Effectiveness of marine protected area networks in traditional fishing grounds of Vanua Levu, Fiji, for sustainable management of inshore fisheries

EBM FIJI ISLANDS

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Executive Summary

Research for this study was carried out under a four-year project to assist communities in Kubulau district and Macuata Province of Vanua Levu to establish networks of marine protected areas within their large, traditional fishing grounds (*qoliqoli*). From 2005-2009, underwater visual census (UVC) surveys of fish size and abundance and benthic habitat condition were carried out at 5 MPAs in Kubulau (2 small, village-managed (*tabu*) areas: Yamotu Lase, Nakali; 3 large, district-managed no-take MPAs: Namena, Namuri, Nasue), while 3 large tabu areas were surveyed in Macuata qoliqoli in 2008 (Cakaulevu, Talai-i-Lau, Vatuka). Reef fish species richness was surveyed in Kubulau in 2009 and compared against values observed from the Great Sea Reef in Macuata in 2004.

Kubulau outer barrier reef sites appear slightly less diverse than those on the Great Sea Reef (including Macuata outer barrier reefs), with average species numbers of 151 and 181 and total species counts of 342 and 495, respectively, for each region. Kubulau outer reefs support a high degree of endemism (~4.5% of all species). The species richness and uniqueness of fish fauna are comparable to other sites in PNG and Indonesia within the centre of the Coral Triangle.

In the Kubulau and Macuata MPA networks, the factors which appear to have the most influence on the success of management include: size; placement of reserves in naturally productive habitats; visibility by villages or others authorized to enforce management rules; distance from potential poachers; and longevity of protection. While the small Yamotu Lase tabu had significantly greater reef fish biomass and abundance compared to adjacent fished areas, overall values per hectare were low compared with other fished and unfished areas in the qoliqoli, suggesting potential effects of substrate cover in the backreef or regular harvesting for an annual feast. The Nakali tabu, while also small, supported over ten times the total fish biomass and nearly four times the total fish abundance per hectare as the Yamotu Lase tabu in 2007. This is likely due to the natural geomorphology of the reef system, which may have helped the reef fish populations recover by 2009 after a series of 3 harvests between the 2007 and 2008 surveys.

Results were equivocal from the larger MPAs that are closer to villages (Namuri, Nasue, Talai-i-Lau, Vatuka). Fished areas adjacent to the Nasue MPA often had greater biomass and abundance of fish: because there were no significant differences in habitat condition between reefs and since the Nasue reefs do not appear to be substantially impacted by recent runoff from the Yanawai River, the most likely explanation for the differences is poaching. Fishers from the adjacent Wailevu district have been caught fishing repeatedly within the MPA, which cannot be seen from any of the villages in Kubulau. While the Namuri MPA initially appeared successful in enhancing fisheries within the boundary of the reserve, by 2009, the patterns were reversed. The causes of the reversal were likely partially due to high populations of scarids seen spawning at some of the adjacent control sites and potentially also due to illegal fishing as an unintended consequence of presenting the data to Kubulau fishers at a planning workshop. Poaching is additionally a likely cause of the lack of response of fish populations to management in Talai-i-Lau and Vatuka MPAs: villagers in Macuata commented that fishers were commonly hiding out within the channels of the mangrove islands and fishing when they were not visible from land.

The large MPAs distant from the mainland (Namena, Cakaulevu) were most effective at enhancing fisheries, likely due to: strong commitment to enforcement; natural geomorphic features which promote recovery; longevity of protection; and distance from villages. The mean total fish biomass observed in Namena MPA (upper range: 2633 kg/ha) in Kubulau and Cakaulevu MPA (3515 kg/ha) in Macuata fall within the range of values reported for Palmyra atoll in the northern Line Islands, considered to have relatively intact trophic structures and minimal impact from humans.

Results of these surveys to 2008 have been presented back to community managers in Kubulau and Macuata to assist with the development of management plans for the qoliqoli and adjacent watersheds and to provide recommendations for MPA design and reconfiguration. The results from the 2005 survey data of Namena and adjacent reefs are being written up as a masters thesis by Naushad Yakub for submission to the University of the South Pacific in 2010.

Table of Contents

Introduction

Recent and historical overfishing, in conjunction with rapid land cover change, has led to a collapse of coastal fisheries, biodiversity and supporting ecosystem services around the globe (Jackson et al. 2001; Pauly et al. 2005; Worm et al. 2006). As many as 55% of island nations may be over-exploiting coral reef fisheries stocks (Newton et al. 2007). Increases in fishing pressure may result in declines of biomass of targeted, largely carnivorous species; declines in species richness;, and potential shifts in benthic habitat condition as grazing herbivores and predators of crown-of-thorns starfish (*Acanthaster planci*) are removed (Jennings and Polunin 1996, 1997; Pet Soede et al. 2001; Dulvy et al. 2004; Mumby et al. 2007). There is great concern to manage inshore fisheries populations both to preserve food security and because ecosystem shifts can occur even under modest levels of artisanal fishing (Jennings and Polunin 1996; McClanahan and Arthur 2001; Dulvy et al. 2004; Campbell and Pardede 2006)

In the Fiji Islands, although fisheries data are often uncertain, there has been a high level of pressure on coastal fisheries in the past few decades (Teh et al. 2009). Of the 400 traditionally managed fishing grounds (*qoliqoli*), at least 70 are considered over-exploited while a further 250 are fully developed (Hand et al. 2005). Rising prices for fish and fishery products have contributed to declines in artisanal catches from 1996 to 2002 (Raj and Evans 2004) while percentages of catches sold are increasing: catch per unit effort (CPUE) from recent surveys of village catch from locations across Fiji suggest that >70% of catch is being sold (IAS 2009). Over a century of beche-de-mer harvesting has resulted in notable depletion of stocks on reefs in southern Viti Levu and Bua Province of Vanua Levu (Teh et al. 2009), with unknown consequences on reef ecosystems.

In recognition of declines in coastal fisheries and marine biodiversity, there has been a global movement to increase the amount of area in the oceans under some form of management (IUCN 2009). The benefits of marine protected areas (MPAs) are recognized to include increases in abundance and biomass of targeted species (Trexler and Travis 2000; Russ 2002; Halpern 2003; Russ et al. 2004; Lester et al. 2009), which may lead to increased recruitment (Tetreault and Ambrose 2007; Evans et al. 2008) and migration of adults into neighbouring areas ("spillover"; Russ and Alcala 1996a). These benefits, however, rely strongly on effective compliance and enforcement as well as selection of appropriate size and spacing of MPAs within a network. Furthermore, most positive and lasting effects have been observed in permanent no-take areas compared with partial protection (Denny et al. 2004) or periodically harvested areas (Alcala et al. 2005).

The composition of fish species assemblages within an MPA may additionally be affected by benthic habitat structure and complexity. On a broad-scale, different habitat zones (e.g. lagoons, backreef, forereef, outer slope) can support naturally different fish communities with different size and trophic structures, which may be due to habitat utilization preferences, degree of disturbance and/or ontogenetic shifts (Friedlander et al. 2003; Adams et al. 2006). Sites with high reef complexity and low disturbance frequency have been shown to support high biomass of reef fish (Friedlander and Parrish 1998). Disturbance (i.e. storms, mortality following coral bleaching) that alters reef complexity may therefore have strong negative effects on reef fish assemblages (Graham et al. 2006; Graham et al.

2007). On Fijian reefs, decline in abundance of small corallivores and other damselfish have been associated with decreases in branching coral and coral-associated habitat complexity: these habitat-associated reductions in availability of prey can be a more important driver of piscivore abundance than fishing pressure (Wilson et al. 2008). Thus, information on differences in benthic habitat is paramount when evaluating reef fish responses to management measures (i.e. protection). Inclusion of these highly complex habitats in MPA network design should also improve reef resilience to disturbance (McLeod et al. 2009).

The main objective of this study was to evaluate reef fish response to protection across MPA networks in two large fishing grounds of Vanua Levu, Fiji. We first compare natural fish diversity from the Cakaulevu (Macuata) and Vatu-i-Ra (Kubulau) reefs. We then evaluate the effectiveness of the two MPA networks and attempt to identify factors influencing their success or failure in increasing fish numbers and sizes. In addition, we discuss how experimental design can limit the ability to detect differences in fish abundance and biomass related to protection.

Methods

Study region

The Kubulau and Macuata traditional fisheries management areas (*qoliqoli*) of Vanua Levu, Fiji, represent globally significant areas of marine biodiversity (WWF 2004a). The southerly facing Kubulau qoliqoli includes a significant portion of the Vatu-i-Ra passage, barrier reef and lagoon, and the Macuata qoliqoli incorporates a large section of the north-facing Cakaulevu Reef and adjacent lagoon (Figure 1).

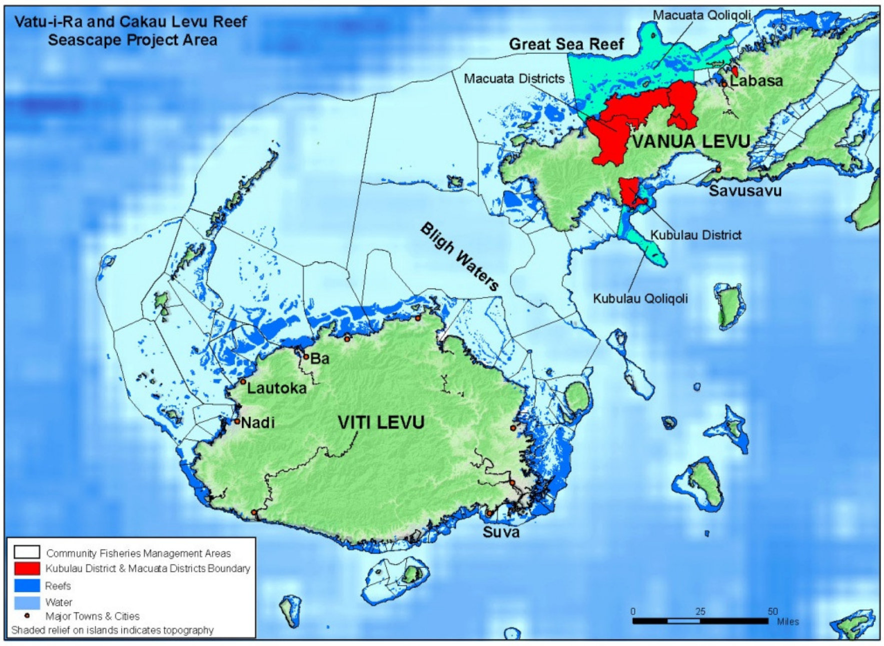


Figure 1. Study locations of Kubulau and Macuata on the island of Vanua Levu located within the main Fiji islands. Land area of districts with traditional fishing rights are indicated in red; qoliqolis are indicated in aquamarine.

Kubulau District, located in Bua Province, has a population of approximately 1,000 spread between ten villages, seven of which are located on the coast. The area of Kubulau's qoliqoli is 260 km^2 and its MPA network comprises 17 community-managed MPAs (*tabu*) sites and 3 district-wide MPAs, totaling approximately 80 km^2 (~30% of the qoliqoli; Figure 2, Table 1).

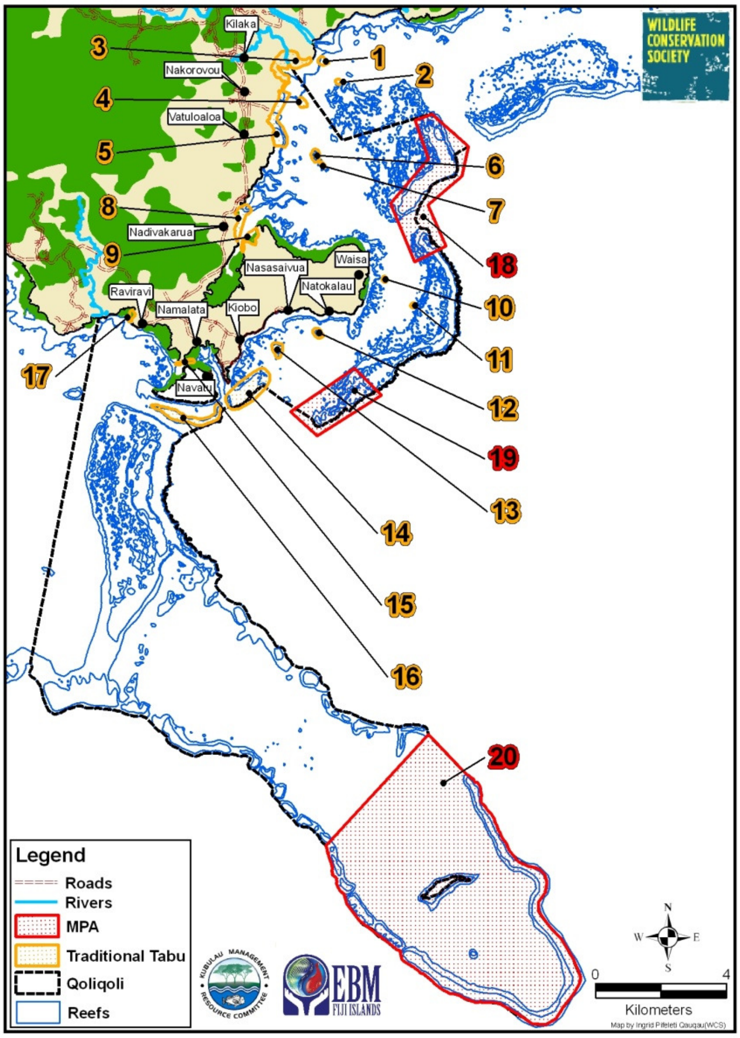


Table 1. List of marine protected areas and sizes (km^2) in Kubulau qoliqoli as of July 2009. * denotes tabu areas technically outside of Kubulau qoliqoli, however the boundary is contested by some of Kubulau's residents.

MPA	Size (km^2)
1. Yamotu ni Ogo*	0.09
2. Bovici*	0.04
3. Bagata	0.91
4. Yamotu ni Kake	0.11
5. Rewa Bota	0.86
6.Yamotu Lase	0.13
7. Cakau Vutia	0.03
8. Vatumakaua	0.40
9. Toba Tabu	0.27
10. Nukuvarasa	0.04
11. Yamotu ni Walu	0.04
12. Cakau Vusoni	0.11
13. Cakau Lekaleka	0.20
14. Naitaga	1.54
15. Buiyayamo	0.09
16. Nakali	0.77
17. Nasoga	0.08
18. Nasue	8.14
19. Namuri	4.25
20. Namena	60.61

Figure 2. Location of village-managed traditional tabu areas (orange-highlighted numbers and outlines) and district-managed MPAs (red-highlighted numbers and shading) within Kubulau qoliqoli.

Macuata Province is composed of 37 villages in four districts with a population of ~10,000 which have traditional fishing rights within the qoliqoli. The area of Macuata's qoliqoli is 1,344 km^2 and its MPA network as of the surveys in 2008 included 9 large community managed tabu areas totalling 111.9 km^2 or ~8% of the qoliqoli (Figure 3, Table 2).

Traditional and hierarchical community-level governance systems have regulated natural resource use and management in the Fiji for centuries (Veitayaki 1997). While the state maintains ownership of qoliqolis throughout Fiji, the *Fisheries Act* explicitly recognizes traditional fishing rights by customary land owners (Clarke and Jupiter in press). Qoliqoli resource management committees were established in both Macuata and Kubulau in 2004 and 2005, respectively, made up of representatives from each village whose management decisions require authorization from the high council of chiefs (*Bose Vanua*) in each region. The resource management committees make broad decisions over regulations for the qoliqoli (including the district MPAs), while village chiefs retain the rights to determine gear restrictions, temporary closures and other local regulations in individual village tabu areas (Clarke and Jupiter in press).

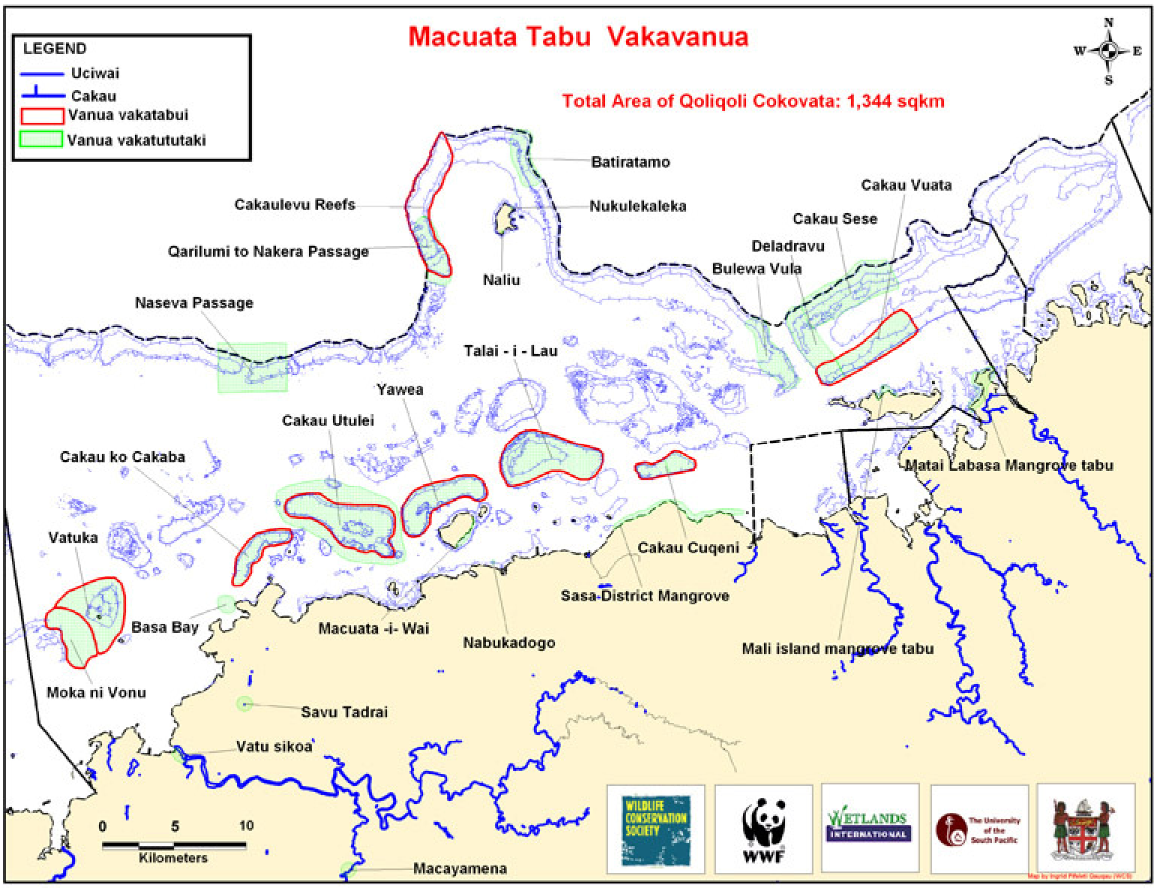


Figure 3. Location of village-managed traditional tabu areas (red outlines) within Macuata qoliqoli, plus proposed areas (green shading) for re-configuration of MPA network.

Table 2. List of marine protected areas and sizes (km^2) in Macuata qoliqoli as of July 2009.

MPA	Size (km^2)	MPA	Size (km^2)
Moka ni Vonu	8.65	**Yawea**	11.89
Vatuka	14.05	**Cakau Cuqeni**	4.72
Cakau ko Cakaba	6.37	**Talai-i-Lau**	18.85
Namotukai	0.25	**Cakau Vuata**	12.76
Cakau Utulei	18.82	**Cakaulevu Reefs**	15.52

Fish diversity surveys

Surveys to assess fish diversity were conducted in Kubulau in April 2009 using the identical methods to techniques used in Macuata qoliqoli along the Great Sea Reef in 2004 (WWF 2004b). Each survey covered approximately a 100 m wide swath in an ascending zig-zag search pattern (~40 m – surface) for approximately 1 hour. Dives were split evenly between: deep slopes (~40 m - 30 m) to search for fast-moving pelagic fish; mid-slopes (~30 m - 10 m) for largely conspicuous mid-water fish; and reef crests/flats (~10 m – surface) for coral and sand-dwelling species. For potentially new species, voucher specimens were collected using a Hawaiian sling spear, photographed, fixed in 10% formalin, and transferred to 70% ethanol solution. All specimens were deposited at the University of the South Pacific in Suva.

