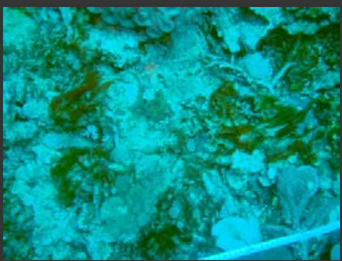

Integrating EBM science to assess marine protected area effectiveness: clues from coral proxies of land disturbance, ecological assessments and socio-economic surveys

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Executive Summary

Research for this study was carried out under a two-year project to support the implementation of Ecosystem-Based Management (EBM) at two catchment-to-reef sites on Vanua Levu, Fiji, during which period a pilot study was initiated to evaluate whether long-lived coral records could be used to detect land-based disturbance to Fijian reefs. Trace element ratios of barium (Ba) to calcium (Ca) were measured at high (~weekly) resolution with laser ablation inductively coupled mass spectrometry (LA-ICP-MS) in cores collected from inshore and offshore *Porites* colonies. The Ba/Ca records from the inshore colony collected approximately 5 km south-east of the Yanawai River mouth and 3 km due west of the Nasue marine protected area (MPA) indicate heavy Ba/Ca enrichment between 1996-1998, which may be related to high levels of sediment delivery to the nearshore while the Mt. Kasi gold mine was operational. Ba/Ca values from the offshore coral collected near the Namena MPA show consistently low baseline values during the same period and over the entire record. Underwater visual census (UVC) surveys of fish biomass, abundance and species richness from 2007 show significantly lower values inside the Nasue MPA than at adjacent sites open to fishing, while the opposite patterns are generally true for the Namena MPA. By synthesizing interdisciplinary data from multiple sources, deductive logic can be used to decipher major drivers of differences in effectiveness of the two district MPAs. Benthic survey data from Nasue closed and open areas showed no significant differences in specific factors which may indicate recent disturbance (e.g. macroalgal cover, rubble) and/or play strong roles in structuring reef fish communities (e.g. live coral cover, presence of fast growing branching corals, reef complexity). Therefore, we conclude that the historical disturbance from the Yanawai River either had minimal effect on benthic communities in Nasue MPA in sites surveyed or they have subsequently recovered and should therefore be able to support healthy reef fish populations if not subject to other types of disturbance. Socioeconomic surveys indicate that Kubulau residents are occasionally witness to infringements of MPA rules and the majority offenders come from outside the district. However, at the same time, Kubulau residents themselves have indicated catch locations within the Nasue (but not Namena) district MPA, suggesting that accidental or deliberate poaching occurs regularly, likely due to lack of awareness of MPA rules and boundaries and inability to see the Nasue MPA from the shore. Recommendations to improve the effectiveness of the MPA are discussed.

Results from this study were presented locally in Fiji at the inaugural Fiji Islands Conservation Science Forum in August 2009 and overseas at the International Marine Conservation Congress in Fairfax, VA, in May 2009. The scientific findings have been presented to residents of Kubulau to provide background information for development of the Kubulau Ecosystem-Based Management (EBM) plan.

Table of Contents

Introduction

Human activity on land has increased global sediment loss by an order of magnitude over natural weathering rates due to human population growth driving land clearing for agriculture and development (Pimentel et al. 1993; Wilkinson 2005). Urbanization and mining have also contributed to localised increases in sedimentation to the nearshore (Fallon et al. 2002). While sediment supply and turbidity are limiting factors in coral reef development (Hopley 1995; Smithers et al. 2006), nearshore reefs are adapted to often highly turbid conditions and, when distant from human disturbance, can be highly diverse (Veron 1995; Mallela et al. 2004; Fabricius et al. 2005). However, nearshore reefs adjacent to highly modified catchments or those with large point-sources of terrestrial pollution may be particularly vulnerable to ecological shifts if chronically degraded water quality reduces resilience to disturbance (McCook 1999). If these disturbances take place within the boundaries of marine protected areas (MPAs), the accompanying loss of resilience may greatly affect the ability of management to yield fisheries benefits and biodiversity conservation.

Field studies from recent decades suggest that coral assemblages from sites within proximity to land based pollution are shifting in response to both point (Smith et al. 1981) and non-point sources (Lapointe 1997; van Woesik et al. 1999). Along natural and anthropogenically enhanced water quality gradients, scleractinian corals living closest to terrestrial and fluvial sources are generally characterized by: (1) high rates of partial mortality; (2) low rates of recruitment; (3) reduced skeletal density; (4) decreased tissue thickness; and (5) reduced depth distributions (Kleypas 1996; Barnes and Lough 1999; Nugues and Roberts 2003; Fabricius 2005). These changes in coral communities are often associated with: increased algal cover (Fabricius et al. 2005); increased abundance and rates of bioerosion by macroborers (Tribollet and Golubic 2005); and reduced octocoral abundance and diversity, particularly from zoothanthellate clades (Fabricius and McCorry 2006). There has also been evidence of reduced fish diversity and biomass related to predictors of terrestrial runoff (e.g. distance from land, visibility, % of mud in sediments), though some fish species, such as *Pleotropomus leopardus*, *Scarus ghobban*, and *Siganus lineatus* may be naturally more closely associated with coastal reefs (Letourner et al. 1998).

In the absence of long-term water quality monitoring data to assess changes to sediment delivery over time, the ratios of certain trace elements to calcium (Ca) within long-lived coral skeletons are good natural tracers of fluvial or pollutant inputs to seawater. Barium (Ba) is one such tracer as ~50-75% of the total dissolved Ba load in nearshore waters is sourced from river discharge (Hanor and Chan 1977; Carroll et al. 1993). Ba is attached to fine-grained clay particles in river runoff but desorbs in low salinity estuarine regions (Coffey et al. 1997). The dissolved Ba moves offshore within the flood plume where it becomes incorporated into coral skeletons in close proportion to its local abundance (Livingston and Thompson 1971; McCulloch et al. 2003). The position of a reef across the continental shelf, its relative proximity to highly modified terrestrial catchments and the tidal range will affect exposure to terrestrial discharge and therefore the recurrence interval of major disturbance. Long-term records of coral Ba/Ca concentrations can be used to identify historic periods of terrestrial disturbance which may have influenced present-day ecological conditions on nearshore reefs (Jupiter et al. 2008).

