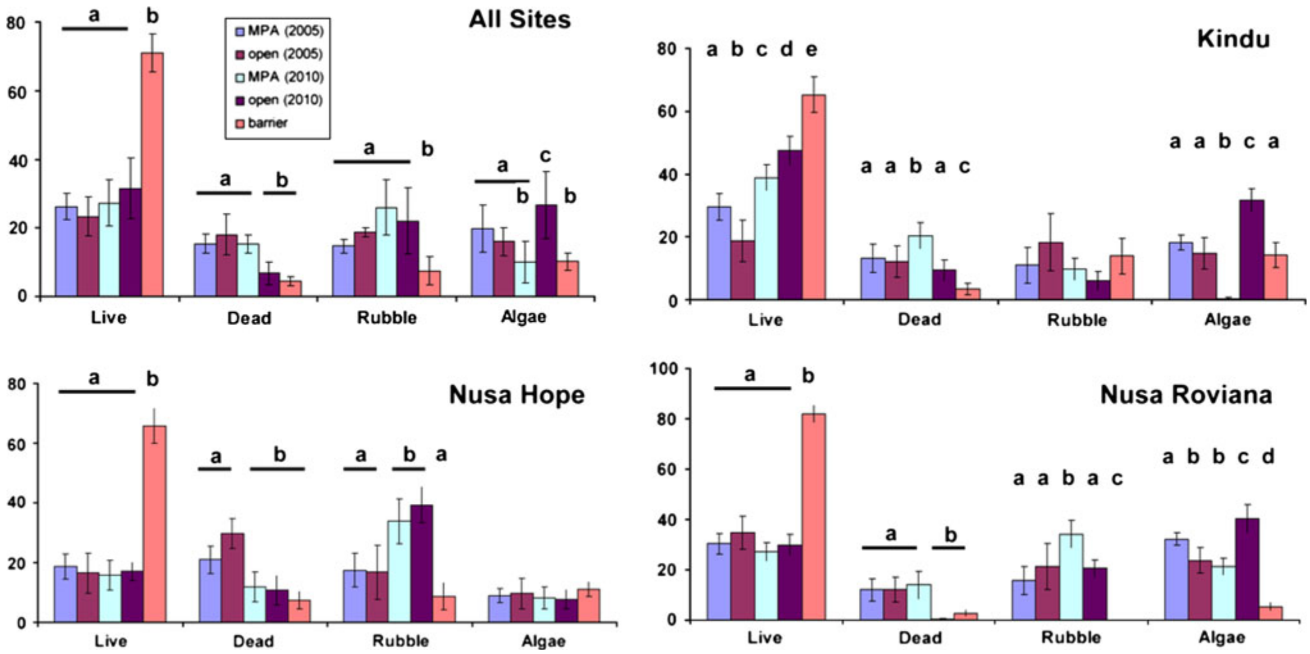

Fig. 4 Differences in benthic cover types between fished and MPA sites within Roviana Lagoon and on barrier reefs immediately outside the lagoon. Significant differences are connoted by *different letters* above *bars*