In order to compare the results of fish species richness between the survey areas and other regions of the Indo-Pacific, the Coral Reef Fish Diversity Index (CDFI) was calculated (Allen 1998). The CFDI is a rating system based on the number of species present in the following six families: Chaetodontidae, Pomacanthidae, Pomacentridae, Acanthuridae, Scaridae and Labridae. These families are particularly good indicator groups of reef fish diversity, are taxonomically well documented, and generally represent greater than 50% of the observable fish species at any tropical reef worldwide. Using the CFDI and the following predictor formula, a reasonable estimate of the total coral reef fish fauna for the area can be calculated:

$$4.234\ (\text{CFDI}) - 114.446\ (\text{d.f.} = 18;\ R^2 = 0.96;\ P = 0.0001)$$

CDFI was calculated from Kubulau surveys and compared to prior surveys from Macuata and the Great Sea Reef and surveys from elsewhere in the Indo-Pacific.

UVC surveys of fish and benthos

Surveys of fish and benthos were carried out in Kubulau qoliqoli 2005, 2007, 2008 and 2009, and in Macuata qoliqoli in 2008[1], with slightly differing methods detailed below. Appendix 1 contains maps of all survey locations.

Fish surveys

Kubulau 2005: For the initial Kubulau baseline surveys in 2005, underwater visual census (UVC) was carried out at 158 locations within the qoliqoli between October and December to measure fish abundance and size of the following families: Acanthuridae, Balistidae, Carangidae, Carcharhinidae, Chaetodontidae, Ephippidae, Haemulidae, Kyphosidae, Labridae, Lethirinidae, Lutjanidae, Mullidae, Pomacanthidae, Scaridae, Scombridae, Serranidae (groupers only), Siganidae, Sphraenidae, and Zanclidae, plus *Chanos chanos* (Chanidae) as it is a targeted food fish. Sites were chosen to maximize spatial representation across reef habitats, resulting in low replication at the individual location level that we acknowledge may have high instantaneous variation in reef community assemblages (McClanahan et al. 2007). Namena MPA was the only protected area established prior to the surveys. To investigate specific differences related to protection within the Namena MPA (the only MPA established prior to the surveys), 112 transects (68 in Namena and 44 in control) were used from 71 total sites (Appendix 1-Figure 1). Measurements of fish size (total length) and abundance were recorded along 5 m x 50 m belt transects at deep (12 -15 m) and shallow depths (5 m – 8 m) at most forereef sites, and in shallow depths only in backreef areas.

[1] Funding from EBM Phase I (2005-2007) and Phase II (2007-2009) was primarily targeted to monitoring in Kubulau qoliqoli, thereby limiting monitoring in Macuata qoliqoli to 2008 only.

Kubulau 2007-2008 and Macuata 2008: For surveys from 2007 onward[2], Nemipteridae were also included in the target family list, and additional training was given to observers to ensure that they could recognize all species from within each target family. Thus, these surveys were analysed separately and no direct comparisons were made to the 2005 survey. Similar to 2005, measurements of fish size (total length) and abundance were recorded along five replicate 5 m x 50 m belt transects at deep (12 -15 m) and shallow depths (5 m – 8 m) at forereef sites, and at reef tops (0.5 – 2 m) and shallow depths at backreef sites.

Kubulau 2009: Exploratory data analysis in late 2008 revealed high variability in fish abundance and biomass recorded from backreef sites which made it difficult to detect differences related to management effects from data collected between October 2005 and October 2008, even when data were pooled across exposure gradients (forereef, backreef). A power analysis indicated that changing the sampling design to increased sample size of *forereef-only* sites would improve the ability to detect differences related to management (Appendix 2). As a consequence only data from forereef sites from datasets prior to 2009 were utilised for all analyses (except 2005). In April-May 2009, 33 sites were surveyed from deep and shallow depths on forereefs only in closed and open areas of Kubulau qoliqoli using methods described above.

Data cleaning and biomass calculation

Observer bias was investigated by assessing the mean number of fish species counted per transect, resulting in the exclusion of data from one observer from Kubulau 2007 surveys (19/346 transects) and data from one observer from the Kubulau 2008 surveys (4/391 transects) who routinely counted significantly fewer species than other observers. Biomass was calculated from size class estimates of length (L) and existing published values from Fishbase (Froese and Pauly 2009) used in the standard length-weight (L-W) expression $W = aL^b$, with *a* and *b* parameter values preferentially selected from sites closest to Fiji (e.g. New Caledonia). If no L-W parameters were available for the species, the factors for the species with the most similar morphology in the same genus was used (Jennings and Polunin 1996). If a suitable similar species could not be determined, averages for the genera were used. As many of the L-W conversions required fork length (FL), a length-length (L-L) conversion factor was obtained from Fishbase where necessary to convert from total length (TL) recorded during the surveys to FL before biomass estimation. Because the L-W formula resulted in some grossly overestimated weights for fishes that substantially change morphology as they age, maximum weights were used for certain species when these fish were sighted above threshold sizes (Table 3).

[2] Surveys were carried out in Kubulau in January 2007 and in January and April to May 2008. Surveys were carried out in Macuata in September - October 2008.

Table 3. Maximum published weights from Fishbase applied to listed species sighted above the indicated threshold size.

Species	Threshold size (cm)	Max published weight (kg)
Trianedon obesus	180	34
Carcharhinus melanopterus	75	13.6
Carcharhinus amblyrhynchos	150	33.7
Chanos chanos	80	14

Benthic substrate composition

Kubulau 2005 surveys: Benthic life-form categories and health were recorded along the 50m transect at 0.5 m intervals as described by English et al. (1997). For the analysis, the life-form categories were classed into five major functional strata, including: algae (algal assemblages, turf algae, macroalgae and *Halimeda* spp), live hard coral (all scleractinian coral lifeforms plus *Tubipora*), reef matrix (recently dead coral, dead coral with algae and coralline algae), other (soft coral, sponges, zooanthids and other soft-bodied invertebrates) and unconsolidated substrate (silt, sand and rubble).

Kubulau 2007-2009 and Macuata 2008 surveys: Similar to 2005, benthic substrate cover was recorded at 0.5 m interval point intercepts along a 50 m transects. However, new life form classes that were combined into 7 functional strata: unconsolidated substrate (US: rubble, sand, silt); reef matrix (RM: dead coral, reef pavement, crustose coralline algae, coralline algae); macroalgae (MA: all fleshy macroalgae > 2 cm, including cyanobacteria); live hard coral (LC: including *Millepora* and *Tubipora*); other soft substrate (OT: including soft corals, sponges, ascidians, anemones); turf algae (TA: ≤ 2 cm height on reef pavement)p; and upright coralline algae (UC: e.g. *Halimeda* spp). Live hard coral was identified to the genus level. In April-May 2009 only, each 0.25 m^2 surrounding the point was also given a complexity score (1 = minimal relief; 2 = some vertical relief (e.g. boulder corals); 3 = high vertical relief (e.g. branching corals, reef crevices)).

Statistical analyses

For the Kubulau 2005 fish and benthic data from the Namena region, the Shapiro-Wilks W test was used to assess normality. Because data were not normally distributed, a Kruskal Wallis non-parametric ANOVA followed by a post-hoc multiple comparison test was used to assess differences related to reef zone and management across fish trophic groups (Zar 1999). Mann-Whitney U tests were used to assess differences in benthic strata within each reef zone. Analyses were performed using JMP version 7.0.1 software.

For the Kubulau 2007-2009 data, non-parametric Mann-Whitney U tests and parametric t-tests (where appropriate) were used to assess differences in total fish, primary targeted fish, secondary target fish and non-target fish forereef abundance and biomass inside and adjacent to protected areas within the qoliqoli. Because sites surveyed around mangrove islands in Macuata did not have traditional forereef and backreef zones, all survey sites were included in Mann Whitney U analyses. All tests were performed with Statistica version 7.0 software.

To assess potential differences in benthic structure, Analsyis of Similarity (ANOSIM) was performed on a similarity matrix calculated with Euclidean distances between arcsine squareroot transformed mean percent benthic strata cover for each site, plus mean complexity and standard deviation of complexity for each site. One way analysis was performed separately with site and reef as factors in Primer-e version 6 software. ANOSIM generates a value of R which is scaled to lie between -1 and +1 with zero values representing the null hypothesis: R-values > 0.75 are considered well-separated; R > 0.5 are considered overlapping, but clearly different; and R < 0.25 are barely separable (Clarke and Warwick 2001).

Additionally, for the Kubulau 2009 data, log10 Modified Gower similarity matrices were calculated from mean fish biomass by species per site and used to ordinate data in multidimensional scaling (MDS) plots in PRIMER-e software. Vectors display trajectories of correlations (>0.35) with benthic habitat variables (7 strata plus mean complexity and standard deviation of complexity) and with potential correlates of fishing pressure and land-based threats (distance from land, distance from runoff, proximity to adjacent districts of Wailevu, proximity to adjacent district of Wainunu, visibility from villages, and distance from villages weighted by fish consumption (ω)). Distance from land was calculated as the perpendicular distance (km) from closest mainland source (including Navatu Island and excluding Namenalala Island). Distance from runoff was calculated as the distance (km) as water would likely flow through the reef network and lagoon to each site from the mouth of the Yanawai River. The proximities to Wailevu and Wainunu were calculated as the distance (km) from each site to the closest point on either qoliqoli boundary through boat passages using a minimum number of turn points. Distances from village were measured as the perpendicular distances (km) from each village to the site: this was weighted based on the frequency of fish consumption in each village as assessed from 2008 household surveys where respondents were asked on how many days of the previous week they consumed caught fin fish, based on the formula:

$$\omega = \frac{\sum_{i}^{N}(d_i * 1/c_i)}{N}$$

where c is the mean number of days per week fish was consumed in the *i*th village, d is the perpendicular distance from the *i*th village to the site, and N is the total number of villages (N = 9 as there was no fish consumption data available for Nasasaivua). All distances were measured in ArcView 3.2a software. Visibility was given a weighted, ranked score as to whether fishers could be spotted from land: 1 = not visible; 6 = can be seen from 1 location or from people walking along coastal fringe; 11 = can be seen from 2 locations; 16 = can be seen from >2 locations.

Results

Kubulau MPA Network

Levels of fish diversity

342 species of fishes were visually documented during rapid surveys in Kubulau, with a predicted fauna (based on the number of CDFI species) of 635 species for Kubulau outer reefs and surrounds (Table 4, Appendix 4). This is approximately 70 % of the total Fijian coral reef fish fauna and 50% of the total number of all fish species recorded in Fijian waters (Allen 2008). Comparisons of predicted fish species numbers from the CFDI suggests that the Kubulau outer reefs contain at least 73% of the species known within Fiji islands, about 20 % of the diversity of the Indo-West Pacific region and 16 % of the diversity worldwide (Table 5).

Table 4. Coral fish diversity index (CDFI) for restricted areas, the number of coral reef fish species as determined by surveys to date, and estimated total species numbers using the CFDI regression formula

Locality	CFDI	# observed Species	Estimated Total Species
Maumare Bay, Flores, Indonesia†	333	1111	1107
Madang, Papua New Guinea§	259	789	858
Capricorn Group, Great Barrier Reef†	232	803	765
Great Sea Reef, Fiji*	217	495	716
Samoa Islands†	211	852	694
KUBULAU, FIJI	177	342	635
Rowley Shoals, Western Australia†	176	505	576
Johnston Island, Central Pacific†	78	227	243

* WWF 2004b
† Allen 1998
§ Jenkins, unpublished data

Table 5. Coral Reef Fish Diversity Index (numbers of species) for Kubulau outer barrier reef sites compared on national, regional and global scales.

Family	Kubulau Outer Reefs	Fiji Islands	Indo-West Pacific	Worldwide
Labridae	55	79	350	402**
Pomacentridae	50	63	274	330
Chaetodontidae	27	35	105	122
Pomacanthidae	9	14	69	82
Scaridae	15	23	64	83
Acanthuridae	21	27	63	71
Total (CFDI)	177	241	925	1090

Degree of endemism

Kubulau outer reefs possess a high degree of faunal uniqueness that includes multiple Fijian endemic reef fishes (*Pomacentrus microspilus, Cirrhilabrus marjorie, Ecsenius fijiensis, Meiacanthus oulouensis, Plagiotremus flavus, Siganus uspi*), as well as a group of regionally endemic damselfishes found only in Fiji and Tonga (*Amphiprion barberi, Neoglyphidodon carlsoni, Pomacentrus callainus, P. spilotoceps*). Overall, the assemblage possesses at the very least 10 country or regionally endemic coral reef fishes. Endemics are also ubiquitous with a mean of almost 7 endemics seen per dive, with site KB 11 possessing the highest number of any site with 9 of 10 endemics. The average level of endemism was 4.6% of the entire fauna seen on any given dive.

Threatened species

From the list of 342 recorded species, 20 species (~6%) are listed on the IUCN Redlist of Threatened Species (IUCN 2008). The humphead wrasse (*Cheilinus undulatus*) is listed as endangered; the coral trouts *Plectropomous areolatus* and *P. laevis* are listed as vulnerable; and the remaining species (*Thunnus albacores, Anyperodon leucogrammicus, Cephalopholis argus, C.miniata, C.sexmaculata, C. urodeta, E. fuscoguttatus, E.howlandi, E.malabaricus, E.merra, E.miliaris, E.polyphekadion, Plectropomous leopardus, P.pessuliferus, Variola louti, Carcharhinus amblyrhyncos and Trianodon obesus*) are listed as either least concern or data deficient.

Species requiring further investigation

Unique species sighted and collected included: one specimen each of a goby (*Trimma sp.)* and a damselfish (*Neoglyphidodon sp*.) that appear different from described taxa; and an unusual species of *Pentapodus sp*. recorded by photograph only. We also observed an unusual *Cirrhilabrus sp*. a KB05 at around 52 m depth and an unusual *Haplolatilus sp*. at KB07 in around 17 m but were unable to collect or photograph either of these fishes. It is also noted that there were a high number of major colour variants of *Centropyge bispinosus*, as well as previously noted variations of *Pomacentrus mollucensis, Chrysiptera talboti* and *Labroides dimidiatus*.

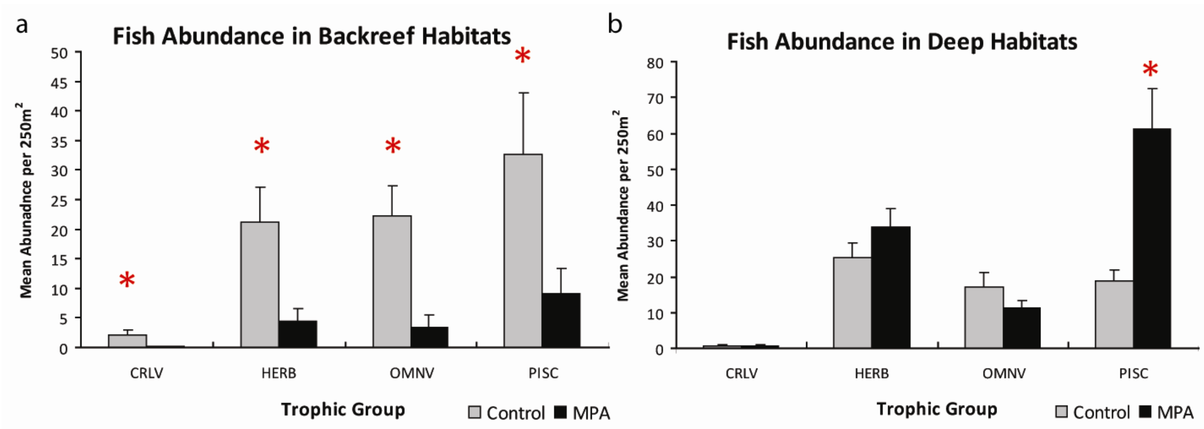
Namena MPA effectiveness from 2005 baseline data

In backreef habitats, mean fish abundance was significantly greater for all trophic levels in control sites versus protected sites (Figure 4a, Table 6a). In deep forereef habitats, there was only significant difference in piscivore abundance, which was greater within Namena than outside (Figure 4b, Table 6b). In shallow foreef habitats, both piscivores had significantly higher mean abundance in closed sites within Namena, while omnivores had higher abundance in control sites (Figure 4c, Table 6c). Mean differences in fish biomass by trophic group (Table 7) were consistent with the abundance data in all of the above cases except that there was no significant difference in omnivore biomass at shallow forereef depths.

The backreef sites of Namena had significantly higher cover of algae and unconsolidated substrate and less cover of hard coral than control sites (Figure 5, Table 8a). Within the forereef zones, the shallow and deep habitat of Namena MPA had significantly greater reef matrix and algae than the control areas, though the mean cover of algae was very low in both cases (Table 8b,c). Cover of unconsolidated substrate was also significantly greater in the deep, protected areas (Table 8b).

Table 6. Mean difference in fish abundance (#/250 m^2) for each trophic group inside and outside Namena MPA. SE = standard error. CRLV = corallivore; HERB = herbivore; OMNV = omnivore; PISC = piscivore. Bold, green p values indicate significantly greater values inside the MPA to $p < 0.05$. Bold, red values indicate significantly greater values outside the MPA to $p < 0.05$.

Reef Zone	Trophic	Control	SE	MPA	SE	p
(a) Shallow Backreef	CRLV	2.15	0.86	0.13	0.13	**0.028**
	HERB	21.15	5.97	4.50	2.09	**0.003**
	OMNV	22.23	5.01	3.38	2.18	**0.001**
	PISC	32.54	10.47	9.13	4.17	**0.005**
(b) Deep Forereef	CRLV	0.69	0.33	0.73	0.28	0.972
	HERB	25.31	3.94	33.96	5.18	0.312
	OMNV	17.00	4.16	11.31	2.09	0.311
	PISC	18.75	3.16	61.19	11.22	**0.001**
(c) Shallow Forereef	CRLV	0.80	0.46	0.46	0.26	0.428
	HERB	26.07	4.39	34.96	4.88	0.401
	OMNV	15.40	3.35	6.88	1.32	**0.042**
	PISC	20.40	5.14	45.77	5.79	**0.003**



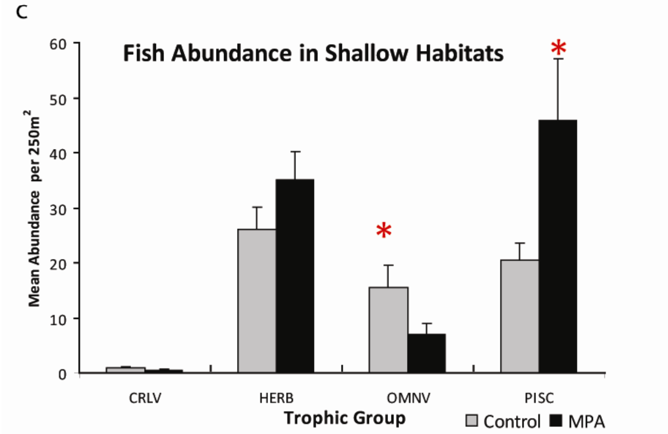


Figure 4. Mean fish abundance ± standard error (#/250 m^2) per trophic group of Namena MPA (black) and adjacent control areas open to fishing (grey). CRLV = corallivore; HERB = herbivore; OMNV = omnivore; PISC = piscivore. (a) Backreef habitats; (b) Deep forereef habitats; (c) Shallow forereef habitats. Red asterisks denote significant difference between protection status.

Table 7. Mean difference in fish biomass (kg/250 m^2) for each trophic group inside and outside Namena MPA. SE = standard error. CRLV = corallivore; HERB = herbivore; OMNV = omnivore; PISC = piscivore. Significant p-values are indicated (green = greater in closed; red = greater in open).