Current reef community structure, in particular reef fish assemblages, can also be strongly influenced by a variety of factors apart from terrestrial disturbance. Reef topography and complexity has been shown to be a major driver of fish assemblages across several spatial scales (Wilson et al. 2007; Purkis et al. 2008; Pittman et al. 2009): storms, mortality following coral bleaching or other forms of natural or anthropogenic disturbance that reduce complexity cause loss of habitat space for fish across multiple trophic levels (Wilson et al. 2006). Overfishing, however, is likely the major driver of fish assemblages on reefs characterized by even modest levels of subsistence and artisanal fishing pressure (Jennings and Polunin 1996; McClanahan et al. 2008). Only studies that take into account multiple stressors across spatial and temporal scales and their potential synergistic reactions will be able to tease apart the main factors structuring current day reef community composition (e.g. Done et al. 2007).

The present study focuses on two sections of coral reef within the traditional fishing grounds (*qoliqoli*) of Kubulau District, Vanua Levu, Republic of Fiji Islands. Strong anecdotal evidence supports the occurrence of massive fish and coral kills on nearshore reefs in Kubulau in 1998, coincident with the appearance of sediment-laden runoff from the Yanawai River that drains land from the vicinity of the Mt. Kasi gold mine (R. Murphy, pers. comm.). The mine was operated between 1932 and 1946, and then re-opened between 1996 and mid-1998. This study therefore had two primary objectives to:

(1) Use long-lived *Porites* coral Ba/Ca records to assess whether there have been detectable incidents of terrestrial pollution above typical offshore values; and
(2) Integrate the histories of disturbance with present-day coral reef community data and socio-economic survey responses to assess which factors may play a dominant role in influencing the effectiveness of MPAs to enable reef fish recovery.

Methods

Study region

Kubulau District is an administrative unit of Bua Province in south-west Vanua Levu, Fiji Islands (Figure 1). The total land area district land area is 97.5 km^2, of which only 18.1% has been cleared for agriculture and forest plantations, while 63.3% remains under natural forest cover. The boundaries of Kubulau's traditional fisheries management area (261.6 km^2) extend from the coastline to the outer edge of the barrier reefs. The total population of Kubulau district is approximately 1,000 people. There are ten villages in the district, including three inland villages and seven coastal villages. Households in Kubulau are highly dependent on fishing and farming to meet their subsistence needs, and rely heavily on fishing, farming and copra harvesting for cash income (WCS 2009).

In response to concerns about over-exploitation of local marine resources during the 1990s, the Kubulau chiefs banned commercial fishing by non-resource owners within the traditional fishing grounds and informally declared the Namena Marine Reserve, a no-take MPA covering 60.6 km^2 of offshore reef and lagoon area around Namenalala Island (Clarke and Jupiter in press). Namena is located approximately 20 km offshore and is tidally flushed by deep water By 2005, the Kubulau communities set up a district resource management committee who formally declared two additional district-wide, no take areas (Nasue, Namuri), as well as recognized 17 smaller, village-managed closures (Figure 2). The backreefs of the Nasue MPA (8.1 km^2) are located approximately 5 km southeast of the mouth of the Yanawai River, which drains the land surrounding the Mt. Kasi gold mine (Figure 3).

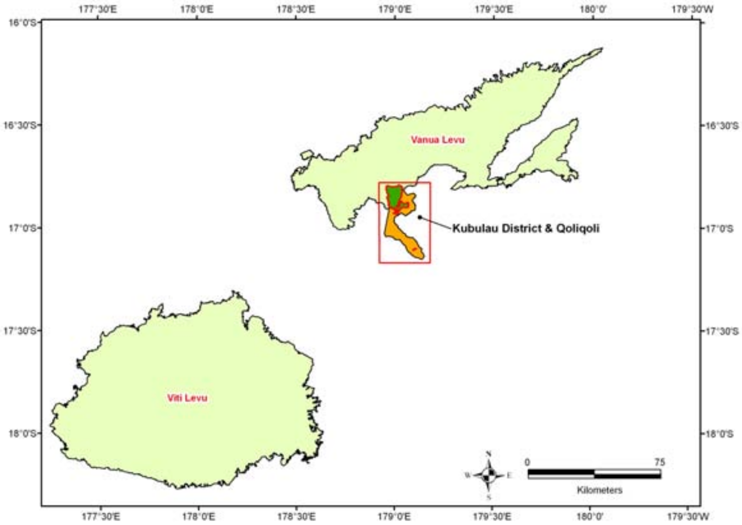
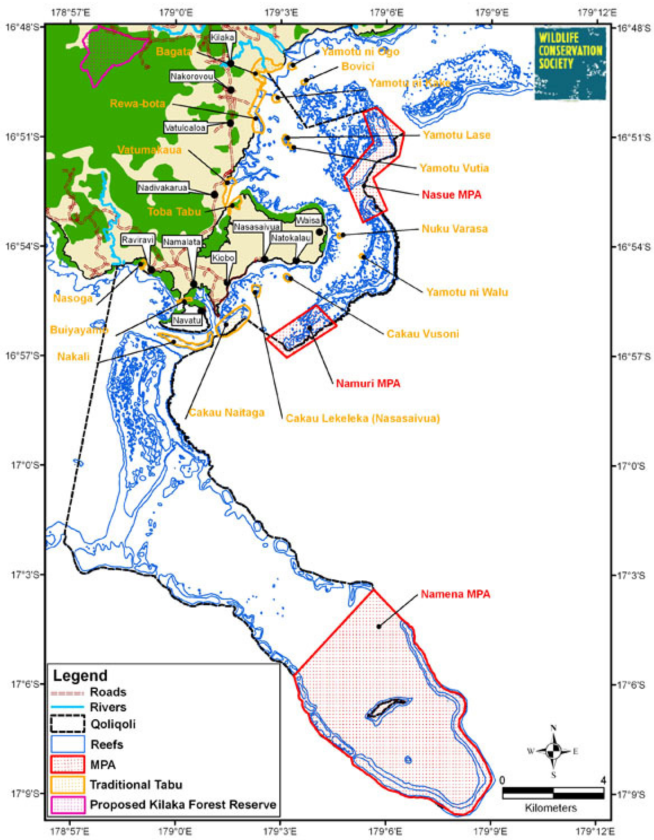


Figure 1. Kubulau District and traditional fisheries management area (*qoliqoli*) located within Bua Province on Vanua Levu, Fiji.