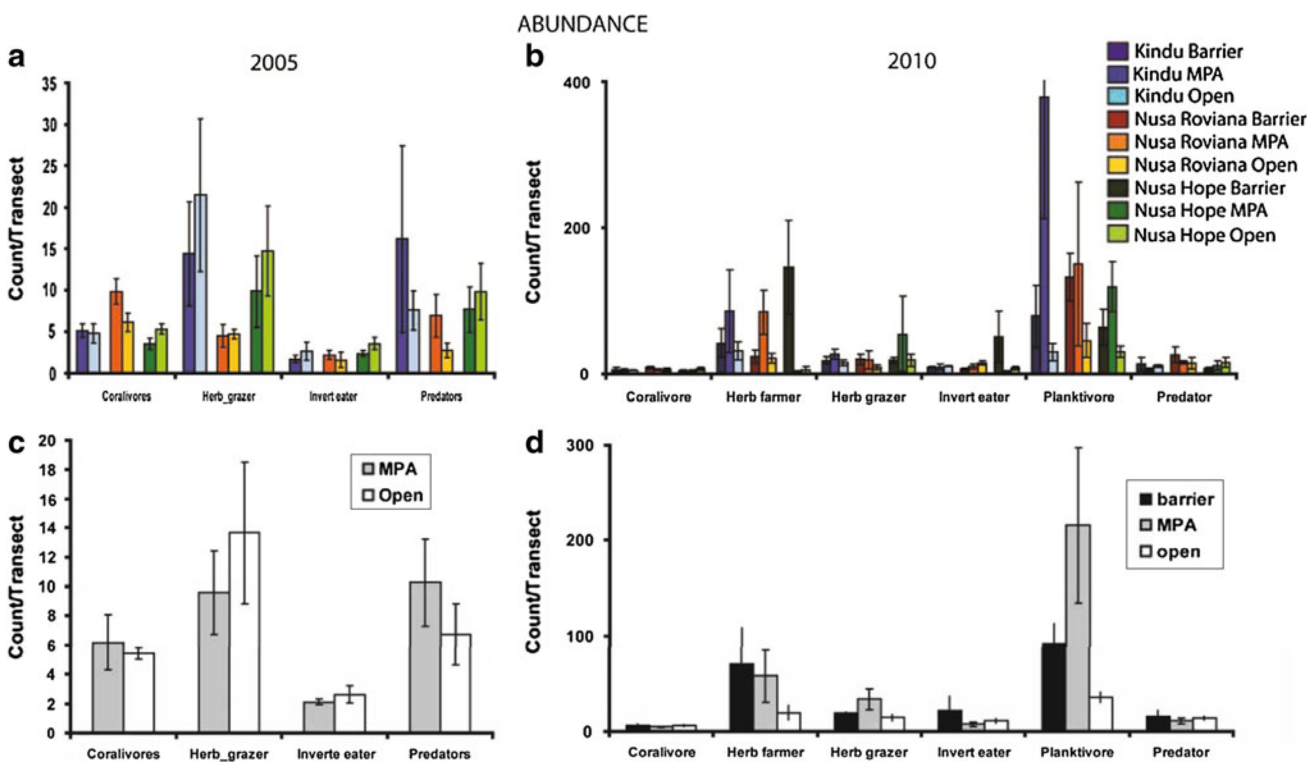

Fig. 5 Differences in abundance of key fish functional groups within MPAs, adjacent areas open to fishing, and immediately outside (barrier reef) Roviana Lagoon. Figures show each site separately **a**, **b** and the Mean ± SE by site type **c**, **d**. Trophic groups include corallivores, farming herbivores, grazing herbivores, invertebrate eaters, planktivores, and predators

suppress algal grazers and other fish trophic groups that help promote coral recovery. Second, sedimentation could be smothering the lagoon reefs and acting as a dominant stressor that MPAs are not able to counteract, in turn also suppressing fish size and community abundances. Although we were not able to survey reef condition in the lagoons