Reef Zone	Trophic	Control	SE	MPA	SE	p
(a) Backreef	CRLV	0.11	0.05	0.01	0.01	**0.033**
	HERB	5.15	1.44	2.05	1.01	**0.012**
	OMNV	2.45	0.68	0.93	0.55	**0.008**
	PISC	8.22	3.30	5.15	2.53	**0.019**
(b) Deep	CRLV	0.01	0.01	0.03	0.01	0.917
	HERB	10.91	3.79	10.73	2.92	0.351
	OMNV	1.59	0.48	26.32	21.38	0.300
	PISC	9.22	2.13	73.14	24.06	**0.003**
(c) Shallow	CRLV	0.01	0.01	0.02	0.01	0.567
	HERB	14.50	4.65	15.44	2.75	0.626
	OMNV	4.24	2.72	1.80	0.42	0.456
	PISC	6.14	1.20	31.64	5.06	**<0.001**

Table 8. Mean difference in cover of benthic strata inside and outside the Namena MPA for each reef zone. SE = standard error. Significant p-values are indicated (green = greater in closed; red = greater in open).

Reef Zone	Benthic Strata	Control	SE	MPA	SE	p
(a) **Backreef**	**Algae**	**0.46**	**0.39**	**5.41**	**2.36**	**0.019**
	Hard Coral	**20.62**	**3.74**	**3.29**	**1.63**	**<0.001**
	Others	**7.15**	**2.12**	**3.53**	**2.40**	**0.003**
	Reef Matrix	3.38	1.15	2.35	1.49	0.092
	Unconsolidated Substrate	**67.92**	**5.36**	**85.41**	**5.36**	**0.003**
(b) Deep	**Algae**	**0.25**	**0.14**	**4.35**	**0.63**	**<0.001**
	Hard Coral	32.13	4.13	32.42	2.54	0.815
	Others	13.00	2.46	19.85	2.48	0.078
	Reef Matrix	**3.88**	**0.95**	**12.15**	**1.62**	**<0.001**
	Unconsolidated Substrate	**42.06**	**5.73**	**26.85**	**4.29**	**0.027**
(c) Shallow	**Algae**	**0.13**	**0.09**	**2.76**	**0.73**	**0.002**
	Hard Coral	39.40	3.81	42.64	3.38	0.776
	Others	12.67	2.70	18.24	2.06	0.074
	Reef Matrix	**6.20**	**2.00**	**14.48**	**1.20**	**0.002**
	Unconsolidated Substrate	27.47	5.61	13.32	2.40	0.069

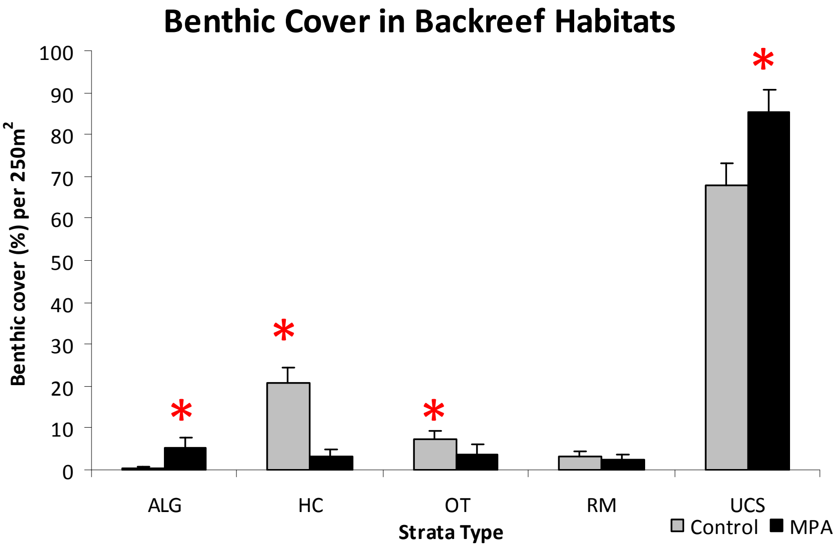


Figure 5. Mean difference in % benthic cover by strata within (black) and outside (grey) of the Namena MPA. Red asterisks indicate significant difference below $p < 0.05$. ALG = algae; HC = hard coral; OT = other; RM = reef matrix; UCS = unconsolidated substrate.

2007 UVC surveys

Total reef fish biomass (kg/ha) and abundance (#/ha) was significantly greater on forereefs inside the Namena MPA and the Nakali community-tabu of Navatu village (Figure 6a,b, Table 9a,b). Total reef fish biomass also significantly greater in the Namuri district MPA. There was no significant difference in reef fish biomass inside and adjacent to the Nasue district MPA, while there were significantly more fish outside the MPA. The highest total mean fish biomass and abundance was from sites inside Namena MPA. While total reef fish biomass and abundance of fish inside and adjacent to the Nakorovou community tabu (Yamotu Lase) were the lowest recorded values, there was significantly greater abundance of total fish and primary targets inside the tabu area (Table 9b,d).

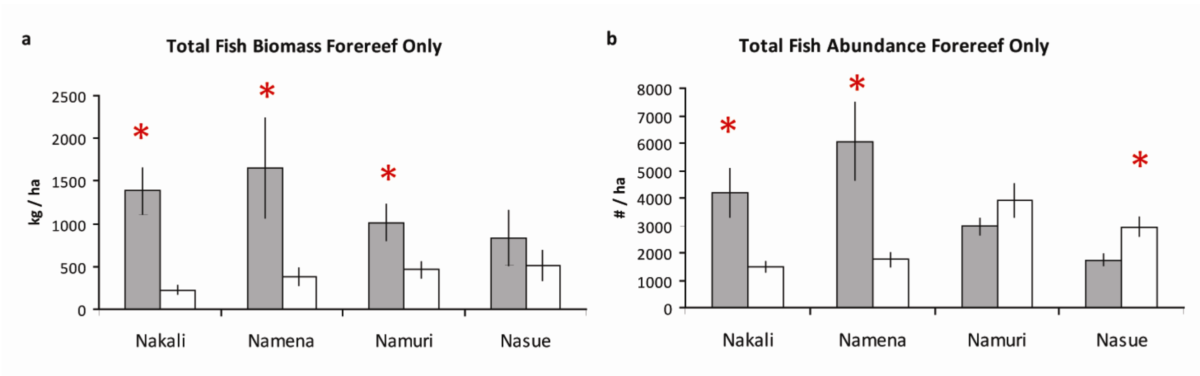


Figure 6. Mean (± standard error) (a) total fish biomass (kg/ha); and (b) total fish abundance (#/ha) from 2007 Kubulau fish survey data on forereefs inside MPAs (grey) and adjacent open fishing grounds (white). Red asterisks indicate significant differences at $p < 0.05$.

Table 9. Mean abundance and biomass (mean ± standard error) for closed and open forereef sites of MPAs and community tabu areas from Kubulau 2007 in: (a) total fish biomass (kg/ha); (b) total fish abundance (#/ha); (c) primary target fish biomass (kg/ha); (d) primary target fish abundance (#/ha); (e) secondary target fish biomass (kg/ha); (f) secondary target fish abundance (#/ha); (g) non-target fish biomass (kg/ha); and (h) non-target fish abundance (#/ha). Z-adjusted values and p-values are reported from Mann-Whitney U tests. Significant p-values are indicated (green = greater in closed; red = greater in open).

Table 9.

Reef	Closed	SE	Open	SE	Z-adj	p-level
(a) Total reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	119.46	57.17	40.12	24.76	1.567	0.117
Nakadamulevu	--	--	443.56	75.78		
Nakali	1386.30	271.03	222.98	47.79	3.980	<0.001
Namena	1647.01	587.05	385.38	103.57	2.624	0.009
Namuri	1013.09	208.82	461.91	91.87	2.516	0.012
Nasue	831.36	321.83	510.12	177.59	0.726	0.468
(b) Total reef fish abundance (#/ha) on forereefs						
Yamotu Lase	1112	210	664	210	1.991	0.047
Nakadamulevu	--	--	3374	545		
Nakali	4184	901	1488	175	2.358	0.018
Namena	6064	1431	1758	249	2.530	0.011
Namuri	2958	305	3902	615	-0.812	0.417
Nasue	1739	223	2947	346	-2.552	0.011
(c) Primary target reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	67.30	52.25	8.75	5.08	1.261	0.207
Nakadamulevu	--	--	89.39	26.27		
Nakali	639.44	202.67	85.35	24.01	2.907	0.004
Namena	867.00	522.56	121.30	29.55	2.137	0.033
Namuri	603.24	201.45	94.65	33.01	2.840	0.005
Nasue	167.08	60.61	38.71	29.92	1.734	0.074
(d) Primary target reef fish abundance (#/ha) on forereefs						
Yamotu Lase	304	158	24	10	2.124	0.034
Nakadamulevu	--	--	382	86		
Nakali	537	109	216	58	2.038	0.042
Namena	1110	282	444	98	1.585	0.113
Namuri	694	155	520	163	0.855	0.393
Nasue	197	32	347	70	-1.186	0.236
(e) Secondary target reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	48.99	16.36	27.92	24.18	1.567	0.117
Nakadamulevu	--	--	317.17	58.83		
Nakali	666.93	139.49	121.90	29.20	3.862	<0.001
Namena	715.90	199.00	246.36	89.77	2.002	0.045
Namuri	356.35	60.74	313.31	63.29	1.109	0.267
Nasue	635.99	305.07	438.59	175.50	0.353	0.724
(f) Secondary target reef fish abundance (#/ha) on forereefs						
Yamotu Lase	608	111	528	160	0.838	0.402
Nakadamulevu	--	--	2424	432		
Nakali	2791	724	900	147	1.785	0.074
Namena	4328	1163	1090	187	2.517	0.012
Namuri	1646	167	2494	435	-0.798	0.425
Nasue	1248	157	2093	267	-2.345	0.019
(g) Non-target reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	2.24	0.97	3.45	2.46	0.431	0.666
Nakadamulevu	--	--	30.44	8.95		
Nakali	60.95	19.38	11.13	2.17	2.231	0.026
Namena	37.41	12.53	7.27	1.78	2.034	0.042
Namuri	51.82	13.33	40.80	9.64	0.528	0.598
Nasue	20.09	9.89	26.15	12.29	-0.478	0.633
(h) Non-target reef fish abundance (#/ha) on forereefs						
Yamotu Lase	168	70	112	70	0.757	0.449
Nakadamulevu	--	--	490	93		
Nakali	711	155	362	83	1.499	0.134
Namena	498	106	190	36	2.241	0.025
Namuri	604	75	778	152	-0.541	0.588
Nasue	288	75	472	101	-1.665	0.096

The bulk of the fish biomass across all sites was from primary and secondary targeted food fish, while secondary targeted food fish had the greatest numbers (Figure 7). The Namena, Nakali and Namuri MPAs all had significantly greater biomass of primary targeted reef fish species than at adjacent open sites (Figure 7, Table 9c). Both the Nasue MPA and Yamotu Lase tabu and their adjacent open fishing areas are notable for the relatively low biomass of major food fish species (Table 9c). The lack of significant difference in primary target fish abundance between open and closed areas of Namena and Namuri indicate that the fish inside the MPAs, while not more numerous, are larger than outside.

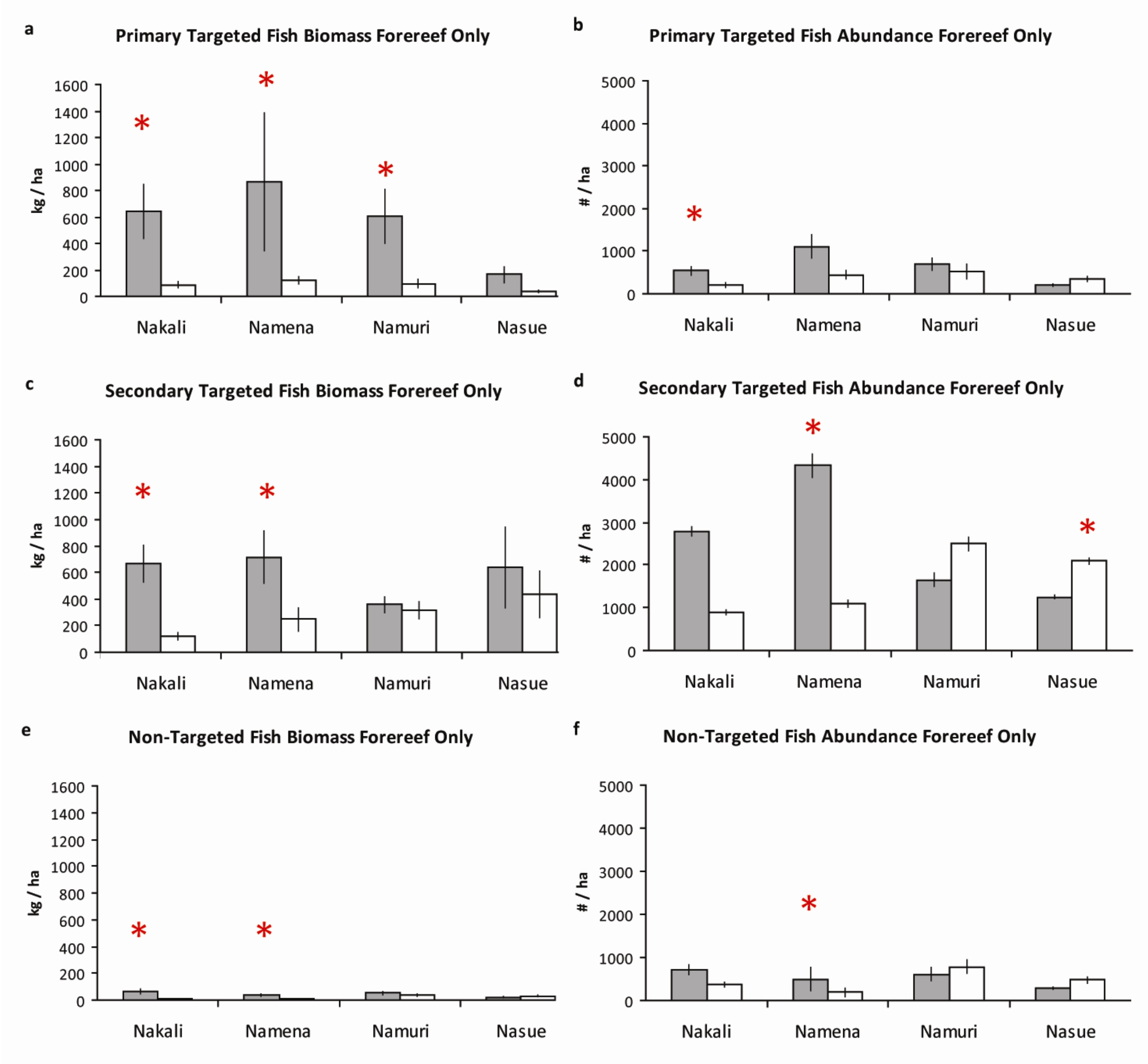


Figure 7. Mean (± standard error) fish biomass (kg/ha) and abundance (#/ha) of (a,b) primary targeted fish species; (c,d) secondary targeted fish species; and (e,f) non-targeted fish species inside and adjacent to MPAs from Kubulau 2007 surveys. Red asterisks denote significant differences at $p < 0.05$.

The Namena and Namuri MPAs additionally had greater biomass of secondary targeted reef fish species, and the Namena MPA had significantly more of these fish (Figure 7c,d, Table 9e,f). The secondary target fish were more numerous than primary targets and non-target fish counted at most locations, and were notably more numerous outside the Nasue MPA than inside the protected area. The biomass of non-target fish was very low for all sites, but strikingly significantly higher inside the Namena MPA in addition to being more numerous (Figure 7e,f, Table 9g,h).

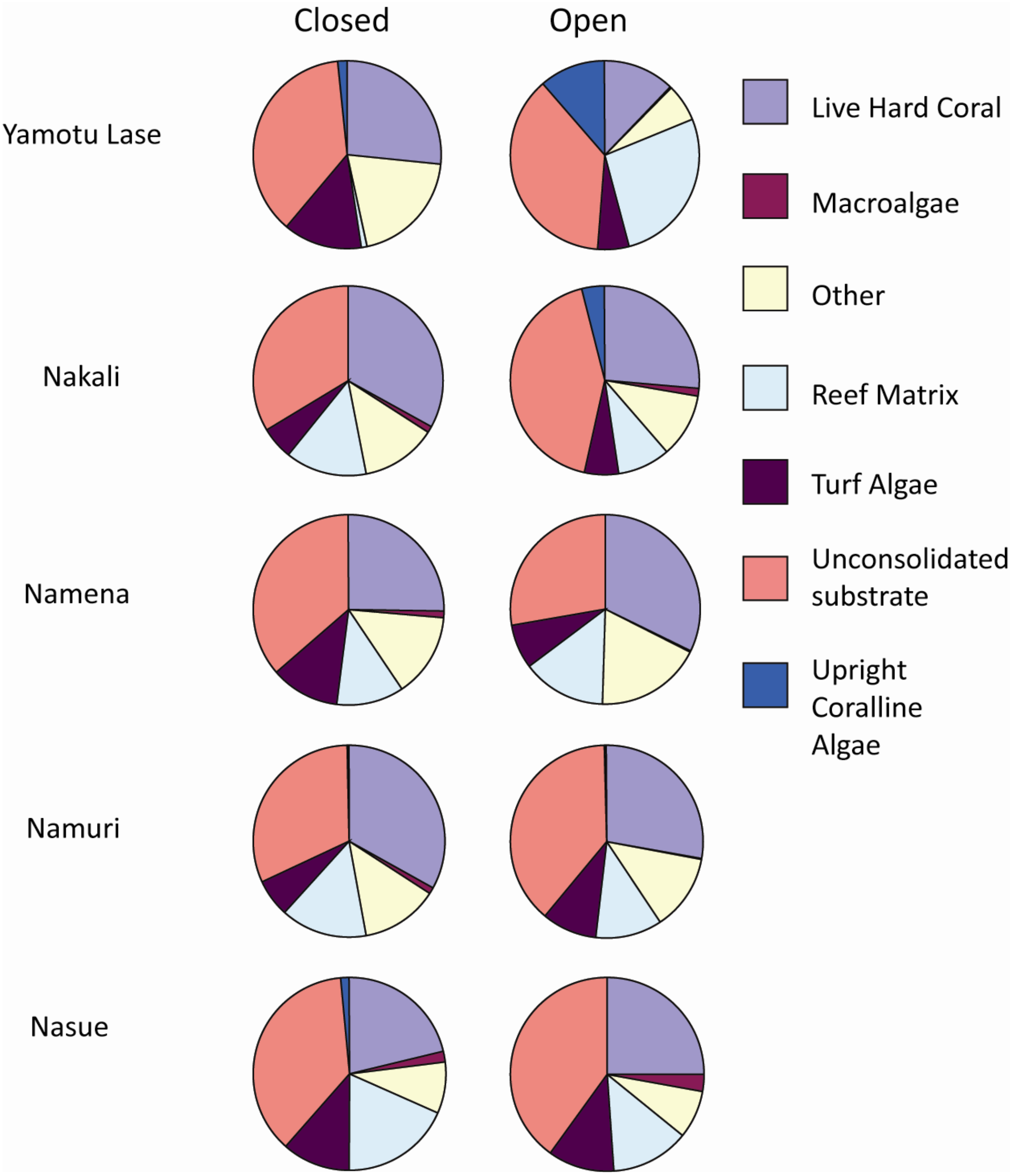


Figure 8. Mean cover of benthic strata from Kubulau 2007 surveys inside and adjacent to protected areas.

Mean benthic cover from 2007 surveys was comparable across most status at closed and open sites for all MPAs, with the exception of Yamotu Lase, where there significantly higher mean percent live coral and other cover along the closed transects (LC: 26.6% closed versus

12.2% open; OT: 20.2% closed versus 6.4% open), while open areas had significantly greater percentage of reef matrix (RM: 0.6% closed versus 27.0% open; Figure 8). ANOSIM of all benthic variables showed some separability between sites, but no significant difference (R = 0.5, p = 0.20) Closed areas of Nakali and Namuri also had slightly higher live coral cover and slightly less unconsolidated substrate than adjacent open areas, but these differences were not significant with Mann Whitney U test comparison. Further presentation of similarities and differences in benthic structure will be presented below from the Kubulau 2009 data.

2008 UVC surveys

Total reef fish biomass (kg/ha) and abundance (#/ha) was significantly greater on forereefs only inside the Namuri MPA with the highest mean fish abundance (8100 ± 910) recorded from any survey location from the survey (Figure 9a,b, Table 10a,b). Acanthurids and scarids (contributed proportionally the most 31% and 37%, respectively) to the elevated abundance inside the MPA. There were no significant differences in biomass or abundance between the Namena MPA and adjacent control area, while the Nasue MPA had significantly greater fish biomass inside. In contrast to the 2007 data, the Nakali community-tabu had significantly fewer fish inside the protected area compared with the adjacent fished areas.