LEFT: Figure 2. District MPAs (red outline) and community tabu areas (orange outline) of Kubulau qoliqoli. **RIGHT: Figure 3.** Photos from the Mt. Kasi gold mine. (photo credits top and middle: A. Jenkins; bottom: E. Tokaduadua)

South-western Vanua Levu, around the city of Savusavu, receives a mean annual rainfall of 2159 mm (Fiji Meteorological Service data, 1977-2006, station V69: 83103), with seasonal peaks during the summer monsoon between November and April (Figure 4). Water temperatures vary between 24.7 and 30.2 over a gridded 1^{o} cell between 16.5 ^{o}S and 179.5 ^{o}E (Figure 5). There were 22 tropical cyclones within the vicinity of Vanua Levu between 1977 and 2007 (Australian Bureau of Meteorology data). Two major incidences of coral bleaching were reported from Fiji reefs in 2000 and 2002, though substantial recovery to pre-bleaching coral cover was reported within 5 years (Lovell and Sykes 2008).

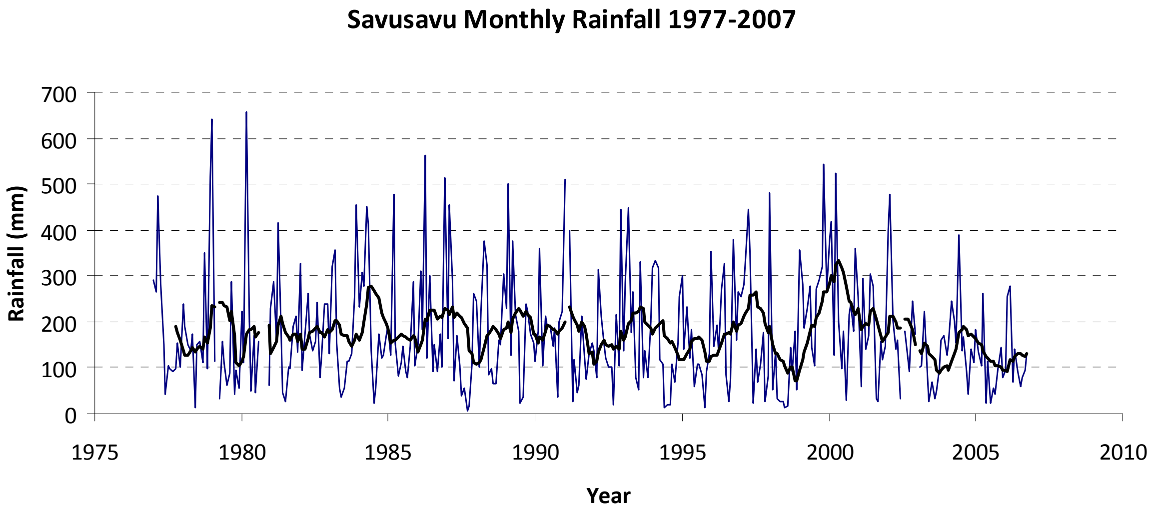


Figure 4. Monthly rainfall from Savusavu airport between 1977-2007 with 10 point running mean, displaying no prolonged wet or dry periods during the record.

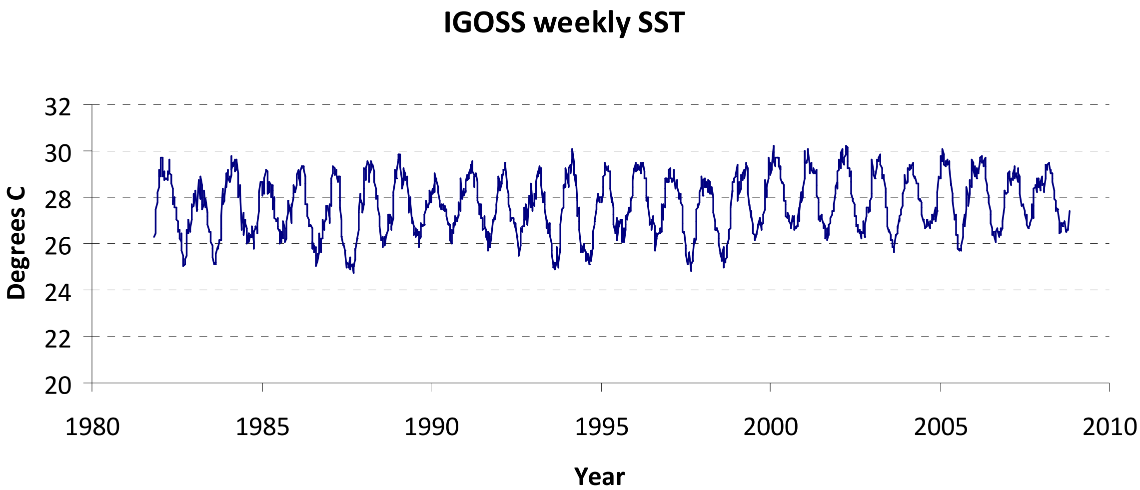


Figure 5. Weekly sea surface temperature (SST) data from 1982-2008 from 16.5 ^{o}S, 179.5 ^{o}E, downloaded from http://www.iridl.ldeo.columbia.edu/SOURCES/.IGOSS/.nmc/).

Coral core collection and analysis

In January 2007, cores were drilled from massive *Porites* coral colonies on backreefs within the Kubulau traditional fishing grounds. One colony was located approximately 5 km south-east of the Yanawai River mouth and 3 km due west of the Nasue MPA, while a comparison core from an offshore location was collected approximately 3 km northwest of the Namena MPA within the backreef lagoon (Figure 6). All cores were collected using SCUBA using a pneumatic, hand-held underwater drill attached to a stainless steel coring barrel.