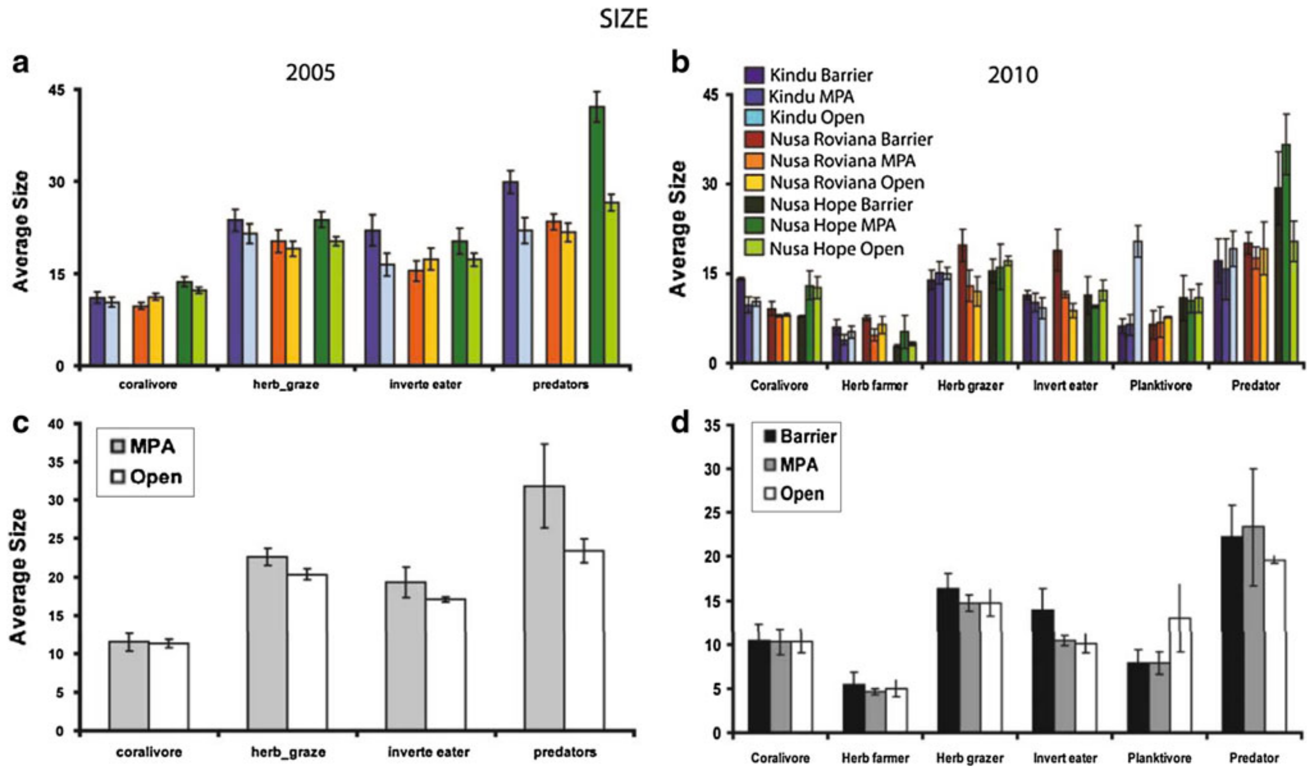

Fig. 6 Differences in average size of key fish functional groups within MPAs, adjacent areas open to fishing, and immediately outside (barrier reef) Roviana Lagoon. Figures show each site separately (**a**, **b**) and the Mean ± SE by site type (**c**, **d**). Trophic groups include corallivores, farming herbivores, grazing herbivores, invertebrate eaters, planktivores, and predators

prior to sedimentation, personal observation (see also Fig. 2) makes it clear that reefs have been severely smothered by sediments, but it is also unlikely that fish communities, in particular average fish size, would be strongly affected by sedimentation, and so it is likely that both factors are at play in keeping MPA coral and fish communities so similar to fished lagoon sites.

Lagoon and barrier reef systems are naturally different, such that some differences between coral reef systems are likely due to natural variability. Lagoon coral reefs tend to be less diverse and can have different composition of species than barrier (more exposed) systems. Even without sedimentation impacting lagoon reefs, barrier reefs tend to have coral communities that are more complex (higher three-dimensionality), greater species richness, and greater spatial extent (lagoon reefs tend to be patchy). We selected the barrier sites to be as close to the lagoon as possible to minimize this effect, such that the barrier sites can serve as a useful reference but not a perfect control site. Given the large differences in coral condition between lagoon and barrier sites, it was surprising that there were almost no differences in fish communities. The most likely explanation for this would be that fishing pressure is uniform and sufficient enough across sites, including poaching within MPAs, to make sites appear uniform; if this is true, then the MPAs are not serving the role they were intended to play and thus unable to provide any resilience to sedimentation.