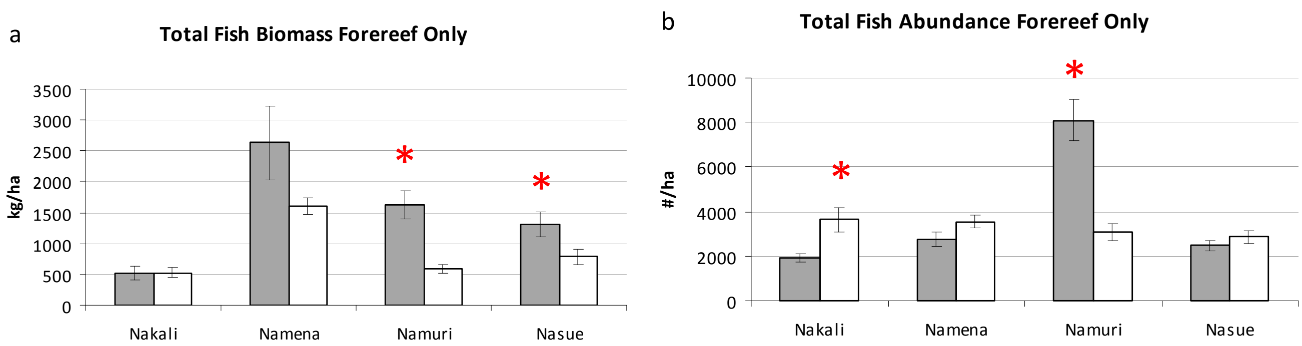


Figure 9. Mean (± standard error) (a) total fish biomass (kg/ha); and (b) total fish abundance (#/ha) from 2008 Kubulau fish survey data on forereefs inside MPAs (grey) and adjacent open fishing grounds (white). Red asterisks indicate significant differences at p < 0.05.

Table 10. Mean abundance and biomass (mean ± standard error) for closed and open forereef sites of MPAs and community tabu areas from Kubulau 2008 in: (a) total fish biomass (kg/ha); (b) total fish abundance (#/ha); (c) primary target fish biomass (kg/ha); (d) primary target fish abundance (#/ha); (e) secondary target fish biomass (kg/ha); (f) secondary target fish abundance (#/ha); (g) non-target fish biomass (kg/ha); and (h) non-target fish abundance (#/ha). Z-adjusted values and p-values are reported from Mann-Whitney U tests. Significant p-values are indicated (green = greater in closed; red = greater in open).

Reef	Closed	SE	Open	SE	Z-adj	p-level
(a) Total reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	673.64	102.10	215.36	34.92	3.175	**0.001**
Nakadamulevu	--	--	905.77	220.25		
Nakali	521.25	122.19	524.70	83.50	-1.095	0.274
Namena	2633.82	601.25	1602.71	141.33	1.040	0.299
Namuri	1625.72	226.91	585.39	67.44	4.317	**<0.001**
Nasue	1309.59	211.43	780.67	129.35	2.357	**0.018**

Reef	Closed	SE	Open	SE	Z-adj	p-level
(b) Total reef fish abundance (#/ha) on forereefs						
Yamotu Lase	3096	301	1560	282	2.721	0.007
Nakadamulevu	--	--	2668	285		
Nakali	1912	194	3633	537	-2.423	0.015
Namena	2746	303	3535	290	-1.841	0.066
Namuri	8100	910	3069	390	4.258	<0.001
Nasue	2480	240	2857	291	-0.733	0.464
(c) Primary target reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	145.55	54.44	64.55	16.49	1.021	0.307
Nakadamulevu	--	--	559.80	197.19		
Nakali	269.21	103.90	99.72	28.50	0.719	0.472
Namena	1897.53	617.53	988.64	123.53	1.911	0.056
Namuri	459.29	172.95	148.75	33.47	2.557	0.011
Nasue	759.40	666.50	280.97	74.88	3.387	<0.001
(d) Primary target reef fish abundance (#/ha) on forereefs						
Yamotu Lase	420	100	340	93	0.228	0.820
Nakadamulevu	--	--	874	199		
Nakali	325	47	711	196	-1.277	0.201
Namena	1108	171	842	86	0.816	0.414
Namuri	1010	147	347	80	3.750	<0.001
Nasue	654	102	396	56	1.934	0.053
(e) Secondary target reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	469.52	92.84	133.68	26.45	3.024	0.002
Nakadamulevu	--	--	317.76	46.42		
Nakali	235.01	37.78	336.86	59.70	-1.328	0.184
Namena	680.13	115.65	796.62	78.67	-1.461	0.144
Namuri	1060.57	114.91	402.70	50.29	4.317	<0.001
Nasue	473.48	105.21	460.59	99.54	-0.158	0.874
(f) Secondary target reef fish abundance (#/ha) on forereefs						
Yamotu Lase	2276	294	1000	155	2.497	0.013
Nakadamulevu	--	--	1598	163		
Nakali	1359	179	2213	350	-1.822	0.068
Namena	1374	227	2265	236	-2.938	0.003
Namuri	5954	737	2316	304	4.070	<0.001
Nasue	1422	166	1949	280	-1.159	0.246
(g) Non-target reef fish biomass (kg/ha) on forereefs						
Yamotu Lase	55.65	14.43	17.14	10.57	2.451	0.014
Nakadamulevu	--	--	11.65	2.96		
Nakali	9.15	1.49	59.80	14.21	-3.593	<0.001
Namena	51.01	26.70	71.93	22.53	-1.298	0.194
Namuri	92.46	14.15	26.96	21.08	2.860	<0.001
Nasue	65.74	21.08	37.63	7.90	1.416	0.157
(h) Non-target reef fish abundance (#/ha) on forereefs						
Yamotu Lase	392	61	220	136	2.223	0.026
Nakadamulevu	--	--	154	31		
Nakali	192	37	506	100	-2.818	0.005
Namena	254	56	317	66	-0.749	0.454
Namuri	1012	151	375	73	3.534	<0.001
Nasue	380	49	505	90	-0.050	0.960

The Namuri and Nasue MPAs had significantly greater biomass of primary targeted reef fish species than at adjacent open sites, while the Namena MPA had greater biomass which was not statistically significant (Figure 11, Table 10c,d). There were considerably more primary target fish in the fished areas adjacent to the Nakali community-tabu, though transects were highly variable: because the biomass was actually greater inside the tabu, individual food fish were still likely to be larger, though less numerous, within the protected area.

The Namuri MPA also had significantly greater biomass and abundance of secondary targeted food fish (Figure 11c,d, Table 10e,f), as did the Yamotu Lase community-tabu which had relatively low fish biomass compared with Namuri and Namena MPAs, but high numbers of secondary targeted fish. Secondary food fish made up the bulk of the fish sighted during the entire 2008 survey.

There were significantly more and bigger non-targeted fish inside the Namuri MPA and Yamotu Lase community-tabu, though the opposite pattern was observed for the Nakali community tabu (Figure 11e,f, Table 10g,h). As with the 2007 data, the contribution of these fish to the overall biomass was very low.

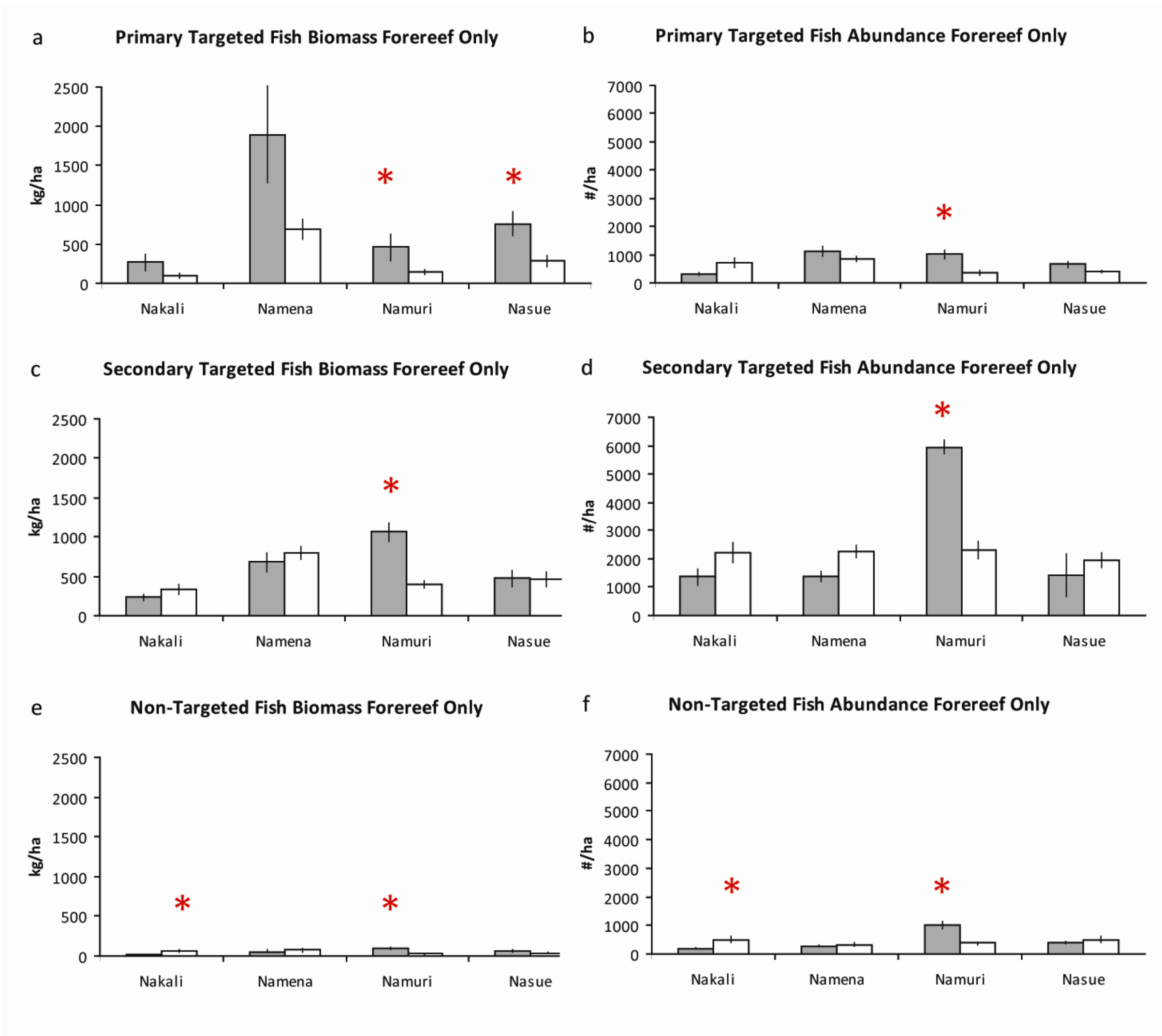


Figure 11. Mean (± standard error) fish biomass (kg/ha) and abundance (#/ha) of (a,b) primary targeted fish species; (c,d) secondary targeted fish species; and (e,f) non-targeted fish species inside and adjacent to MPAs from Kubulau 2008 surveys. Red asterisks denote significant differences at $p < 0.05$.

2009 UVC surveys

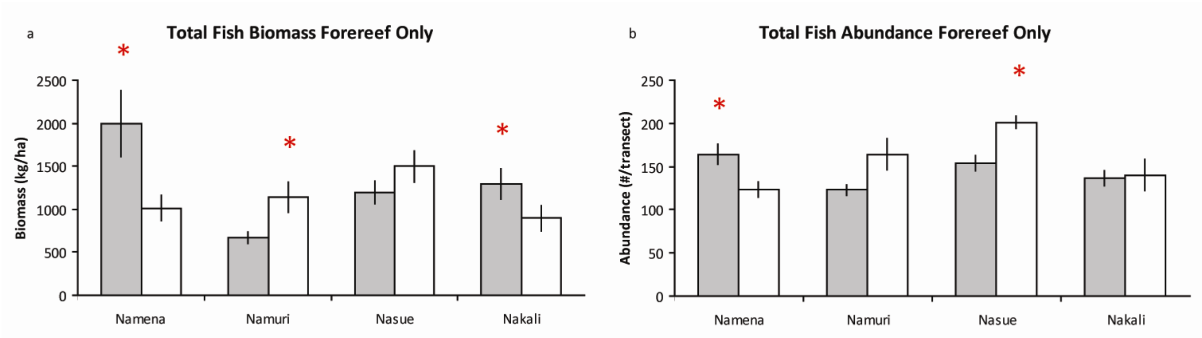


Figure 12. Mean (± standard error) (a) total fish biomass (kg/ha); and (b) total fish abundance (#/ha) from 2009 Kubulau fish survey data on forereefs inside MPAs (grey) and adjacent open fishing grounds (white). Red asterisks indicate significant differences at $p < 0.05$.

Total fish biomass was significantly higher inside the Namena MPA and the Nakali community tabu than in adjacent control areas, while fish abundance was also significantly greater in the Namena MPA (Figure 12a,b, Table 11a,b). Opposite patterns were true for the Namuri and Nasue MPAs: total fish biomass was significantly greater outside the Namuri MPA, while total fish abundance was greater outside the Nasue MPA (Figure 12a,b, Table 11a,b).

Table 11. Mean abundance and biomass (± standard error) between forereef closed and open areas for MPAs and tabus from Kubulau 2009 survey data in: (a) total fish biomass (kg/ha); (b) total fish abundance (#/transect); (c) primary target fish biomass (kg/ha); (d) primary target fish abundance (#/transect); (e) secondary target fish biomass (kg/ha); (f) secondary target fish abundance (#/transect); (g) non-target fish biomass (kg/ha); and (h) non-target fish abundance (#/transect). P-values are reported from nonparametric Mann-Whitney U tests (*) and t-tests (†) where data were normal. Significant p-values are indicated (green = greater in closed; red = greater in open).

Reef	Closed	SE	Open	SE	p-level
(a) Total reef fish biomass (kg/ha) on forereefs					
Nakali	1296.97	177.59	897.14	149.31	**0.005***
Namena	1994.50	387.98	1009.31	147.87	**0.007***
Namuri	673.47	66.47	1143.99	174.66	**0.042***
Nasue	1194.76	8.87	1498.94	7.39	0.353*
(b) Total reef fish abundance (#/transect) on forereefs					
Nakali	137	9	140	18	0.178*
Namena	164	11	124	9	**0.006**†
Namuri	123	6	164	18	0.199*
Nasue	154	9	201	7	**<0.001**†
(c) Primary target reef fish biomass (kg/ha) on forereefs					
Nakali	807.22	166.39	342.00	85.98	**<0.001***
Namena	986.87	284.29	350.23	72.60	**0.002***
Namuri	256.30	58.71	438.66	106.12	0.166*
Nasue	481.42	80.51	627.35	163.38	0.504*
(d) Primary target reef fish abundance (#/transect) on forereefs					
Nakali	37	5	16	4	**<0.001***
Namena	33	5	19	3	**0.004***
Namuri	18	3	21	5	0.912*
Nasue	26	4	28	4	0.942*
(e) Secondary target reef fish biomass (kg/ha) on forereefs					
Nakali	421.39	40.78	478.94	84.34	0.112*
Namena	886.36	156.76	599.17	110.52	0.091*
Namuri	356.38	32.66	617.75	85.48	**0.025***
Nasue	635.88	75.99	770.89	86.88	0.130*

Reef	Closed	SE	Open	SE	p-level
(f) Secondary target reef fish abundance (#/transect) on forereefs					
Nakali	56	6	81	13	0.265*
Namena	90	9	69	7	0.129*
Namuri	64	6	98	12	0.078*
Nasue	84	6	111	6	**0.002**†
(g) Non-target reef fish biomass (kg/ha) on forereefs					
Nakali	59.49	9.18	60.37	10.51	0.849*
Namena	80.50	8.17	57.51	7.92	**0.003***
Namuri	56.87	3.67	67.17	10.55	0.379*
Nasue	64.89	5.38	80.26	7.26	0.095*
(h) Non-target reef fish abundance (#/transect) on forereefs					
Nakali	43	3	40	2	0.510†
Namena	40	2	34	3	0.060*
Namuri	40	2	43	2	0.365*
Nasue	43	3	60	4	**<0.001**†

Part of the reason for the greater biomass outside Nasue and Namuri is due to the unusually high abundance and biomass of parrotfish (Scaridae) which observers visually observed spawning on Drokana reef (Figure 13). For other targeted fish families, there was significantly higher biomass of serranids, acanthurids, and lutjanids insides Namena MPA compared with adjacent open fishing areas (Figure 14). There was additionally more lutjanid biomass inside Nakali tabu and Nasue MPA, though the Nasue MPA had less biomass of acanthurids than in adjacent controls (Figure 14b,d).

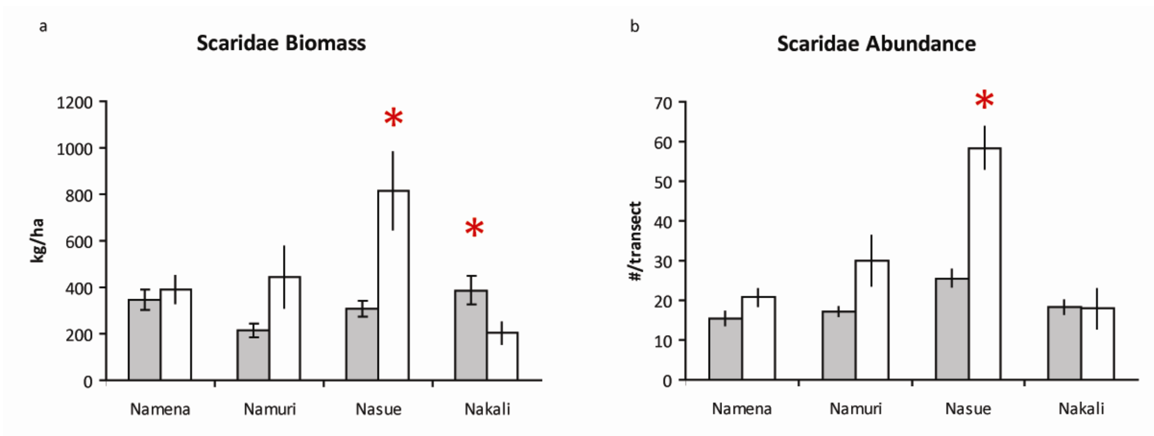


Figure 13. Mean (± standard error) (a) biomass (kg/ha) and (b) abundance (#/transect) of Scaridae on forereefs inside MPAs (grey) and adjacent open fishing grounds in Kubulau qoliqoli in 2009. Red asterisks denote significant differences at p < 0.05.

As with the 2007 and 2008 monitoring data, primary and secondary targeted food fish comprise the bulk of the biomass, while secondary targets are the most abundant of reef fish surveyed (Figure 15). The Namena MPA and Nakali community tabu had significantly greater amounts of primary targeted fish than adjacent control areas (Figure 15a,b). By contrast, the Namuri and Nasue MPAs had significant lower secondary targeted fish biomass and abundance, respectively (Figure 15c,d), and the Nasue MPA additionally had lower abundance of non-targeted fish (Figure 15f).