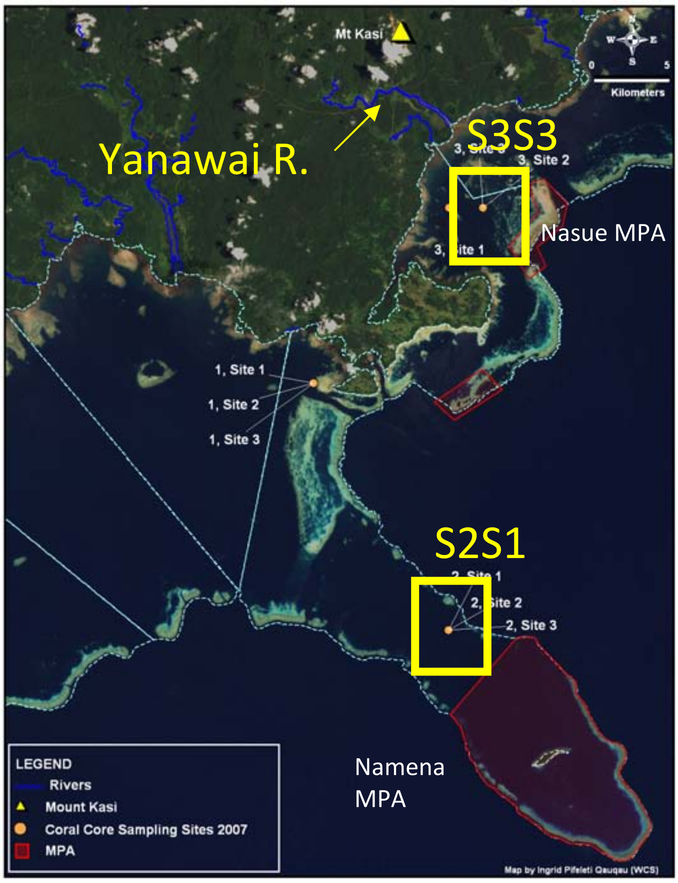


Figure 6. Locations of *Porites* coral cores collected within the reefs of Kubulau qoliqoli. The location of the Mt. Kasi mine is indicated with a yellow triangle directly to the north of the Yanawai River.

Cores were slabbed (~7 mm thick) and slices from three cores (S_2S_1; S_3S_1; S_3S_3) were selected for detailed analysis of trace element concentrations. Slabs were cut to 25 mm x 90 mm pieces and taken to the Australian National University where they were cleaned ultrasonically in 18 MΩ water, and X-radiographed to visualize annual density bands to aid sampling for isotope analysis and chronology assignment (Figure 7, Table 1). Coral pieces were analysed for trace element concentrations of ^{43}Ca, ^{84}Sr, ^{138}Ba and ^{238}U by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) with an ArF excimer attached to a Varian 820 ICP-MS using the exact protocol of Jupiter et al. (2008). All isotopic concentrations were normalized to ^{43}Ca (0.13% Ca) to account for variations in coral surface architecture and density. Preliminary assessment of data from the S_3S_1 coral indicate high levels of surface contamination that we were unable to remove with standard cleaning techniques, therefore data from this coral were not analysed further. Data from the remaining two corals were smoothed using a 10-point running median to remove outliers, followed by a 10-point mean to reduce data volume. Time series of the corals were calibrated by matching Sr/Ca maximum values to minimum values from IGOSS 1º C weekly SST records (Beck et al. 1992). For data before 1981, the average week of SST winter minima was used. Data from tissue layers in the top piece of each core were excluded it contained residual particulate organic material which is typically enriched in Ba (Sinclair 1999).

Table 1. *Porites* coral characteristics, including: date and depth collected, location, length analysed by LA-ICP-MS, and mean growth rate (± standard error)

Coral	Date	Lat	Lon	Depth (m)	Length (cm)	Growth rate (mm)
S_3S_3	16 Jan 2007	16˚ 51.566	179˚ 04.513	5	27.2	8.8 ± 0.47
S_2S_1	15 Jan 2007	17˚ 03.176	179˚ 03.983	1.5	23.2	10.3 ± 0.80

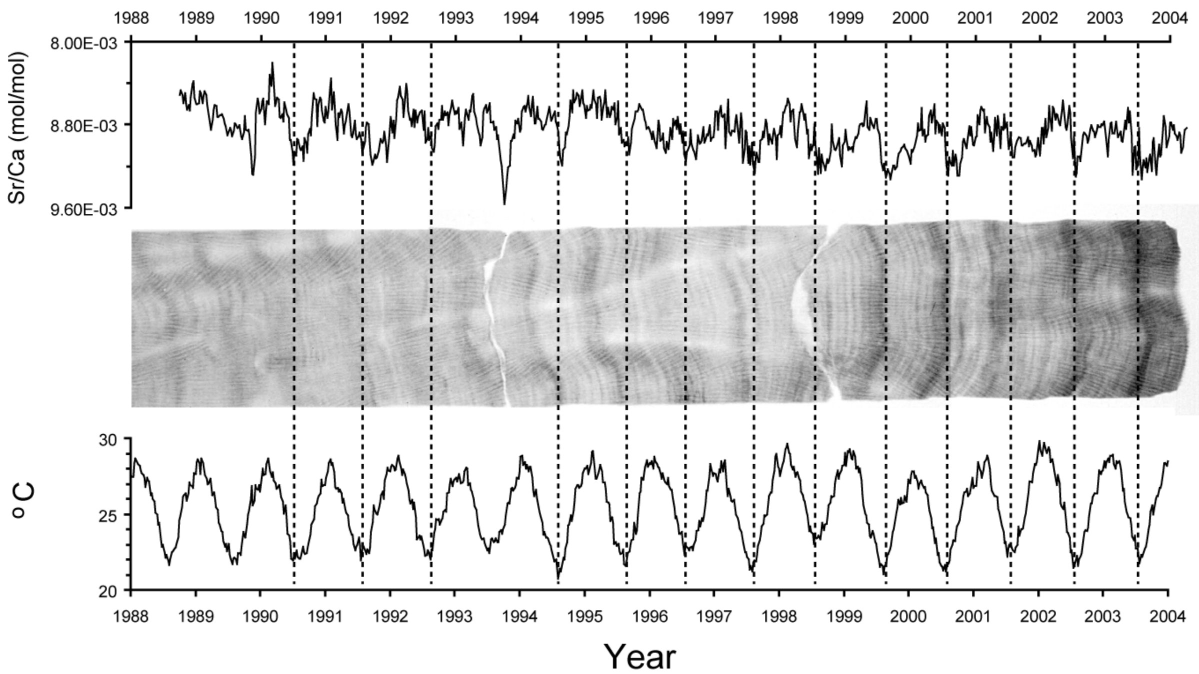


Figure 7. Example of chronology construction from coral core collected in the south-central Great Barrier Reef off Scawfell Island. Dashed lines show alignment between: winter maxima of ~weekly Sr/Ca (top); seasonal density bands (middle); and winter SST minima (bottom). The same process was used for constructing chronologies from the Fiji corals. (Figure used with permission from (Jupiter 2006)).