It is notable that the MPAs had no significant effect on coral condition or the abundance or size of most fish trophic groups when compared to lagoon control sites (with a few exceptions, such as planktivore abundance; Fig. 5). There are four main potential explanations for this pattern. First, the sedimentation impacts could have been strong enough on the reef systems as to overwhelm the reefs, keeping MPAs from being able to improve conditions in a notable way. This seems highly plausible given the degree and extent to which we observed sedimentation on these reefs (in some places, sediments were so thick as to have completely smothered the corals) and the typical impact of logging in the area (Furusawa et al. 2004), and is supported by water quality data (Fig. 3) and local perceptions of increased sediment loading due to logging activities over the past two decades (Lauer and Aswani 2010). The second explanation is that fishing pressure is too low on the lagoon reefs for MPAs to have an impact. Under this scenario, differences in coral condition could be attributable to sedimentation impacts, but a lack of differences in fish communities between MPA and control sites would arise simply because fishing in the control sites is fully sustainable with minimal impact. Human population density is

variable around these lagoons, with some very sparsely populated regions (e.g., roughly 23 people per km^2 of reef habitat) and others where population (roughly 65 people per km^2 of reef habitat; values based on 3 % growth rate; Aswani 2002) and concomitant fishing pressure can be quite high because local people rely heavily on their community's reefs to supply fish. Indeed, the impetus for establishing the MPAs arose from tribal concern about maintaining or improving fish stocks on the lagoon reefs. A third explanation is similar to the second but posits that poaching is sufficient within MPAs to remove their conservation benefit. In a social science survey conducted in 2005 across the Roviana and Vonavona Lagoons for understanding general local perceptions of MPAs ($N = 147$), over 50 % of questioned households said that members of their villages were poaching in their respective MPAs (although differences existed between different hamlets under different tenure regimes; Aswani 1999). For instance, only 39 % of Nusa Hope respondents ($N = 33$) reported some kind of within-village incident or conflict as a result of their MPA, while nearly all Nusa Roviana respondents (91 %, $N = 22$) reported conflict as result of their MPA (Aswani, pers. comm.). The former has strong marine tenure governance while the latter does not, and this may explain why Nusa Hope is a better managed MPA. Finally, it is possible that the MPA sites, prior to designation, were in worse shape then they are now and that protection has actually improved them. Although we do not have pre-impact reference points to help directly address this issue, our temporal data (2005 vs. 2010) suggest that MPAs are not improving ecosystem condition as we would have expected under normal circumstances in which land-based stressors are not so pervasive. Fish communities were the same inside and outside MPAs at both time points, and coral conditions actually seem to be declining.

Lagoon systems may have greater resilience to disturbance because they naturally experience sediment runoff, and so it might be expected that if or when sediment loading into the lagoon is reduced, the reefs could rebound and MPA effects on coral and fished species would accrue quickly. Because logging continues throughout the region, there has been little opportunity for this resilience to take effect, and now additional stressors, most notably from climate change and increasing interest in mining, are making such recovery less likely.

Because the customary tenure system in the Solomon Islands gives significant control to local residents for how natural resources are used in upland and reef systems, improving ecosystem health can in theory be achieved relatively quickly by ceasing upland logging and, if needed, better enforcement of MPA regulations. Similar use of local knowledge and participation within the customary tenure system to affect conservation planning has been shown to be effective in other parts of the Solomon Islands (Game et al. 2011). However, effective community-based resource management practices rely on the ability of local resources to detect, understand, and interpret the effect of ecological changes. Results from our previous studies suggest that Roviana villagers manage and protect marine resources because they perceive that destructive fishing practices and overharvesting marine resources have negatively impacted marine ecological services (primarily fish stocks) on which they depend. Logging activities, on the other hand, are perceived by villagers as not disrupting the marine ecology enough to degrade its ability to provide ecological services (Lauer and Aswani 2010). Communicating results from this study to local residents will be a critical next step toward improving coral reef condition in the area.

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