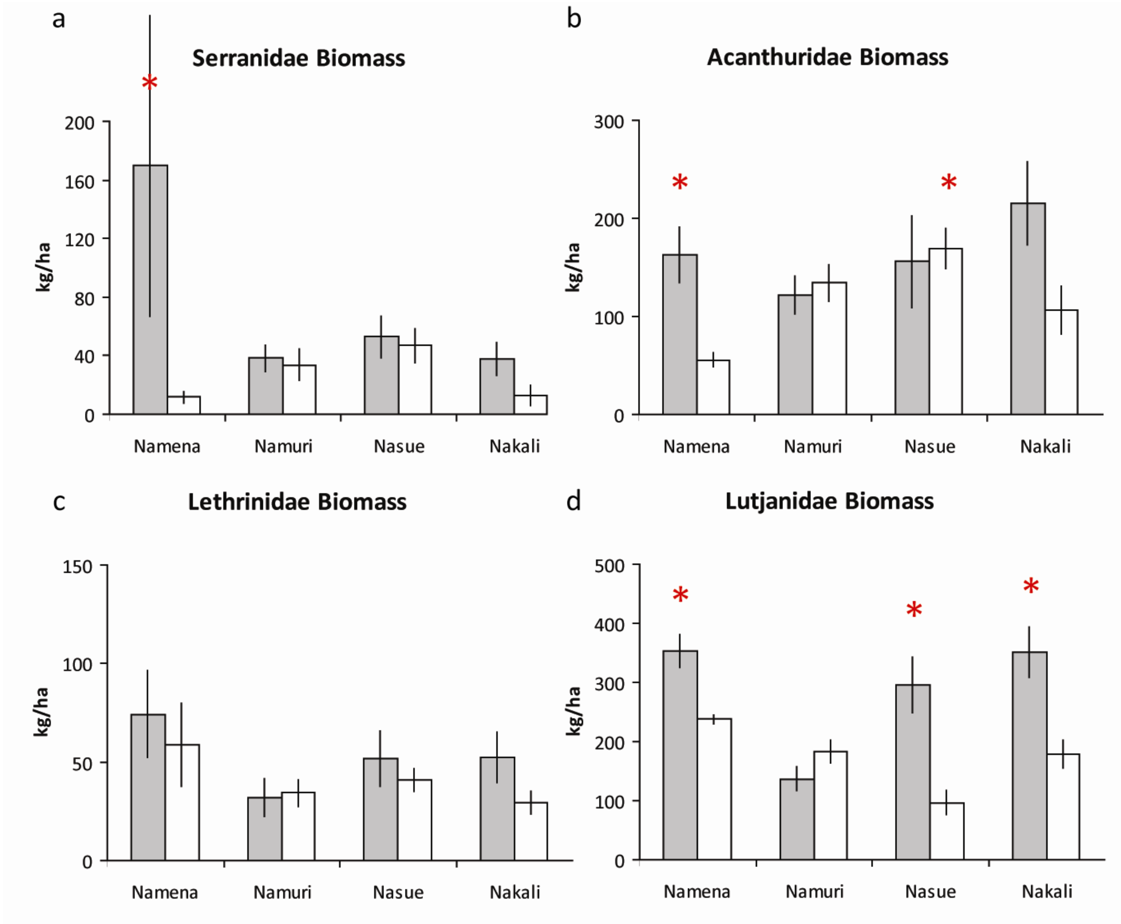


Figure 14. Mean (± standard error) biomass (kg/ha) of (a) Serranidae; (b) Acanthuridae; (c) Lethrinidae; and (d) Lutjanidae on forereefs inside MPAs (grey) and adjacent open fishing grounds in Kubulau qoliqoli in 2009. Red asterisks denote significant differences at $p < 0.05$.

ANOSIM results comparing benthic composition at the site level showed no overall difference between open and closed sites in the Kubulau qoliqoli ($R = 0.014$; Figure 16). When benthic composition was compared between reefs, there were only strong differences between Nakali and Namuri reefs and between Namena and Cakaunivuaka reefs (which were not directly compared for fish composition) (Table 12). Namuri and Cakaunivuaka reefs were also significantly different, however control sites for Namuri MPA only contained 2 sites from Cakaunivuaka reef and 2 from Drokana reef, which was highly similar to Namuri.

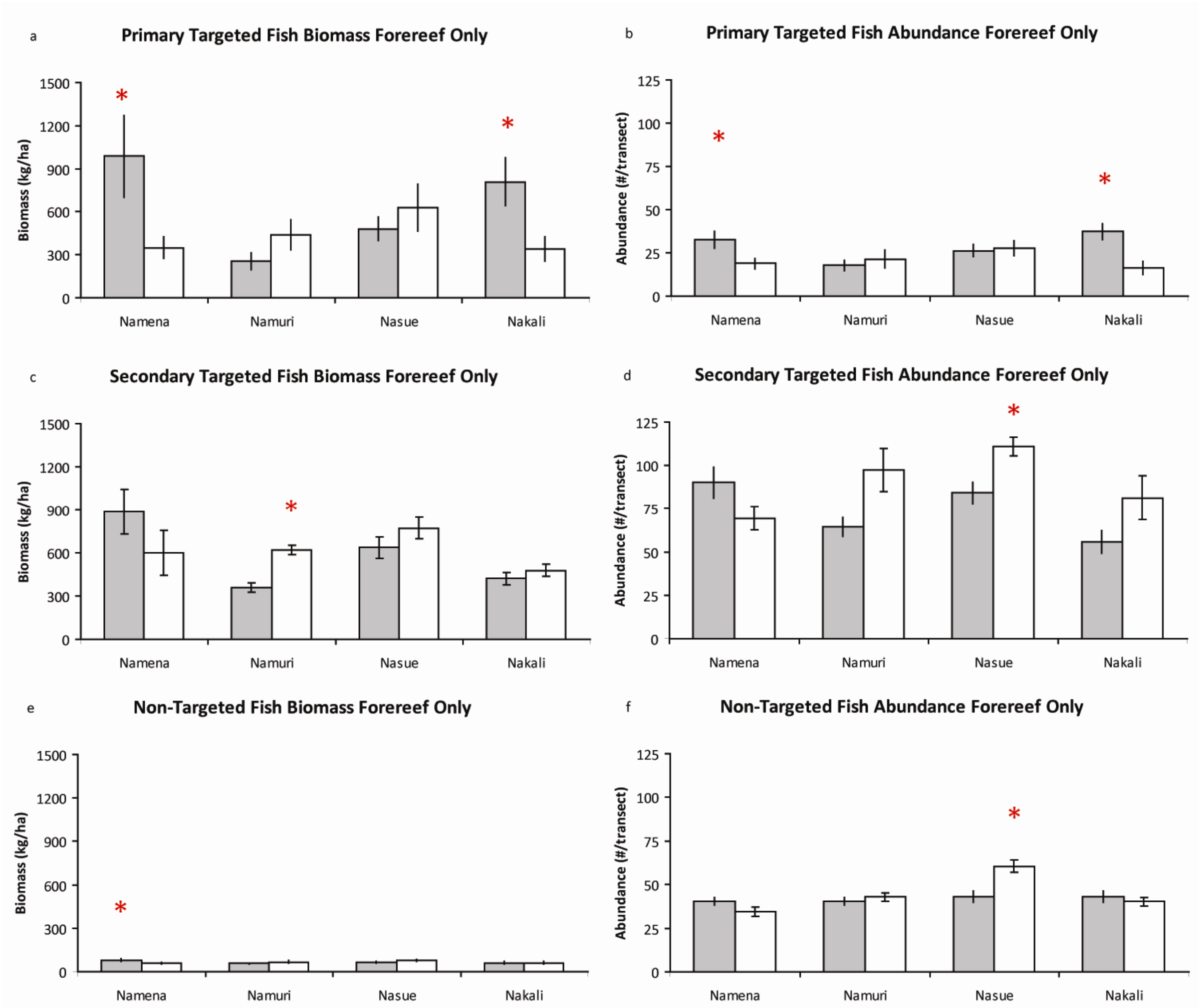


Figure 15. Mean (± standard error) fish biomass (kg/ha) and abundance (#/transect) of (a,b) primary targeted fish species; (c,d) secondary targeted fish species; and (e,f) non-targeted fish species inside and adjacent to MPAs from Kubulau 2009 surveys. Red asterisks denote significance at $p < 0.05$.

Table 12. R values from ANOSIM comparison of benthic composition between reefs. Significant differences at $p < 0.05$ are highlighted in red.

	Nakadamu	Cakaunivuaka	Nakali	Namena	Namuri	Drokana
Nakadamu						
Cakaunivuaka	0.267					
Nakali	0.079	-0.063				
Namena	0.091	0.420	0.200			
Namuri	0.290	0.700	0.531	-0.200		
Drokana	-0.003	0.300	0.163	-0.124	-0.038	
Nasue	0.060	0.363	0.271	-0.131	0.052	-0.144

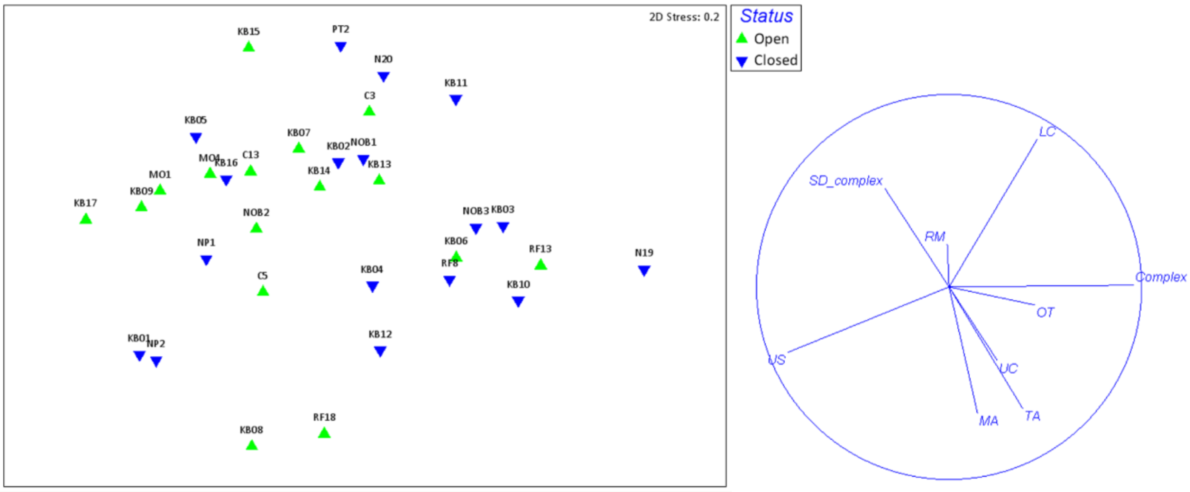


Figure 16. MDS plot of Kubulau 2009 mean benthic community composition by site at closed (blue) and open (areas). Axes to right show trajectories of vectors for each benthic habitat variable.

Ordination of fish biomass data using centroid distance at the site level across all MPAs and traditional tabus revealed no distinct clustering between closed and open sites (Figure 17). However, the closed (green) sites with high negative values along MDS axis 1 are all highly productive sites within the Namena and Nakali MPAs. The sites that also have strong negative scores along MDS axis 2 (N20, KB03, C3) are all categorized by large distances from runoff, land, villages (weighted by fish consumption), and the Wailevu qoliqoli boundary. These biophysical factors all had significant ($p < 0.05$) negative Pearson correlations with sites values along MDS1, while macroalgae was significantly positively correlated with MDS2 (Table 13).

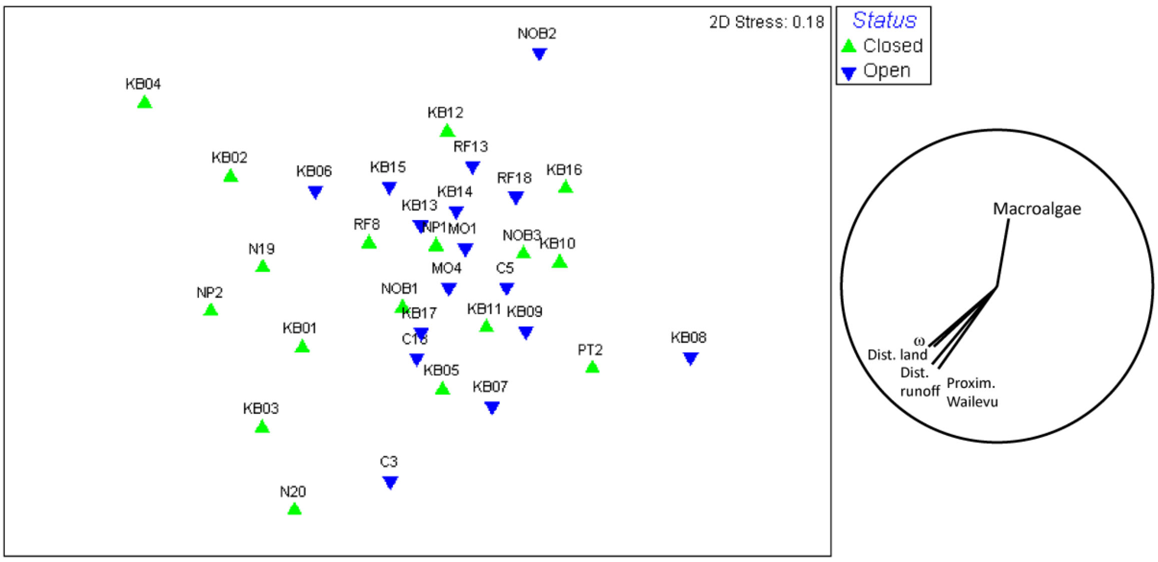


Figure 17. MDS plot of Modified Gower resemblance matrix of fish biomass by species for each site, shown with vector trajectories of biophysical factors with Pearson correlations of at least ±0.35 with data positions along MDS axis 1 or 2.

Table 13. Pearson correlations (r) with positions of resemblance matrix of mean fish biomass per species ordinated along MDS axes 1 and 2. Values highlighted in red are significant at $p < 0.05$ with univariate regressions.

Biophysical Factor	MDS1	MDS2
Distance from land	-0.376	-0.359
Distance from runoff source	-0.413	-0.490
Visibility	0.040	0.101
Proximity to Wailevu	-0.371	-0.517
Proximity to Wainunu	-0.150	0.143
Weighted distance from villages	-0.398	-0.367
Reef complexity	-0.232	0.160
STDEV reef complexity	-0.048	-0.165
Live coral	-0.196	-0.199
Macroalgae	0.082	0.457
Other substrate	0.042	-0.142
Reef matrix	0.260	0.232
Turf algae	-0.134	0.106
Unconsolidated substrate	0.042	0.006
Upright coralline algae	0.036	0.294

Macuata MPA Network

2008 UVC surveys

Cakaulevu tabu had significantly greater biomass and abundance of total and primary targeted food fish (Figures 18a,b, 19a,b, Table 14c,d). Vatuka tabu had significantly more non-targeted fish inside the protected area, and had the greatest number of secondary targeted food fish of all regions surveyed in Macuata, though the difference between the control areas was marginally not significant (Figure 19d,f, Table 14f,h). As observed in Kubulau, secondary targeted food fish across all sites were most numerous within the qoliqoli.

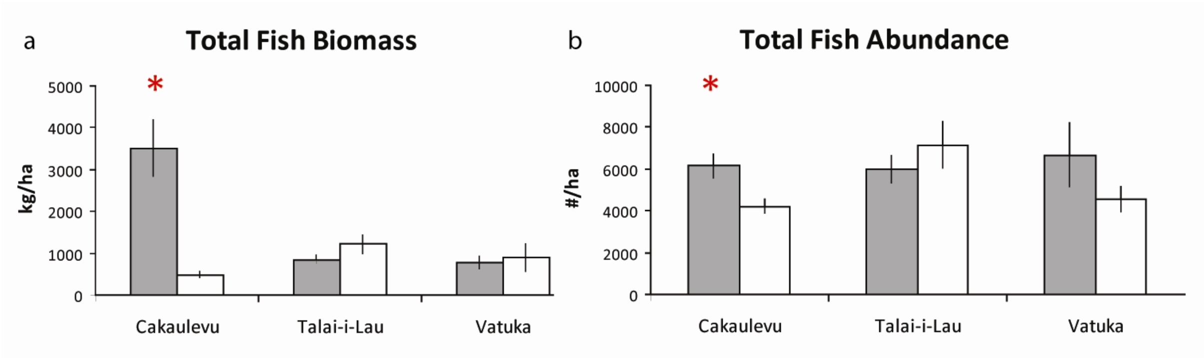


Figure 18. Mean (± standard error) (a) total fish biomass (kg/ha); and (b) total fish abundance (#/ha) from 2008 Macuata fish survey data on forereefs inside MPAs (grey) and adjacent open fishing grounds (white). Red asterisks indicate significant differences at $p < 0.05$.

Table 14. Mean abundance and biomass (± standard error) between closed and open areas for MPAs and tabus from Macuata 2008 survey data in: (a) total fish biomass (kg/ha); (b) total fish abundance (#/ha); (c) primary target fish biomass (kg/ha); (d) primary target fish abundance (#/ha); (e) secondary target fish biomass (kg/ha); (f) secondary target fish abundance (#/ha); (g) non-target fish biomass (kg/ha); and (h) non-target fish abundance (#/ha). Z-adjusted values and p-values are reported from Mann-Whitney U tests. Significant p-values are indicated in green (higher in closed areas).

Reef	Closed	SE	Open	SE	Z-adj	p-level
(a) Total reef fish biomass (kg/ha) on forereefs						
Cakaulevu	3514.73	663.15	491.74	65.90	2.984	**0.003**
Talai-i-Lau	848.73	102.72	1222.53	226.11	0.250	0.802
Vatuka	777.14	153.00	890.16	324.93	0.597	0.551
(b) Total reef fish abundance (#/ha) on forereefs						
Cakaulevu	6142	565	4217	325	2.296	**0.022**
Talai-i-Lau	5989	674	7151	1128	0.496	0.620
Vatuka	6670	1533	4564	614	0.933	0.351
(c) Primary target reef fish biomass (kg/ha) on forereefs						
Cakaulevu	2331.04	515.99	156.80	40.32	3.410	**<0.001**
Talai-i-Lau	351.57	51.78	538.53	123.75	0.683	0.494
Vatuka	279.73	75.29	609.18	329.01	0.423	0.672
(d) Primary target reef fish abundance (#/ha) on forereefs						
Cakaulevu	1440	215	578	140	2.991	**0.003**
Talai-i-Lau	1747	211	2061	432	1.473	0.141
Vatuka	822	114	1181	203	-0.347	0.729
(e) Secondary target reef fish biomass (kg/ha) on forereefs						
Cakaulevu	954.98	165.63	277.40	47.02	2.479	**0.013**
Talai-i-Lau	388.79	70.85	549.85	117.09	0.000	1.000
Vatuka	436.24	136.30	217.13	37.30	1.472	0.141
(f) Secondary target reef fish abundance (#/ha) on forereefs						
Cakaulevu	2943	280	2385	264	1.028	0.304
Talai-i-Lau	3117	474	3621	662	-0.038	0.969
Vatuka	4639	1419	2469	453	1.910	0.056
(g) Non-target reef fish biomass (kg/ha) on forereefs						
Cakaulevu	187.63	91.74	52.89	6.34	1.889	0.059
Talai-i-Lau	83.76	12.90	116.01	23.34	-0.510	0.610
Vatuka	55.18	9.05	41.57	7.72	1.876	0.061
(h) Non-target reef fish abundance (#/ha) on forereefs						
Cakaulevu	1565	142	1387	119	0.727	0.467
Talai-i-Lau	1042	138	1236	167	-0.881	0.378
Vatuka	1123	150	650	77	2.398	**0.016**

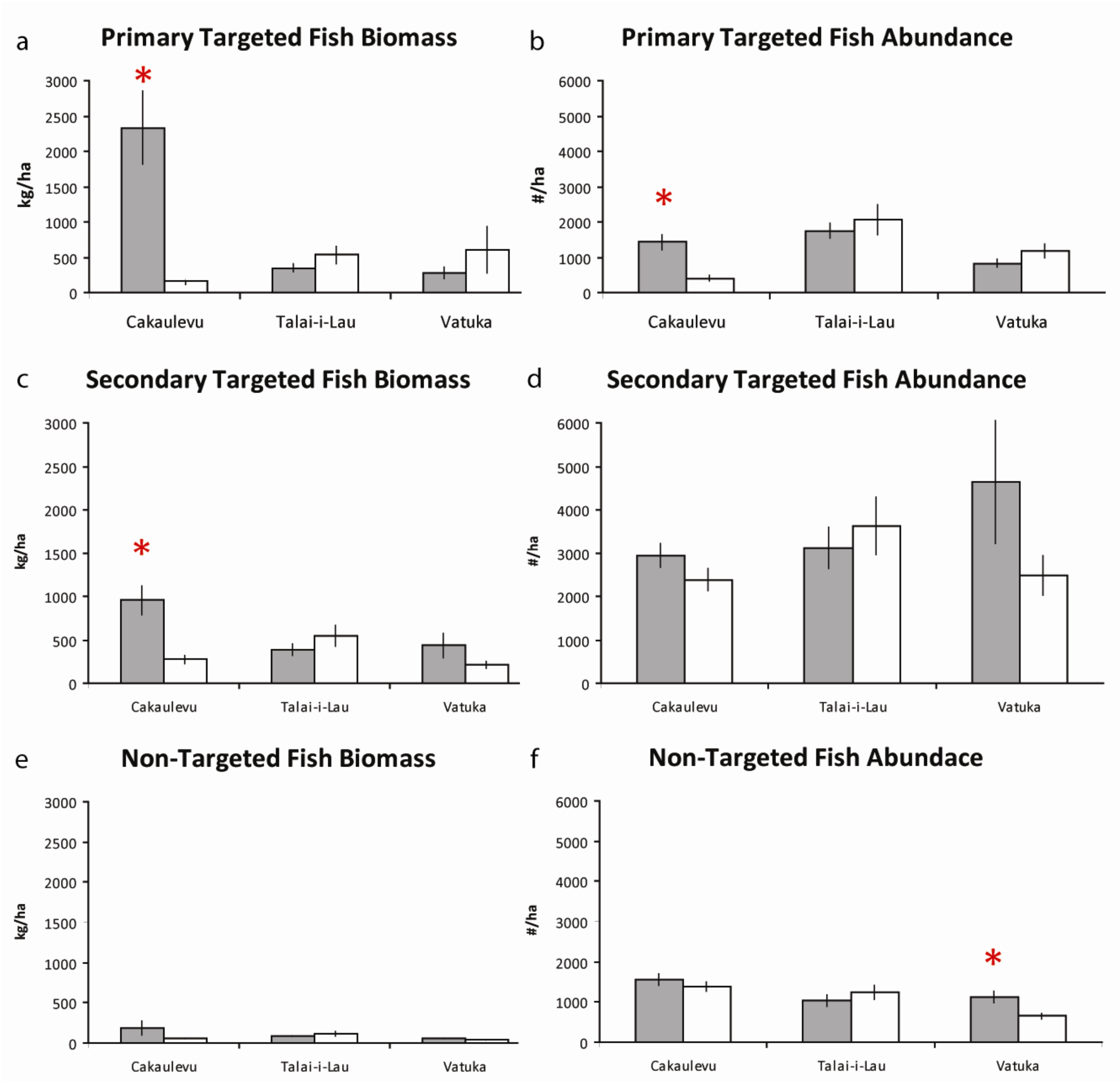


Figure 19. Mean (± standard error) fish biomass (kg/ha) and abundance (#/transect) of (a,b) primary targeted fish species; (c,d) secondary targeted fish species; and (e,f) non-targeted fish species inside and adjacent to MPAs from Macuata 2008 surveys. Red asterisks denote significance at $p < 0.05$.