Ecological surveys

Reef fish composition

In January-February 2007, underwater visual census (UVC) of fish were carried out at sites inside and outside the district-wide MPAs to measure fish abundance and size of the following families: Acanthuridae, Balistidae, Carangidae, Carcharhinidae, Chaetodontidae, Haemulidae, Kyphosidae, Labridae, Lethirinidae, Lutjanidae, Mullidae, Nemipteridae, Pomacanthidae, Scaridae, Scombridae, Serranidae (groupers only), Siganidae, and Zanclidae. Eight sites total (2 forereef and 2 backreef inside and outside) were monitored in and adjacent to the Namena MPA, while six sites total (1 forereef and 2 backreef inside and outside) only were monitored in and adjacent to the Nasue MPA due to weather constraints. Measurements of fish size (total length) and abundance were scored 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 at reef tops (0.5 – 2 m) and shallow depths at backreefs sites. Each sighted fish > 2 cm was classified to species level within size categories (2-5, 6-10, 11-15, 16-20, 21-25, 26-

30, 31-35, 36-40 cm). The length of fishes >40 cm was recorded to the nearest cm to improve estimates of biomass. Biomass was calculated from size class estimates of length (L_T) and existing published values from Fishbase (Froese and Pauly 2009) used in the standard weight-length expression $M = aL_T^b$, with *a* and *b* values preferentially selected from sites closest to Fiji (e.g. New Caledonia). If no length-weight (L-W) conversion factor was present for the species, the factors for a species of similar morphology in the same genus was used (Jennings & Polunin 1996). If a suitable similar species could not be determined, averages for the genera were used. As most of the New Caledonia fishes were measured to fork length (FL), a length-length (L-L) conversion factor was obtained from Fishbase where possible to convert from total length (TL) to FL before biomass estimation.

Benthic substrate composition

Benthic substrate cover was recorded at 0.5 m interval point intercepts along the same 50 m transects in 2007 for the following life form classes that were classified into 7 reef 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, forereef only shallow and deep sites were surveyed inside and adjacent to the district MPAs for the same benthic cover classes and in addition, each 0.25 m^2 surrounding the point was given a complexity score (1 = minimal relief; 2 = some vertical (e.g. boulder corals); 3 = high vertical relief (e.g. branching corals, reef crevices)).

Statistical analyses

Total fish and primary target fish abundance, biomass and species number were pooled across depth for each site. Because the data failed to meet assumptions of normality, non-parametric Mann-Whitney U tests were used in Statistica version 7 software to assess differences in fish abundance and biomass related to management of the Nasue and Namena MPAs. A principal components analysis (PCA) was performed in Primer version 6 software on arcsine-square root transformed benthic strata data from 2007 to evaluate differences within and among sites inside and outside the district MPAs. Mann-Whitney U tests were additionally used to assess differences in specific variables (e.g. live coral cover, macroalgae) between the Nasue and Namena regions. Comparisons of 2009 benthic data were used to assess differences in reef complexity and cover of rubble, macroalgae, live coral and fast growing *Acropora* and *Pocillopora* species to assess whether historical land-based disturbance has influenced current benthic community composition. Where data were normally distributed (macroalgae; *Acropora* plus *Pocilopora* cover), t-tests were used: otherwise, non-parametric Mann-Whitney U tests were employed for (live hard coral; rubble; complexity; standard deviation of complexity).

Socio-economic surveys

Measures of the levels of internal and external poaching in Kubulau qoliqoli were gauged in two ways. (1) In November-December 2008, 51 households were surveyed across 8 villages in Kubulau. Respondents were asked how often they encounter people fishing in breach of MPA rules (regularly, sometimes, rarely, never), and, if they do witness offences, who are the offenders. A nonparametric Friedman ANOVA was used to assess differences in reponses across villages. (2) Within the four villages (Raviravi, Navatu, Kiobo, Nakorovou) participating in weekly catch per unit effort monitoring between May 2008 and February 2009, fishers were asked to draw on a map the locations where they caught fish: maps did not include the MPA boundaries.

Results

Coral Ba/Ca

Mean coral Ba/Ca from the offshore coral S_2S_1 between winter 1986 and winter 2006 was 4.06 ± 0.48 μmol Ba/Ca (± 1 standard deviation), with minor seasonal variations. The overall mean coral Ba/Ca from the coral drilled close to Nasue MPA between 1977 and 2006 was comparable (3.96 ± 1.45 μmol Ba/Ca), with greater variability in concentrations throughout the record. From winter 1976 to winter 1996, the coral Ba/Ca concentration was low (3.13 ± 0.87 μmol Ba/Ca), then became rapidly enriched in Ba (6.12 ± 2.72 μmol Ba/Ca) and remained elevated until the end of 1998, after which higher background Ba/Ca concentrations (4.50 ± 0.84 μmol Ba/Ca) were maintained until 2006 (Figure 8).

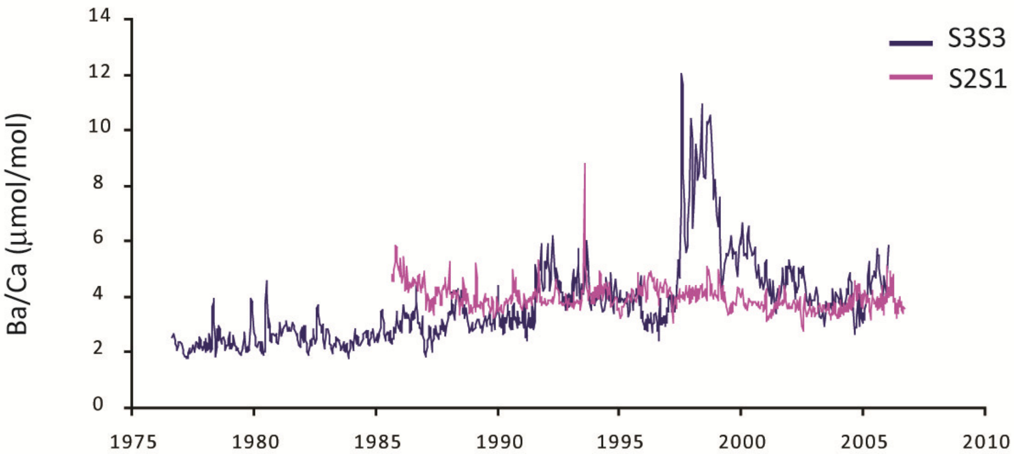


Figure 8. Coral Ba/Ca from the inshore core (S_3S_3: blue) collected near Nasue MPA and the offshore core (S_2S_1: purple) collected near Namena MPA.

Fish biomass, abundance and species richness

Total fish biomass (kg/ha) and abundance (#/ha) were significantly less (Mann-Whitney U test, $p < 0.01$ and $p < 0.001$ respectively) inside the Nasue MPA than at control sites directly to the south and further away from the Yanawai River mouth (Figure 9a,b; Tables 2). Further offshore, neither total fish biomass nor total fish abundance was significantly greater inside the Namena MPA than outside. When only forereef sites were considered, total fish biomass and abundance were significantly greater inside the Namena MPA than outside ($p < 0.01$ and $p < 0.05$, respectively), whereas fish biomass was not significantly different in Nasue MPA and abundance was significantly lower ($p < 0.05$; Figure 9c,d; Table 2). Mean fish species number sighted per transect was not significantly different between the Namena (14.8 species) and Nasue (14.5 species) regions: there were, however, nearly significantly fewer species within Nasue closed (12.8 species) versus open (16.4 species) areas (Mann-Whitney U test, $p = 0.070$)

Table 2. Differences (mean ± standard error) between closed and open areas in Nasue and Namena district MPAs in (a) total fish biomass (kg/ha); (b) total fish abundance (#/ha); (c) forereef fish biomass (kg/ha); and (d) forereef fish abundance (#/ha). Critical z-adjusted values and p-values are reported from Mann-Whitney U tests. Significant p-values are indicated in bold.

MPA	Closed	Open	Z-adj	p-value
(a) Biomass (all sites; kg/ha)				
Nasue	400.0 ± 149.9	524.0 ± 421.5	-2.901	**0.004**
Namena	976.0 ± 677.3	345.2 ± 70.9	0.433	0.665
(b) Abundance (all sites; #/ha)				
Nasue	1643 ± 137	3243 ± 438	-3.569	**< 0.001**
Namena	4444 ± 822	1711 ± 176	1.167	0.106
(c) Biomass (forereef only sites; kg/ha)				
Nasue	831.4 ± 321.8	510.1 ± 177.5	0.726	0.468
Namena	1647.0 ± 587.1	385.4 ± 103.6	2.624	**0.009**
(d) Abundance (forereef only sites; #/ha)				
Nasue	1739 ± 223	2947 ± 346	-2.552	**0.011**
Namena	6064 ± 1431	1758 ± 249	2.530	**0.011**

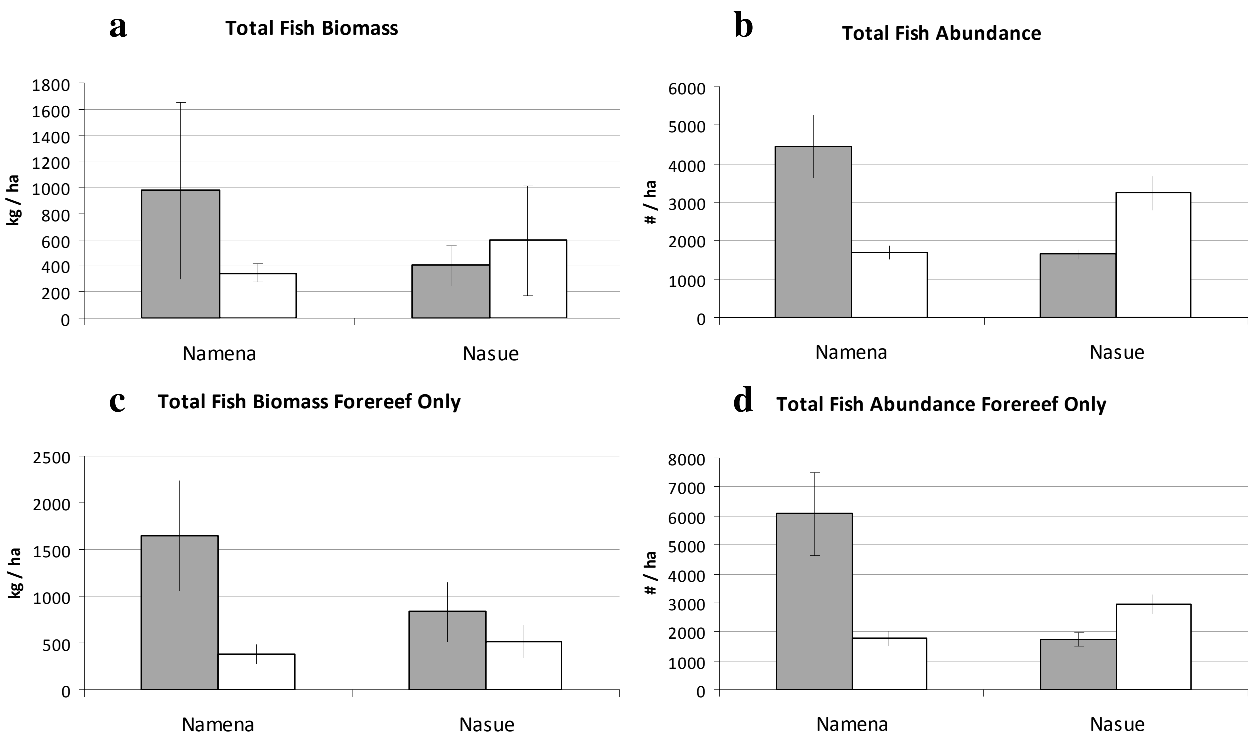


Figure 9. Total reef fish (a) biomass (kg/ha) and (b) abundance (#/ha) inside (grey) and outside (white) district MPAs. (c-d) Total reef fish (a) biomass (kg/ha) and (b) abundance (#/ha) inside (grey) and outside (white) district MPAs for forereef sites only. Error bars are ± 1 standard error.

Variation in benthic structure

From the 2007 data, although live coral cover was significantly greater in and around Namena compared with the reefs around Nasue (Mann Whitney U-test; p = 0.01; Table 3), ordination of the transformed, mean percent cover of each benthic strata of each site surveyed showed no holistic differences between Nasue and Namena sites, whether inside or adjacent to the MPAs (Figure 10). Negative values along the first principal component (PC1) were most related to unconsolidated substrate (factor score -0.685), while positive values were more related to live coral and other (factor scores 0.442 and 0.555, respectively): the backreef sites inside the Namena MPA (N28, N27) had the most negative values along PC1, while the forereef sites inside and outside Namena had the highest positive values along PC1. In addition, at the transect level, sampling locations within the Nasue MPA did not appear to have marked habitat differences to transect locations outside the MPA (Figure 11). Site distribution along PC1 is largely explained by turf algae and reef matrix, which had high negative (-0.645) and positive (0.746) factor scores, respectively. PC1 comprised 53% of the total variance. PC2 explained a further 22% of the overall variance, and site distribution along this axis is primarily explained by live hard coral and unconsolidated substrate, which had high negative (-0.570) and positive (0.762) factor scores, respectively.