Discussion

Factors influencing MPA effectiveness

Many different factors can potentially influence whether or not marine protected areas and MPA networks are effective in reaching their conservation and management goals. These factors can include, but are not limited to: degree of protection (no-take, permanent, periodic opening, partial); awareness of and degree of compliance with MPA rules; visibility from land; design of MPAs and MPA networks; benthic habitat condition; frequency and intensity of current and historical disturbance (e.g. land-based pollution, bleaching, tropical cyclones, crown-of-thorns outbreaks); and longevity of protection. As the goals of the Kubulau and Macuata MPAs were primarily to increase stock of food fish, we evaluate the results of our fish surveys in the context of the above factors to determine where management has been effective and where there needs to be improvements.

Small, community-managed MPAs

Over the past decade, hundreds of communities in the western Pacific have established locally managed marine areas (LMMAs) to control the perceived decline of marine natural resources. The primary management tool applied for the management of coastal marine resources within LMMAs is the use of traditional tabu areas, where the local community chooses the location, size and management regime for their closed area. These permanently or periodically closed tabu areas tend to be small, averaging just 0.2 – 3.3 km^2 for the Cook Islands, Fiji, Papua New Guinea, Samoa, Solomon Islands and Tonga (Govan et al. 2009). Because their boundaries tend to fall within the secure, customary tenure of one village or clan, they are typically easy to manage because there are no overlapping governance constraints and their location is often within visual distance from villages (Aswani and Hamilton 2004). However, while the benefits of many, small reserves can maximize fisheries yields (Hastings and Botsford 2003), there may be a threshold size below which potential benefits of protection are outweighed by negative edge effects. Furthermore, the reserves must be placed in appropriate habitat that will maximize fisheries production. There is strong evidence to support reduced biomass in habitats characterized by macroalgae and unconsolidated sediments (Friedlander et al. 2007), which are typically found on fringing reef flats and backreef lagoons where tabus are often established.

Monitoring the effectiveness of these small tabus has been challenging, largely because they may be too small to fit replicate survey sites within their boundaries, thus confounding rigorous statistical analysis. For example: only 1 survey site with 5 replicate transects could be placed inside the Yamotu Lase tabu (0.13 km^2) without the risk of pseudo-replication. Even with this low statistical power, results from both 2007 and 2008 indicate positive significant differences in total reef fish biomass (2008 only) and abundance compared to adjacent fished areas. However, further examination of the data from 2008 show that: (1) overall mean biomass and abundance per hectare is low compared with larger, unfished protected areas in the qoliqoli, reducing the potential benefits of adult spillover; and (2) the mean biomass and abundance of primary targeted food fish comprised only 21.6% and 13.6% of the total biomass and abundance recorded within the tabu, which is a substantially lower percentage than in the Namena MPA where primary targets comprised 72.0% of the total fish biomass and 40.3% of the abundance. The low values for primary food fish may be due to the fact that the management rules for Yamotu Lase include a provision for an annual harvest for the feast of Saint Theresa (WCS 2009). Repeated harvests and sustained fishing pressure may reduce the size structure of fishing communities, resulting in fewer, smaller individuals (Jennings et al. 1999; Nicholson and Jennings 2004). Also, the location of Yamotu Lase adjacent to nearby seagrass beds may naturally support more juvenile fish that use the backreef, lagoonal habitat as a stepping stone before migrating to the offshore barrier reef as larger bodied adults (Nagelkerken et al. 2000), which would impact overall biomass.

The Nakali tabu, while also small (0.77 km^2), supported over ten times the total fish biomass and nearly four times the total fish abundance per hectare as the Yamotu Lase tabu in 2007. This is likely due to the natural geomorphology of the reef system in which the offshore barrier is located within 1 km from land and is regularly flushed with high currents through the Naisonisoni Passage. High currents along reef walls provide important fluxes of zooplankton, upon which planktivorous fish feed (Hamner et al. 1988): some of these planktivores (e.g. schooling damselfish) are prey for larger-bodied carnivores, while other large acanthurids (e.g. *Naso* spp) can grow up to 100 cm and are preferred food fish of many Fijian fishers. By 2008, however, sites in Nakali no longer supported greater biomass than adjacent fished areas and there was significantly more fish outside the MPA. This is most likely because the village of Navatu harvested the tabu three times between survey periods, which is within the community-declared management provisions of the Nakali (WCS 2009). However, despite the high frequency of harvests, the natural features of the reef may be highly resilient to exploitation as reef fish populations, in particular of primary food fish, had recovered substantially by 2009.

Large MPAs in close proximity to fishers

The results from the larger MPAs located <10 km offshore in Kubulau (Nasue, Namuri) and Macuata (Talai-i-Lau, Vatuka) are equivocal. For example, in 2007, the mean total fish abundance was higher on fished forereef areas outside the Nasue MPA than inside. When data were pooled across forereef and backreef sites, total fish biomass is also significantly greater outside the MPA (Jupiter et al. 2010). Long-term coral proxy records from the region indicated potential extreme disturbance from land-based runoff when the nearby Mt. Kasi gold mine was operational between 1996 and 1998. Nevertheless, current surveys of benthic habitat condition indicate no significant differences between Nasue and adjacent fished areas in factors that may indicate recent disturbance (e.g. macroalgal cover, rubble) and influence fish assemblages (e.g. live coral cover, branching coral cover, reef topographic complexity) (Jupiter et al. 2010). This suggests that neither proximity to runoff nor benthic characteristics are driving broad differences in reef fish assemblages between Nasue MPA and the adjacent Drokana reef. Instead, external poaching is likely to play a major role as proximity to Wailevu district was one of the major factors which contributed significantly to reef fish biomass structure at the site level. The Nasue MPA shares a boundary with the neighbouring Wailevu qoliqoli and Wailevu fishers have been repeatedly caught fishing in the MPA, a problem compounded by the fact that the MPA is not visible from any of the villages in Kubulau.

The Namuri MPA appeared to be effectively protecting marine resources in 2007 and 2008, with significantly higher total fish and primary food fish biomass inside compared with adjacent fished. The opposite pattern was observed from 2009 surveys, provoking some concern that when Kubulau fishers were made aware of the exceptionally high biomass inside Namuri MPA during a management planning workshop in February 2009, they may have proceeded to covertly fish the area. Indeed, the monitoring sites within Namuri all had exceptionally low consumption-weighted distance-to-village scores (ω), indicating that they are near numerous villages whose residents frequently consume fish. Thus, in an attempt to use the monitoring data to foster discussions related to management implementation, its public presentation may have had detrimental consequences for the fishery (e.g. Maurstad 2002). Customary management rules rely on respect for traditional authority (Aswani 2005; Hoffman 2006), which may be weakened through access to markets (Cinner et al. 2007). Although there is generally good local compliance in Kubulau, fishers may have been tempted by access to a potential profitable market opportunity given that a middleman lives in the district who sells fish to a local vendor in Savusavu.

The limited effectiveness of the Talai-i-Lau and Vatuka tabu areas in Macuata qoliqoli may be caused by similar market pressures. The urban city of Labasa sits adjacent to the qoliqoli where there are nearly as many residents without marine resource rights as traditional fishing rights owners (TFROs) within the 37 villages. Residents of the village of Macuata-i-wai noted that many poachers hide out within the channels of the mangrove islands of Talai-i-Lau and Vatuka during the day and come out to poach at night when they are not seen. The clear frustration with levels of external poaching was making the TFROs question why they were sacrificing their fish to the benefit of outsiders and there was talk in Macuata-i-wai of lifting the tabu altogether (S. Jupiter, pers. obs.).

Large MPAs distant from fishers

The two large MPAs located furthest away from the mainland (Namena in Kubulau; Cakaulevu in Macuata) demonstrated the strongest results in terms of increasing food fish biomass and abundance. The most likely reasons for their success are: strong commitment to enforcement; natural geomorphic features which promote recovery; longevity of protection; and distance from villages.

The Namena MPA has been informally established as a permanent no-take protected area since 1997, when the high council of chiefs both banned commercial fishing from the qoliqoli and set up the reserve around the reefs of Namenalala Island (Clarke and Jupiter in press). The longevity and permanence of the closure has enabled recovery of large-bodied piscivores such as serranids and lutjanids, which have low growth and recruitment rates and are highly vulnerable to overfishing (Russ and Alcala 1998). Increases in biomass of these taxa from growth alone may take a decade to observe, as opposed to biomass increases from successful recruitment ("spill-in") following closure of an MPA, which can occur rapidly over 1-3 years (White 1988; McClanahan and Kaunda-Arara 1996; Russ and Alcala 1996b).

At 60.6 km^2, Namena is the largest MPA in Fiji, covering an extensive barrier reef system that extends outward into the deep waters of the Vatu-i-Ra passage. High currents flush the reef, supporting an abundance of top predators, including schools of hammerhead sharks which draw dive tourists from around the globe. The northern end of the Cakaulevu forereef has a similar environment, with abundant populations of large, schooling, planktivorous acanthurids and predatory carangids. These naturally favourable habitats can promote rapid recovery of exploited populations, while unfavourable habitats, such as the backreef of Namena which is dominated by reef pavement, may see temporal increases in fish abundance and size in response to management but may appear to be less effective if the reef fish populations are compared to those from control habitats with higher topographic complexity (Friedlander et al. 2003).

Given the international dive tourism in Namena which brings revenue to the communities of Kubulau through the payment of user fees to dive in the MPA, there is high incentive from the communities to enforce the MPA regulations. The chiefs of Kubulau have empowered the owners of Namena Island Resort, located within the reserve, to patrol the area and trained community fish wardens may board vessels suspected of illegal fishing activity (Clarke and Jupiter in press). Due to this vigilance, and the vigilance of villagers living on the offshore Kia Island in Macuata qoliqoli who are strongly committed to protecting the Cakaulevu tabu, there is unlikely to be poaching for subsistence fishing from fishers coming from the mainland given the high price of boat fuel: fishers would only be attracted to the area if they have guaranteed access to a market to sell their catch. While villagers say that this still remains a potential problem, the current extent of illegal fish extraction for sale does not appear to be overly compromising the effectiveness of these MPAs. Other factors, as discussed above, appear to outweigh this factor, in particular: productivity, size and location of the MPA.

Comparison of Kubulau and Macuata qoliqolis within the Indo-Pacific context

The MPA networks of Kubulau and Macuata were initially established both because the communities themselves initiated requests for assistance in managing their perceived declining resources (Clarke and Jupiter in press) and because local and regional experts had identified both areas as supporting globally significant biodiversity (WWF 2004a; Allen 2008). Our recent surveys show that the Kubulau outer barrier reef sites appear slightly less diverse than those on the Great Sea Reef (including Macuata outer barrier reefs; WWF 2004b), with average species numbers of 151 and 181, respectively, sighted per dive. The highest recorded species richness of reef fishes in Kubulau from 2009 was 191 species, located just adjacent to the Namena Marine Reserve, in which Marnane et al. (2003) had previously recorded 220 and 227 species on 2 dives during surveys of the Vatu-i-Ra region in 2003. These values are comparable to the highest species richness record (221 species) from Macuata off Kia Island, surveyed by the same observers in 2004 (WWF 2004b). At the most speciose sites, the diversity in Kubulau and Macuata is comparable to mean reef fish species richness from sites in New Britain and southern Papua New Guinea and Bali, Indonesia (Marnane et al. 2003).

The species richness and degree of endemism in Kubulau may be further elevated with additional research into the morphological and genetic distinctiveness of the unique colour variants of *Centropyge bispinosus*, *Pomacentrus mollucensis, Chrysiptera talboti* and *Labroides dimidiatus*. Following the recent description of the Fiji colour variant of *Amphiprion melanopus* as *Amphiprion barberi* based on genetic data (Allen et al. 2008) and identification of strong genetic distinctiveness of some of Fiji's fish fauna previously thought to be cosmopolitan species (Drew et al. 2008), it is quite possible that these fish could be regional endemics as they appear significantly different than those seen outside of Fiji and Tonga. Molecular investigation of local reef fish species suggests that Fijian reefs may be reproductively isolated, thereby resulting in high regional endemism (Drew and Barber 2009).

Comparisons of fish biomass from Kubulau and Macuata with other published records (Table 15) indicate high productivity relative to many other sites in the Indo-Pacific. The mean total fish biomass observed in Namena MPA (upper range: 2633 kg/ha) in Kubulau and Cakaulevu MPA (3515 kg/ha) in Macuata fall within the range of values reported for Palmyra atoll in the northern Line Islands, considered to have relatively intact trophic structures and minimal impact from humans (Sandin et al. 2008). The ranges of total fish and targeted fish biomass in the small, community-managed tabu of Yamotu Lase in Kubulau are closer to the ranges reported for the small periodically closed areas on inshore, fringing reefs adjacent to Muluk village of PNG and Karkarotan village of Indonesia (Cinner et al. 2005b) and in Efate, Vanuatu (Bartlett et al. 2009). These major differences in fish biomass in the small community tabus may be largely reflective of natural differences in structural heterogeneity of habitats and its influence on key ecological processes (Friedlander and Parrish 1998; Gratwicke and Speight 2005). They may also be due to the fact that the size of the closures may be smaller than the home range of some of the targeted fish species, which makes them vulnerable to exploitation by fishers who concentrate their efforts at MPA boundaries (McClanahan and Kaunda-Arara 1996; Roberts et al. 2001).

Table 15. Comparison of fish biomass evaluated from underwater visual census (UVC) from locations around the Indo-Pacific.

Location	Fish Group	Mean Biomass Range (kg/ha)	Source
Kubulau, Fiji Namena	Total fish protected Primary targeted fish protected Total fish open	1647 – 2633 867 – 1898 1009 – 1758	This study
Kubulau, Fiji Namuri/Nasue	Total fish protected Primary targeted fish protected Total fish open	673 – 1626 167 – 759 462 – 1499	This study
Kubulau, Fiji Yamotu Lase	Total fish protected Primary targeted fish protected Total fish open	119 – 674 67 – 146 40 – 215	This study
Vatu-i-Ra, Fiji	Total fish	~550 – 900	Marnane et al. 2003
Macuata, Fiji Cakaulevu	Total fish Primary targeted fish Open	3515 2331 492	This study
Macuata, Fiji Talai-i-Lau/Vatuka	Total fish protected Primary targeted fish protected Total fish open	777 – 849 280 – 352 890 – 1222	This study
Northern Lagoon, New Caledonia	Targeted fish along terrestrial gradients	148 – 447	Letourner et al. 1998
North Efate, Vanuatu	Vulnerable fish protected Vulnerable fish open Less vulnerable fish protected Less vulnerable fish open	508 – 669 175 – 296 307 – 381 261 – 302	Bartlett et al. 2009
Ahus Island, Papua New Guinea	Total fish protected Total fish open	~225 ~120	Cinner et al. 2005a
Muluk, Papua New Guinea	Targeted fish protected Targeted fish open	378 301	Cinner et al. 2005b
Karkarotan, Indonesia	Targeted fish protected Targeted fish open	139 101	Cinner et al. 2005b
Apo Island, Philippines	Targeted fish protected† Targeted fish open	~250 – 1200 ~<100 - 850	Alcala et al. 2005
Main Hawaiian Islands, USA	Total fish CHB protected†† Total fish CHB open Total fish UCS protected Total fish UCS open	971 502 183 18	Friedlander et al. 2007
Line Islands, Kiribati and USA	Total fish along human impact gradient	1300 - 5300	Sandin et al. 2008

† Ranges cover 20 years of monitoring of the following fish families: Acanthuridae, Carangidae, Lethrinidae, Lutjanidae
†† CHB: colonized hard bottom habitat; UCS: unconsolidated sediment habitat

While even small managed areas with some degree of fishing might show higher biomass or abundance then adjacent open areas, it is important to compare the absolute values to areas with minimal human impact. Only by doing this is it possible to fully grasp the impact fishing has had on an ecosystem and to assess how well MPAs are facilitating recovery to a more natural, unexploited state.

Conclusions and Recommendations

In the Kubulau and Macuata MPA networks, the factors which appear to have the most influence on the success of management to provide protection of exploited species include: size; placement of reserves in naturally productive habitats; visibility; distance from potential poachers; and degree and longevity of protection. Some key recommendations to improve and expand MPA networks to other sites in Fiji include:

- Size: MPAs need to be larger than the home ranges of targeted fish species. Recent fish tagging studies from the Coral Coast of Fiji have shown that *Lethrinus* spp. can move up to 700m and do so mostly at night (Grober-Dunsmore et al. 2009). Therefore, MPAs should be at least double this length on both sides in order to ensure that fish are not caught while foraging.

- Permanence and placement: Though some studies have observed limited increases in fish biomass and abundance despite periodic opening (Cinner et al. 2005b; Bartlett et al. 2009), the ability of fish populations to recover from harvests is likely to depend both on the frequency and intensity of harvest events (Seidel 2009). Permanently closed areas provide the maximum level of protection and degree of recovery. They also depend on other factors relating to placement such as, natural geomorphology and oceanographic features of the region and the life-history patterns of targeted species. Ideally, MPAs should be placed in highly resilient locations. For other cases, Russ and Alcala (2003) make a strong argument for permanent closures as a precautionary principle because the “benefits accrue slowly but are lost quickly” with repeated fishing event.

- Visibility: Visibility of MPAs need not always imply that they be placed within direct sight of villages. In the case of the Macuata tabus established around mangrove islands, although the landward side is visible, the trees impede the view of the seaward-facing reef which can be easily targeted by poachers by day or by night. Visibility can be improved by frequent enforcement patrols, though resourcing is required for boats and fuel. Resource management committees must therefore place priority on financing enforcement activities through their varied sources of revenue.

The data collected here can provide important baselines for future comparisons with other sites across Fiji and the Pacific. The lessons learned are being shared with the communities of Kubulau and Macuata and the broader Fiji Locally Managed Marine Area network to help inform adaptive management of inshore fisheries resources.

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Appendix 1. Locations of survey sites in Kubulau and Macuata qoliqolis

The maps below indicate the location of baseline and monitoring survey sites in Kubulau and Macuata qoliqolis from which data on fish assemblages and benthic communities were collected to assess MPA effectiveness.

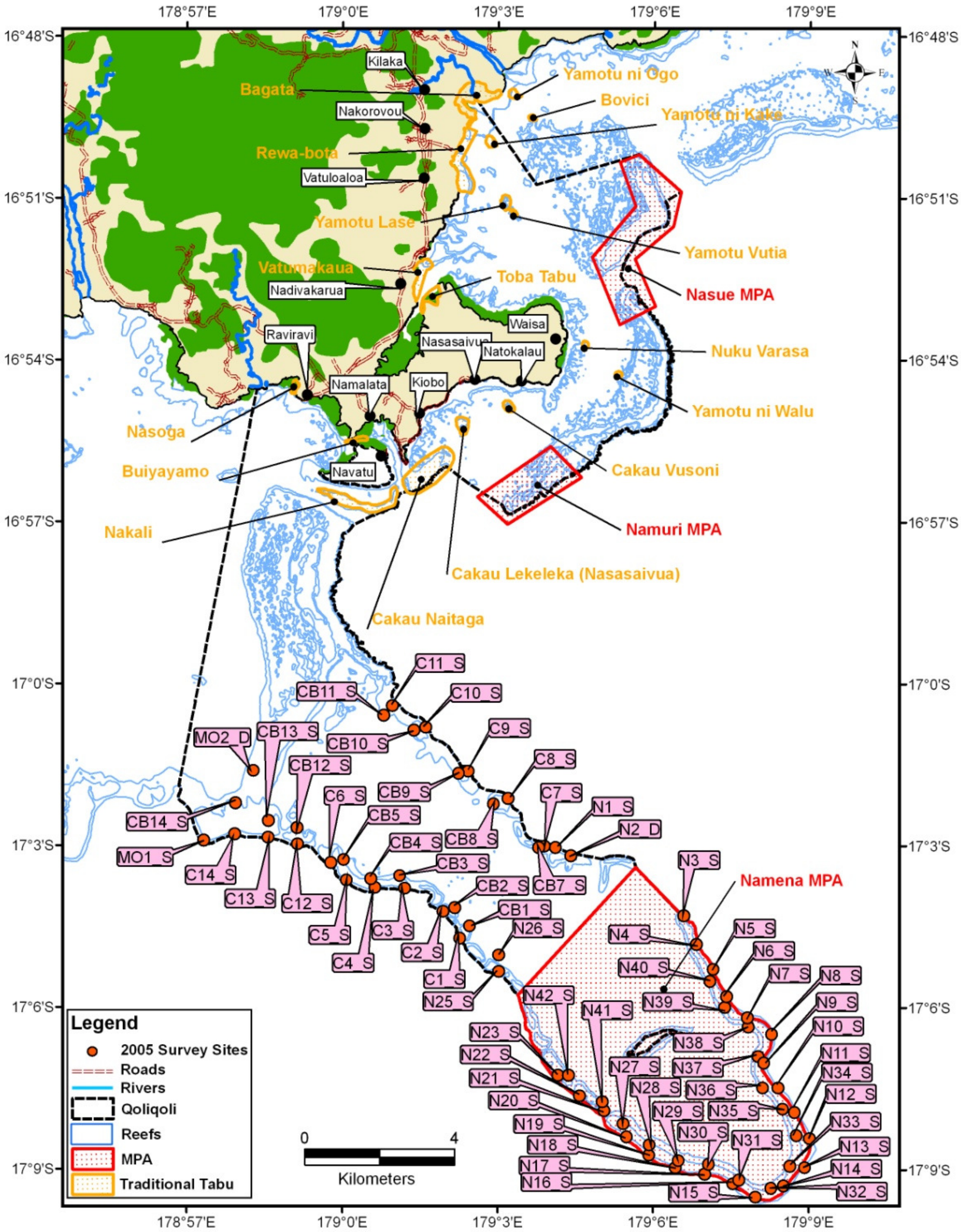


Figure 1. Location of forereef and backreef sites surveyed within Kubulau qoliqoli between October and December 2005 used for assessing the effectiveness of Namena MPA.

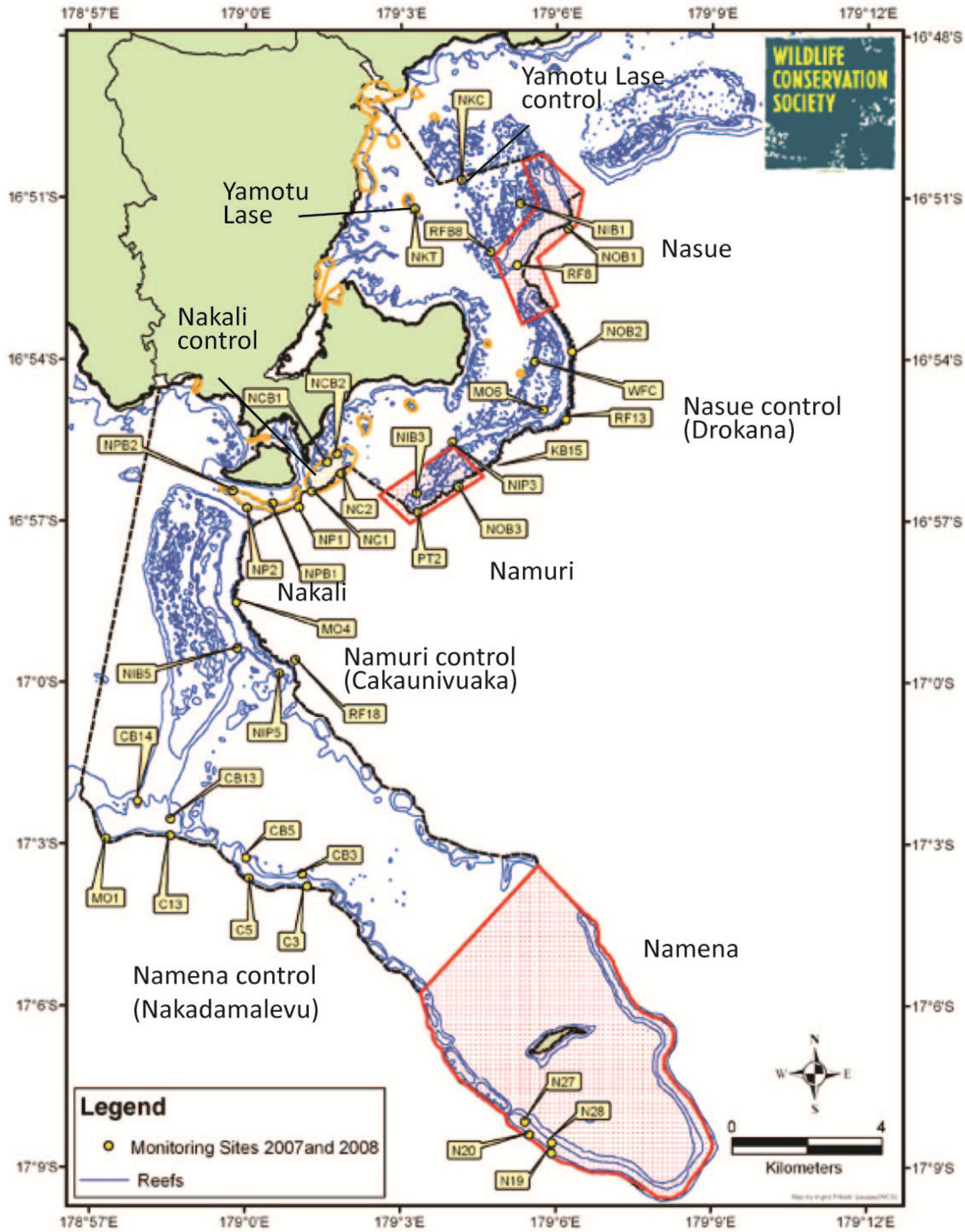


Figure 2. Location of forereef and backreef sites surveyed within Kubulau qoliqoli between January-February 2007 and April-May 2008.

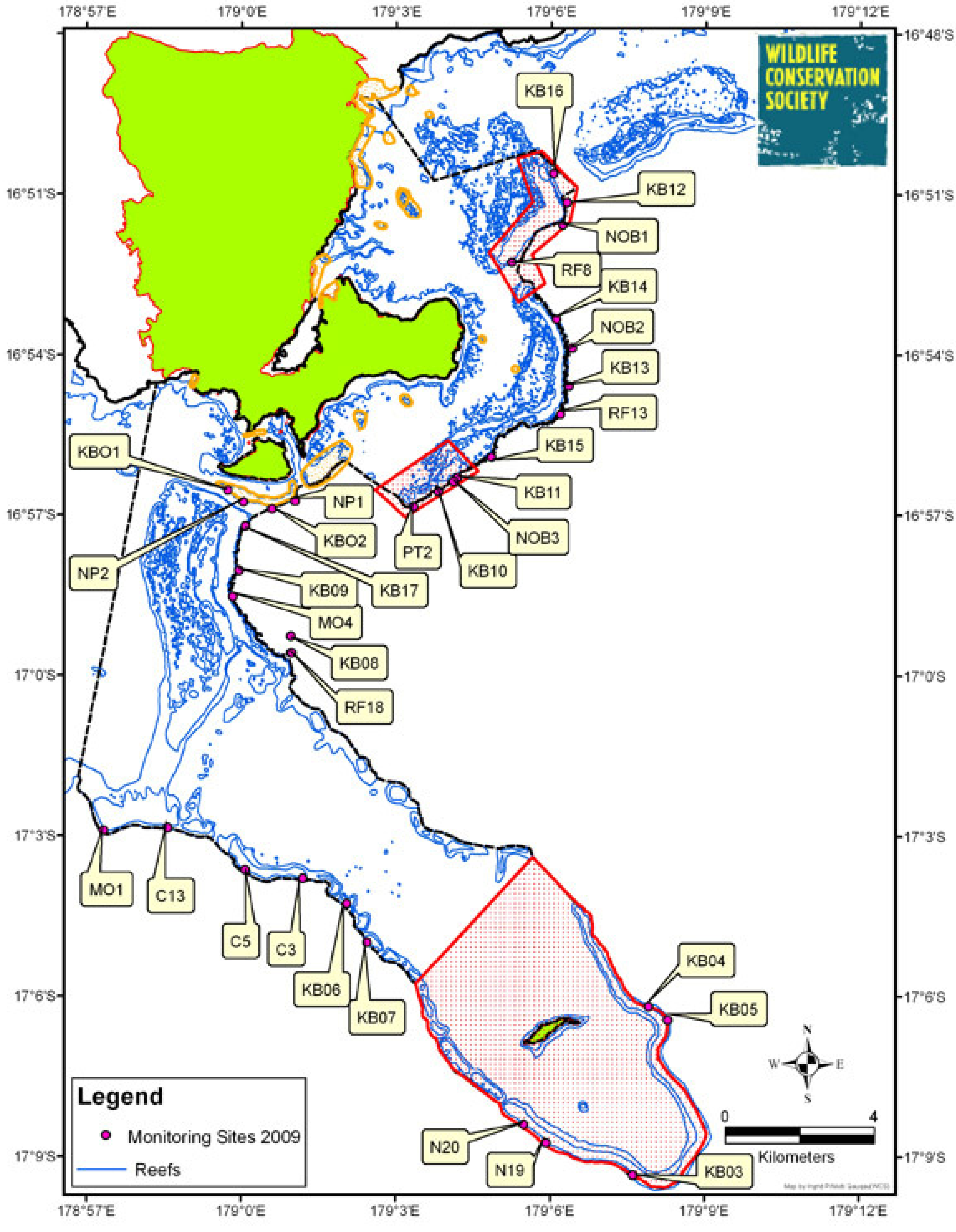


Figure 3. Location of forereef sites surveyed within Kubulau qoliqoli between April-May 2009. Controls for Nasue were site: KB13, KB14, NOB2, RF13; controls for Namuri were: KB09, KB15, KB17, RF13; controls for Nakali were: KB08, KB09, KB17, MO4; controls for Namena were: C13, C3, C5, KB06, MO1.

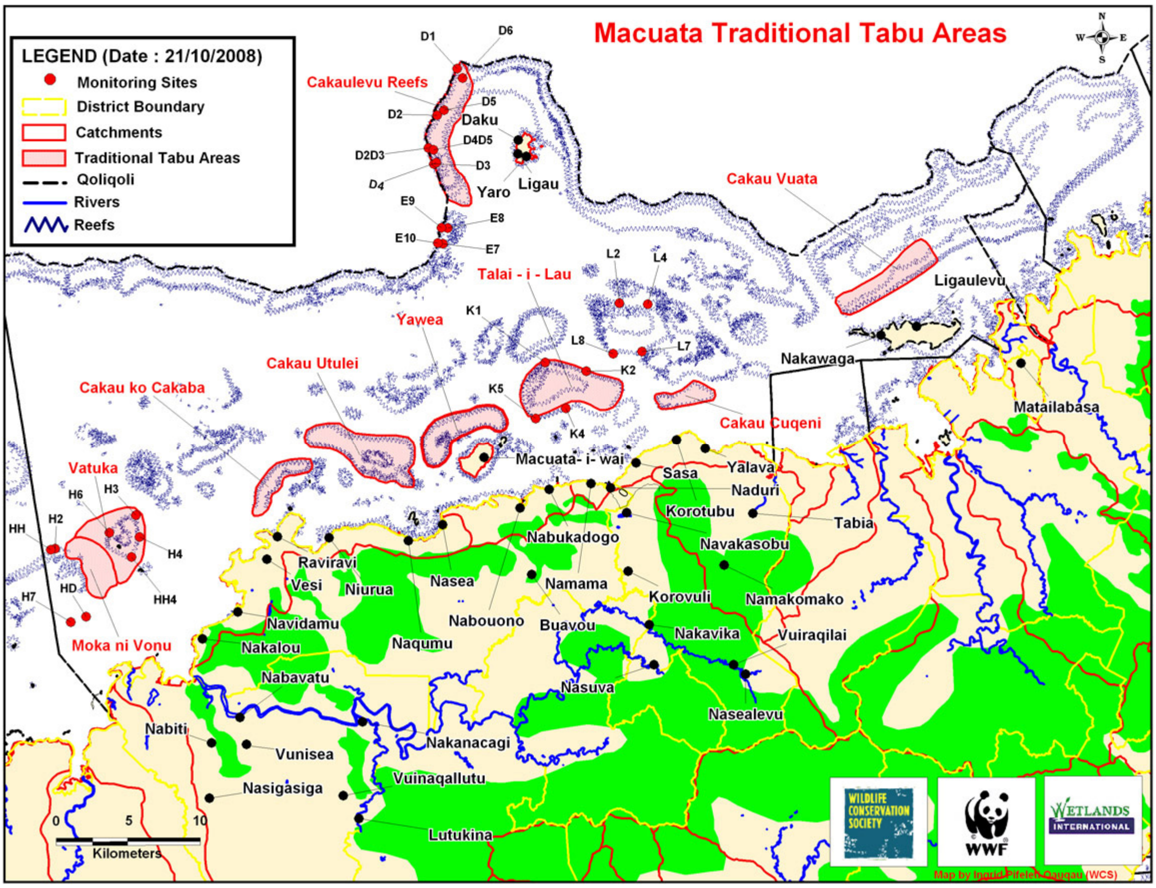
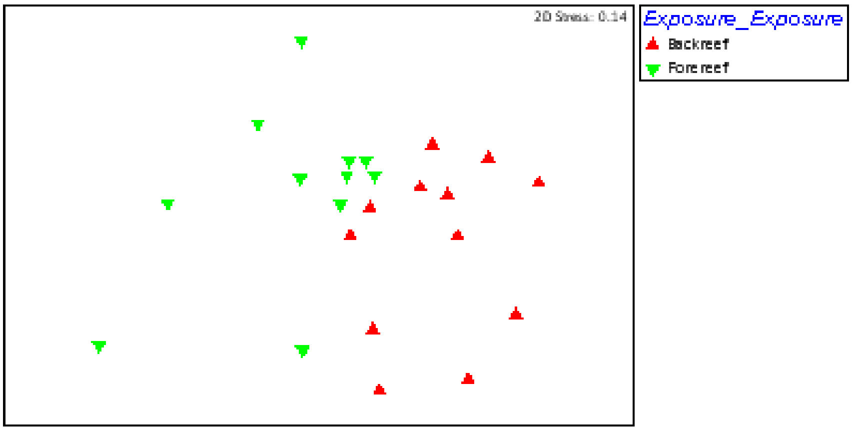


Figure 4. Location of forereef and backreef sites surveyed within Macuata between September-October 2008.

Appendix 2. Revision of experimental design for monitoring MPAs

Variation in fish assemblages across exposure (forereef, backreef) and protection (open, closed) from Kubulau 2007 data was explored with multivariate tests using PRIMER-e version 6 software.

A Modified Gower similarity matrix with a log10 was used to compare the biomass of reef fish assemblages at each site from inside and adjacent to the district MPAs (Anderson et al. 2008). A multidimensional scaling (MDS) plot of the matrix shows distinct separation between forereef and backreef sites (Figure 1), while no clear separation is evident related to protection status (Figure 2). This suggests that the observed pattern of reef fish assemblages is more likely driven by exposure gradients that override potential management effects; therefore focus on one exposure factor only will reduce the influence of additional variables and likely improve our ability to detect differences related to management.



1. MDS plot of ied Gower blance matrix of 2007 sh biomass for all lentified by exposure backreef sites; green reef sites).

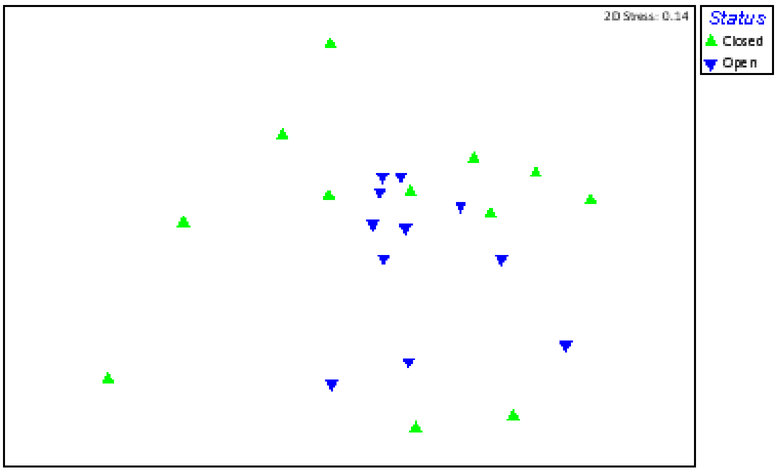
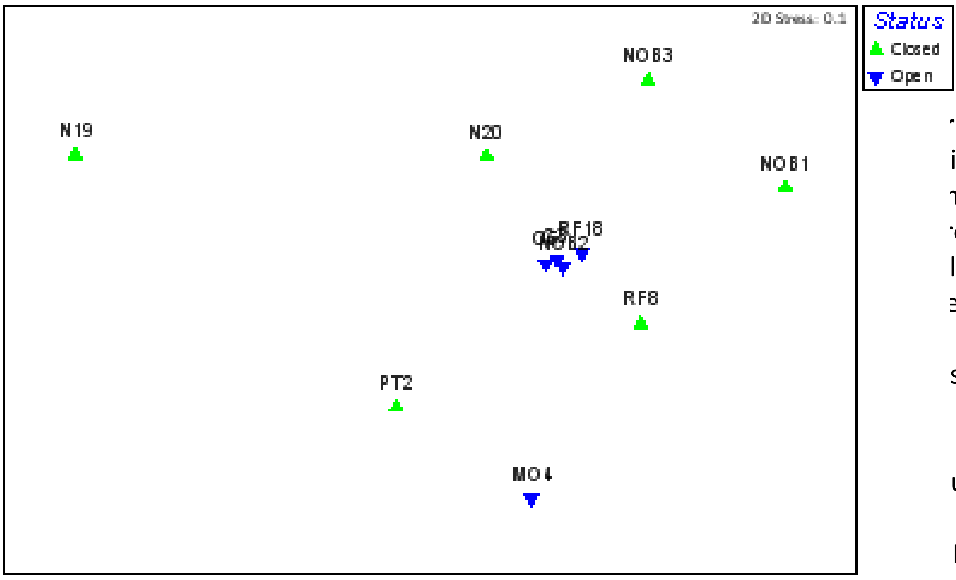


Figure 2. MDS plot of Modified Gower resemblance matrix of 2007 reef fish biomass for all sites identified by protection status (blue = sites open to fishing; green = closed MPA sites.)