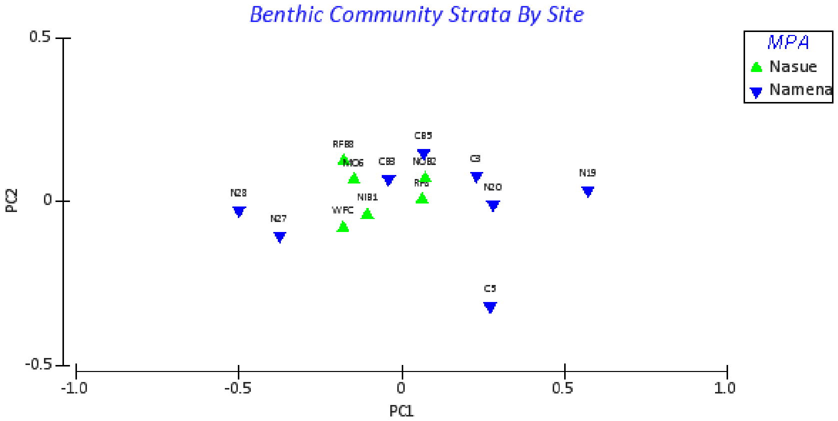


Figure 10. Principal components analysis of 7 main benthic strata from all sites surveyed inside and adjacent to the Nasue (green) and Namena (blue) MPAs.

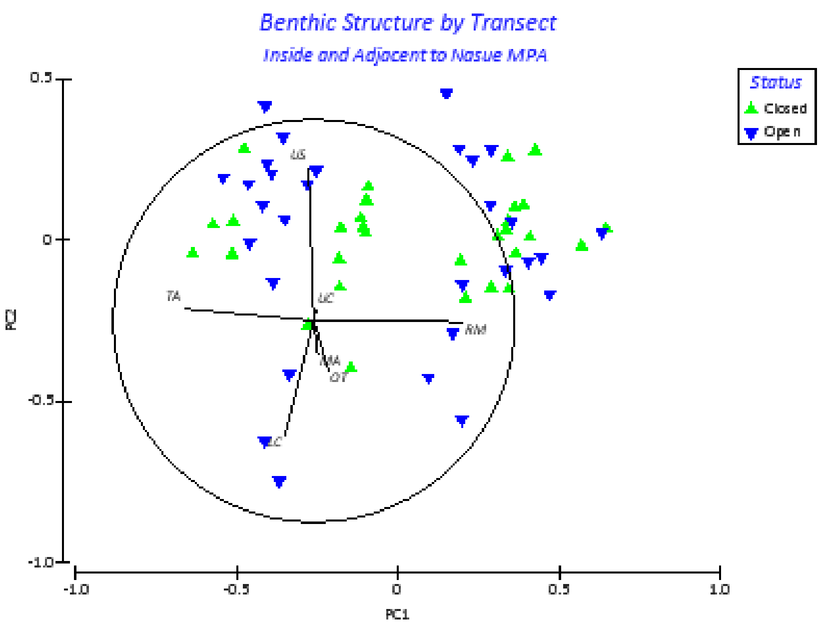


Figure 11. Principal components analysis of 7 main benthic strata from all transects surveyed inside (green) and adjacent (blue) to the Nasue MPA.

Repeat surveys at forereef only sites in 2009 found slightly higher amounts of rubble inside the Nasue MPA and slightly higher coverage of fast growing *Acropora* and

Pocillopora corals that tend to recovery quickly from disturbance, but these abundances were not significantly greater and the coverage of macroalgae was fairly constant (Table 4). In addition, measures of reef complexity were statistically similar both inside and outside the Nasue MPAs (Table 4).

Table 3. Differences (mean ± standard error) in 2007 benthic cover per transect between Nasue and Namena monitoring sites, pooled across management (closed plus open). Critical z-adjusted values and p-values are reported from Mann-Whitney U tests. Significant p-values are indicated in bold.

Benthic Strata	Nasue	Namena	Z-adj	p-value
Live hard coral	25.5 ± 2.3	32.2 ± 2.2	-2.535	**0.011**
Macroalgae	2.4 ± 1.3	0.5 ± 0.2	1.781	0.075
Reef matrix	17.5 ± 2.6	13.7 ± 1.9	0.961	0.337
Unconsolidated substrate	43.9 ± 2.6	34.6 ± 3.2	3.054	**0.002**
Other	8.7 ± 0.9	17.8 ± 1.9	-2.488	**0.013**
Turf algae	12.3 ± 2.1	10.4 ± 1.6	-0.351	0.726
Upright coralline algae	0.8 ± 0.4	0.5 ± 0.2	0.057	0.955

Table 4. Differences (mean ± standard error) in benthic cover categories per transect between closed and open areas in the Nasue MPA region. T-values(*) and p-values are reported for t-tests for normally distributed data. Critical z-adjusted(†) values and p-values are reported from Mann-Whitney U tests for non-normal data. Significant p-values are indicated in bold.

Benthic Category	Closed	Open	Z-adj / t-value	p-value
Nasue MPA				
Live hard coral	47.8 ± 2.5	49.6 ± 1.7	0.915*	0.360
Macroalgae	2.1 ± 0.7	2.4 ± 0.5	-0.142†	0.887
Rubble	41.5 ± 2.9	37.2 ± 2.1	-1.062*	0.292
Acropora and *Pocillopora*	16.7 ± 2.6	15.5 ± 2.6	-0.942†	0.349
Complexity	1.97 ± 0.04	1.98 ± 0.04	0.707*	0.479
STDEV complexity	0.65 ± 0.03	0.61 ± 0.02	-1.905*	0.057

Socioeconomic survey results

There were no significant differences by village in response to how frequently the respondent observed infringements of MPA rules in the Kubulau qoliqoli (Friedman's ANOVA, $\chi^2_{4,7}$ = 5.833, p = 0.559; Figure 12), with most respondents reporting that they sometimes or rarely witnessed offences. Of the 33 respondents who answered the question of who was committing offences, 75.8% (n = 25) replied that they were non-resource rights owners coming from outside the Kubulau qoliqoli. Only 9.1% (n = 3) reported that the offenders came exclusively from within Kubulau, however notably, only 2 of the 8 residents of Navatu village responded to this question: Navatu residents have been repeatedly caught fishing within the Namena MPA.