When only forereef sites are considered, there is strong clustering of fish assemblages by species biomass for sites open to fishing (Figure 3). The large variability within MPA sites is likely due to the different responses of individual sites to protection, which can strongly influence the biomass of protected species and also the composition of fish assemblages.



re **3.** MDS plot of
ified Gower
mblance matrix of 2007
eef reef fish biomass
ll sites identified by
ection status (blue =
open to fishing; green
sed MPA sites.) Sites
within Namena MPA:
N20; sites from within
uri MPA: PT2, NOB3;
within Nasue MPA:
NOB1

Power analysis of experimental design showed a reduction in critical F-statistic values when sites are pooled across exposure (Table 1a,b) and when higher replicates of forereef only sites are surveyed (Table 2a,b). The main improvements were an expected increase of power to detect an effect of status (crit F reduced from 12.2 to 7.57), which was the main question addressed by the original experimental design.

Table 1. Critical F-statistics needed to conclude significant differences at p < 0.05 level for experimental design of Kubulau 2007 and 2008 surveys where (a) exposure, site and depth are considered as separate factors; and (b) sites are pooled across exposure categories.

Factor	Levels	Nesting	Fixed/ Random	Numerator	Denominator	Critical F-statistic
(a) Exposure, Site and Depth as factors						
Status	2 (open, closed)		fixed	1	4	12.2
Exposure	2 (back-, forereef)		fixed	1	4	12.2
Site	2	status x exposure	random	4	96	2.93
Depth	3 (top, shallow, deep)	status x exposure x site	fixed	2	8	6.06
N	5					
Sample size	120					
(b) Site and Depth as factors						
Status	2 (open/closed)		fixed	1	6	8.81
Site	4	status	random	6	96	2.55
Depth	3 (top, shallow, deep)	status x site	fixed	2	12	5.1
N	5					
Sample size	120					

Table 2. Critical F-statistics needed to conclude significant differences at $p < 0.05$ level for experimental design of Kubulau 2009 surveys for (a) Namena MPA with 5 closed sites and 5 open sites surveyed; and (b) Namuri and Nasue MPAs with 4 closed sites and 4 open sites each surveyed.

Factor	Levels	Nesting	Fixed/ Random	Numerator	Denominator	Critical F-statistic
(a) Namena MPA (n = 10 sites total)						
Status	2 (open, closed)		fixed	1	8	7.57
Site	5	status	random	8	80	2.35
Depth	2	status & site	fixed	1	8	7.57
N	5					
Sample size	100					
(b) Namuri/Nasue MPA (n = 8 sites total)						
Status	2 (open, closed)		fixed	1	6	8.81
Site	4	status	random	6	64	2.63
Depth	2	status & site	fixed	1	6	8.81
N	5					
Sample size	80					

Based on the results of the above sets of analyses, a decision was made to survey forereef sites only in Kubulau in April-May 2009 and to increase the number of sites surveyed in closed and open areas to improve the statistical power to detect differences related to management and depth. Results from pre-2009 are reported from forereef sites only in the body text.

Appendix 3. Fish Trophic Group Classification from 2005 Kubulau Data

Fish species were classed into four major trophic groups such as: (1) corallivore, (2) herbivore, (3) omnivore and (4) piscivores depending on feeding types obtained from FishBase. Species pooled into the separate trophic groups are listed below.

Corallivores	
Chaetodon bennetti	*Chaetodon plebius*
Chaetodon baronessa	*Chaetodon rafflesi*
Chaetodon lunula	*Chaetodon reticulatus*
Chaetodon oxycephalus	*Chaetodon trifascialis*
Herbivores	
Acanthurus blochii	*Scars altipinnis*
Acanthurus fowleri	*Scarus chameleon*
Acanthurus guttatus	*Scarus dimiatus*
Acanthurus grammoptilus	*Scarus forsteni*
Acanthurus lineatus	*Scarus freantus*
Acanthurus nigricans	*Scarus ghobban*
Acanthurus nigroris	*Scarus globiceps*
Acanthurus xanthopterus	*Scarus niger*
Acanthurus.sp	*Scarus prasiognathos*
Cetoscarus bicolor	*Scarus psittacus*
Chlorurus bleekeri	*Scarus rivulatus*
Chlorurus microrhincus	*Scarus rubroviolaceus*
Chlorurus sordidus	*Scarus spinus*
Chlorurus species	*Siganus doliatus*
Hipposcarus longiceps	*Siganus punctatus*
Hipposcarus species	*Siganus punctatissimus*
Naso lituratus	*Siganus vermiculatus*
Naso tuberosus	*Zebrasoma scopas*
Naso unicornis	*Zebarsoma veliferum*
Omnivores	
Acanthurus nigricauda	*Chaetodon ulietensis*
Acanthurus olivaceous	*Chaetodon unimaculatus*
Acanthurus pyroferus	*Chaetodon vagabundus*
Bolbometopon muricatum	*Ctenochaetus binotatus*
Chaetodon auriga	*Ctenochaetus cyanocheilus*
Chanos chanos	*Ctenochaetus striatus*
Chaetodon citrinellus	*Macolor macularis*
Chaetodon ephippium	*Naso vlamingii*
Chaetodon kleinii	*Scarus oviceps*
Chaetodon lineolatus	*Scarus schlegeli*
Chaetodon mertensii	*Siganus guttatus*
Chaetodon pelewensis	*Siganus spinus*
Chaetodon punctatofasciatus	*Siganus uspi*

Piscivores	
Acanthurus mata	*Lutjanus bohar*
Anyperodon leucogrammicus	*Lutjanus fulvus*
Aphareus furca	*Lutjanus fulviflamma*
Aprion virescens	*Lutjanus gibbus*
Balistoides viridescens	*Lutjanus kasmira*
Carcharhinus amblyrhynchos	*Lutjanus monostigma*
Carangoides ferdau	*Lutjanus quinquelineatus*
Carangoides gymnostethus	*Lutjanus russeli*
Caranx ignobilis	*Lutjanus semicinctus*
Caranx melampygus	*Macolor niger*
Carcharhinus melanopterus	*Monotaxis grandoculis*
Carangoides oblongus	*Mulloidichthys flavolineatus*
Carangoides orthogrammus	*Naso annulatus*
Carangoides plagiotaenia	*Naso brachycentron*
Caranx sexfasciatus	*Naso brevirostris*
Carangoides.sp	*Parupeneus barberinus*
Cephalopholis argus	*Parupeneus barberinoides*
Cephalopholis miniata	*Parupeneus bifasciatus*
Cephalopholis sonnerati	*Parupeneus cyclostomus*
Cephalopholis urodeta	*Parupeneus multifasciatus*
Cheilinus undulatus	*Platax teira*
Elagatis bipinnulata	*Plectorhinchus albovittatus*
Epinephelus caeruleopunctatus	*Plectorhinchus chaetodonoides*
Epinephelus chlorostigma	*Plectorhinchus picus*
Epinephelus howlandi	*Plectorhinchus vittatus*
Ephinephelus maculatus	*Plectorhinchus.sp*
Epinephelus merra	*Plectropomus areolatus*
Epinephelus spilotoceps	*Plectropomus laevis*
Gnathodentex aureolineatus	*Plectropomus leopardus*
Gracila albomarginata	*Plectropomus macularis*
Grammatorcynus bilineatus	*Plectropomus pessuliferus*
Gymnocranius.sp	*Rastrelliger kanagurta*
Heniochus monoceros	*Scomberomorus commerson*
Lethrinus atkinsoni	*Scomberoides lysan*
Lethrinus erythropterus	*Sphyraena forsteni*
Lethrinus harak	*Sphyraena qenie*
Lethrinus obsoletus	*Trachinotus blochii*
Lethrinus olivaceus	*Triaenodon obesus*
Lethrinus xanthochilus	*Variola albimarginata*
Lutjanus argentimaculatus	*Variola louti*

Appendix 4. Fish species lists from Kubulau

List of fish species observed in Kubulau during surveys in April 2009 at sites within Cakaunivuaka (CK), Nakadamalevu (ND), Nakali (NK), Namuri (NM) and Namena (NA). The site NK1 was near site KB01 on the backreef of Nakali. Endemic fish are in red.,

		CK		ND		NK	NM	NA	
SPECIES		**MO4**	**KB09**	**C13**	**KB07**	**NK1**	**KB11**	**KB03**	**KB05**
Carcharhinidae									
Carcharhinus	*amblyrhynchos*								
Triaenodon	*obesus*								
Myliobatidae									
Manta	*birostris*								
Synodontidae									
Synodus	*variegatus*								
Holocentridae									
Myripristis	*adusta*								
	berndti								
	kuntee								
	pralinia								
Neonipon	*sammara*								
	argenteus								
Sargocentron	*caudimaculatum*								
	diadema								
	microstoma								
	spiniferum								
	tiere								
	violaceum								
Aulostomidae									
Aulostomus	*chinensis*								
Serranidae									
Belonaperca	*chabanaudi*								
Cephalopholis	*argus*								
	miniata								
	sexmaculata								
	urodeta								
Epinephalus	*fuscoguttatus*								
	howlandi								
	malabricus								
	merra								
	miliaris								
	polyphekadion								
Plectropomous	*areolatus*								
	laevis								
	leopardus								
	pessuliferus								
Pseudanthias									
	pleurotaenia								
	squamipinnis								
	tuka								
Serranocirrhitus	*latus*								
Variola	*albimarginata*								

		CK		ND		NK	NM	NA	
SPECIES		**MO4**	**KB09**	**C13**	**KB07**	**NK1**	**KB11**	**KB03**	**KB05**
Variola	*louti*								
Pseudochromidae									
Pictichromis	*porphyreus*								
Cirrhitidae									
Cirrhitichthys	*oxycephalus*								
Paracirrhites	*arcatus*								
	hemistictus								
	forsteri								
Priacanthidae									
Heteropriacanthus	*cruentatus*								
Apogonidae									
Apogon	*angustatus*								
	exostigma								
	fraenatus								
	kallopterus								
	neotes								
	nigrofasciatus								
	novemfasciatus								
Archamia	*fucata*								
Cheilodipterus	*artus*								
	macrodon								
	quinquelineatus								
Malacanthidae									
Hoplolatilus	*sp.*								
Echeneidae									
Echeneis	*naucrates*								
Carangidae									
Carangoides	*ferdau*								
	plagiotaenia								
Caranx	*melampygus*								
	sexfasciatus								
	tille								
Scomberoides	*lysan*								
	tol								
Lutjanidae									
Aphareus	*furca*								
	ritulans								
Aprion	*virescens*								
Lutjanus	*biguttatus*								
	bohar								
	fulviflamma								
	fulvus								
	gibbus								
	kasmira								
	monostigma								
	rivulatus								
	russeli								
	semicinctus								
Macolor	*niger*								
	macularis								

SPECIES		CK		ND		NK	NM	NA	
		MO4	KB09	C13	KB07	NK1	KB11	KB03	KB05
Caesionidae									
Caesio	*caerulaurea*								
	lunaris								
	teres								
Pterocaesio	*pisang*								
	tile								
	trilineata								
Haemulidae									
Plectorhinchus	*chaetodonoides*								
	gibbosus								
Lethrinidae									
Lethrinis	*erythracanthus*								
	harak								
	microdon								
	nebulosus								
	obsoletus								
	olivaceous								
	xanthochilus								
Monotaxis	*grandoculis*								
Nemipteridae									
Scolopsis	*bilineata*								
	trilineata								
Pentapodus	*sp*								
Mullidae									
Parupeneus	*barbarinus*								
	barbarinoides								
	cyclostomous								
	crassilabrus								
	multifasciatus								
	pleurostigma								
Pempheridae									
Pempheris	*schwenkii*								
	oualensis								
Kyphosidae									
Kyphosus	*cinerascens*								
Chaetodontidae									
Chaetodon	*auriga*								
	baronessa								
	bennetti								
	citrinellus								
	ephippium								
	kleinii								
	melannotus								
	mertensii								
	ornatissimus								
	oxycephalus								
	pelewensis								
	melanotus								
	plebius								
	rafflesi								
	speculum								
	trifascialis								

SPECIES		CK		ND		NK	NM	NA	
		MO4	KB09	C13	KB07	NK1	KB11	KB03	KB05
Chaetodon	*trifasciatis*								
	unimaculatus								
	ulietensis								
	vagabundus								
Forcipiger	*flavissimus*								
	longirostris								
Hemitaurichthys	*polylepis*								
Heniochus	*acuminatus*								
	monocerus								
	singularis								
	varius								
Pomacanthidae									
Apolemichthys	*trimaculatus*								
Centropyge	*bicolor*								
	bispinosa								
	flavicauda								
	flavissima								
	multicolor								
	nox								
Geniacanthus	*melanospilos*								
Pomacanthus	*semicirculatus*								
Pygoplites	*diacanthus*								
Pomacentridae									
Abudefduf	*septemfasciatus*								
	sexfasciatus								
	vaigiensis								
Amblyglyphidodon	*aureus*								
	curacao								
	leucogaster								
	ternatensis								
Amphiprion	*chrysopterus*								
	barberi								
	perideraion								
Chromis	*amboinensis*								
	atripes								
	delta								
	elerae								
	iomelas								
	lineata								
	lepidolepis								
	margaritifer								
	retrofasciata								
	ternatensis								
	viridis								
	weberi								
	xanthura								
Chrysiptera	*talboti*								
	taupau								
	unimaculata								
Dascyllus	*aruanus*								
	reticulatus								
	trimaculatus								

SPECIES		CK		ND		NK	NM	NA	
		MO4	KB09	C13	KB07	NK1	KB11	KB03	KB05
Neoglyphidodon	*cf carlsoni*								
Plectroglyphidodon	*dickii*								
	imparipennis								
	johnstonianus								
	lacrymatus								
Pomacentrus	*bankanensis*								
	brachialis								
	coelestis								
	callainus								
	imitator								
	lepidogenys								
	mollucensis								
	nigromarginatus								
	pavo								
	philippinus								
	vaiuli								
	microspilos								
	spilotoceps								
Stegastes	*albifasciatus*								
	fasciolatus								
	lividus								
	nigricans								
Labridae									
Anampses	*geographicus*								
	meleagrides								
	neuginaceous								
	twistii								
Bodianus	*anthoides*								
	axillaris								
	daina								
	loxozonus								
	mesothorax								
Cheilinus	*chlororus*								
	diagrammus								
	fasciatus								
	orientalis								
	oxycephalus								
	undulatus								
Choerodon	*jordani*								
Cirrhilabrus	*marjorie*								
	punctatus								
	roseafascia								
	sp								
Coris	*aygula*								
	batuensis								
	gaimard								
Epibulus	*insidiator*								
Gomphosus	*varius*								
Halichoeres	*argus*								
	biocellata								
	hortulanus								
	nebulosus								

		CK		ND		NK	NM	NA	
SPECIES		**MO4**	**KB09**	**C13**	**KB07**	**NK1**	**KB11**	**KB03**	**KB05**
Halichoeres	*ornatissimus*								
	prosopeion								
	richmondi								
	trimaculatus								
Hemigymnus	*fasciatus*								
	melapterus								
Hologymnosus	*annulatus*								
Labrichthys	*unilineatus*								
Labroides	*bicolor*								
	dimidiatus								
Labropsis	*australis*								
	xanthonota								
Macropharyngodon	*meleagris*								
	negrosensis								
Novaculichthys	*taeniurus*								
Pseudochelienus	*evanidus*								
	hexataenia								
	octotaenia								
Pseudocoris	*yamashiroi*								
Stethojulis	*bandanensis*								
	strigiventor								
Thallosoma	*amblycephalum*								
	hardwicke								
	janseni								
	lunare								
	lutescens								
	quinquevittatum								
Scaridae									
Calotomous	*spinidens*								
Chlororus	*bleekeri*								
	longiceps								
	microrhinos								
Cetoscarus	*ocellatus*								
Leptoscarus	*vaigiensis*								
Scarus	*chameleon*								
	dimidiatus								
	ghobban								
	globiceps								
	niger								
	rubroviolaceous								
	schlegeli								
	sordidus								
	spinus								
Pinguipedidae									
Parapercis	*clathrata*								
	cylindrica								
	hexopthalma								
	tetracantha								
Blenniidae									
Ecsenius	*bicolor*								
	fijiensis								
	opsifrontalis								

SPECIES		CK		ND		NK	NM	NA	
		MO4	KB09	C13	KB07	NK1	KB11	KB03	KB05
Meiacanthus	*atrodorsalis*			■	■				
	bundoon								
	ovalauensis	■	■	■	■	■	■		■
Plagiotremus	*flavus*	■	■	■	■	■	■	■	■
	laudandus	■	■		■		■		
	rhinorhynchos			■			■	■	■
	tapeinosoma					■		■	■
Gobiidae									
Amblyeleotris	*randalli*	■			■		■		
	fasciata	■							
	guttata	■							
	phalaena				■				
	rainfordi	■	■		■	■			
Bryaninops	*natens*				■				
Eviota	*cometa*		■			■	■		■
	distigma		■						
	nebulosa	■			■		■		■
	nigriventris							■	
	punctulata			■			■		
	zonura	■							
Exyrias	*belissimus*	■					■		
Fusigobius	*neophytus*	■			■		■		
Istigobius	*decoratus*	■			■				
	ornatus	■				■			
Paragobiodon	*echinocephalus*		■						
Signigobius	*sp*		■				■		
Trimma	*sp*				■			■	■
	caesiura								■
Valenciennea	*sexguttata*				■				
	strigata	■	■		■		■		
Microdesmidae									
Nemateleotris	*magnifica*			■			■		■
Ptereleotris	*evides*	■	■	■	■		■		
	hanae	■							
	heteroptera			■					
Ephippidae									
Platax	*orbicularis*				■		■		■
Siganidae									
Siganus	*argenteus*		■						
	doliatus	■	■	■			■		
	punctatissimus	■	■		■		■	■	
	uspi	■	■	■	■		■		■
Zanclidae									
Zanclus	*cornutus*					■	■	■	■
Acanthuridae									
Acanthurus	*auranticavus*	■		■	■				
	lineatus	■		■			■	■	■
	maculiceps					■			■
	nigricans					■			
	nigrifuscus	■			■				

		CK		ND		NK	NM	NA	
SPECIES		**MO4**	**KB09**	**C13**	**KB07**	**NK1**	**KB11**	**KB03**	**KB05**
Acanthurus	*nigroris*								
	pyroferus								
	thompsoni								
	triostegus								
Ctenochaetus	*binotatus*								
	striatus								
Naso	*brachycentron*								
	brevirostris								
	caesius								
	hexacanthus								
	lituratus								
	tonganus								
	unicornis								
	vlamingi								
Zebrasoma	*scopas*								
	veliferum								
Sphyraenidae									
Sphyraena	*barracuda*								
	qenie								
Scombridae									
Acanthocybium	*solandri*								
Gymnosarda	*unicolor*								
Rastrelliger	*kanagurta*								
Scomberomorous	*commersoni*								
Thunnus	*albacares*								
Balistidae									
Balistapus	*undulatus*								
Balistoides	*viridescens*								
	flavimarginatus								
Rhinecanthus	*rectangulus*								
Sufflamen	*bursa*								
	chrysopterum								
Monacanthidae									
Oxymonocanthus	*longirostris*								
Pevagor	*janthinosoma*								
Ostraciidae									
Ostracion	*cubicus*								
Tetraodontidae									
Arothron	*hispidus*								
Canthigaster	*valentini*								
	TOTAL SPECIES	**162**	**113**	**136**	**191**	**109**	**185**	**160**	**152**
	TOTAL ENDEMIC	**8**	**7**	**8**	**6**	**5**	**9**	**4**	**6**
	CDFI SPECIES	**88**	**71**	**89**	**106**	**73**	**106**	**99**	**90**