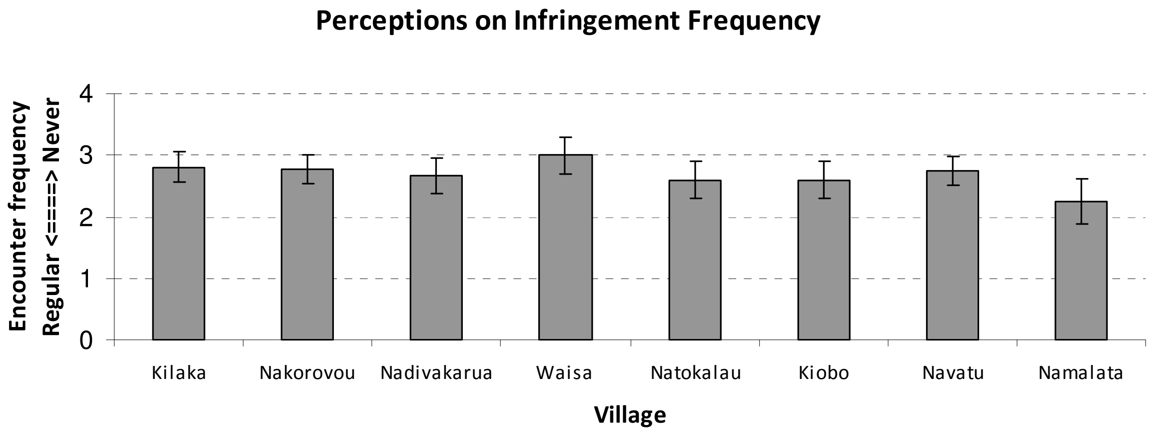


Figure 12. Responses by village to the question “how often do you encounter people fishing in breach of MPA rules (1 = regularly; 2 = sometimes; 3 = rarely; 4 = never).

Synthesis of catch locations from CPUE surveys showed multiple instances of fishing activity from within MPA boundaries by local Kubulau fishers, in particular within: Nasue district MPA; Namuri district MPA; Yamotu ni Oqo and Bagata (Kilaka’s village MPAs); and Rewa Bota and Cakaulekaleka (Nakorovou’s village MPAs; Figure 13).

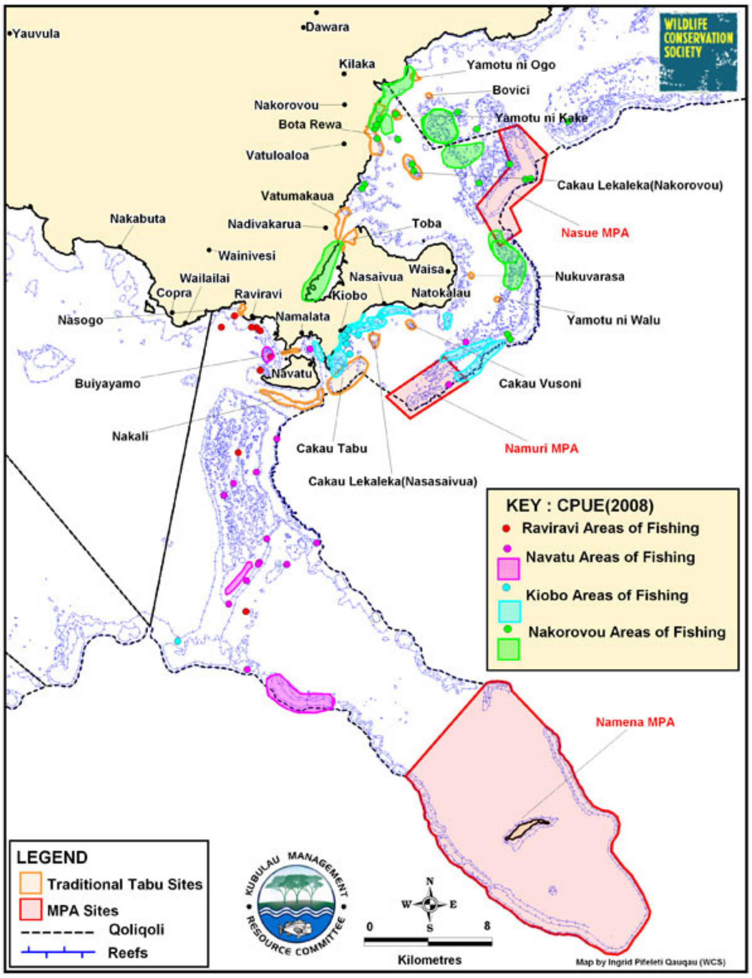


Figure 13. Locations of catch recorded by fishers from four villages (Raviravi: red; Navatu: purple; Kiobo: blue; Nakorovou: green) during catch per unit effort surveys between May 2008 and February 2009.

Discussion

Current day coral reef community composition is a product both of present-day factors and historical disturbance (Connell et al. 1997; Hughes and Connell 1999; Jupiter et al. 2008). Predation, competition and recruitment are among some of the major ecological processes that determine species composition and diversity on reefs. The rates and dynamics of these processes are influenced by natural and man-made disturbances (e.g. tropical cyclones, disease, floods, coral bleaching, overfishing) that cause differential mortality, open space for recruitment, and shift the balance between trophic levels and functional groups (Hughes 1989; Connell et al. 2004). Along inshore to offshore gradients, natural differences in benthic cover, coral growth rates and species diversity may exist subject to the frequency with which inshore reefs are exposed to land-based runoff.

In undisturbed systems, nearshore reefs can be highly diverse: on the Great Barrier Reef (GBR), at least 97% of hard coral genera (DeVantier et al. 2006), 80% of octocoral genera (Fabricius and Alderslade 2001), and 85% of the fleshy macroalgae (McCook et al. 2000) occur on nearshore reefs adjacent to continental land. Coral cover can be high: across sites surveyed on the GBR in 2004 by the Australian Institute of Marine Science (AIMS), nearshore reefs averaged 33% live coral cover, with >50% cover at nearly a quarter of the locations (Sweatman et al. 2007). Nearshore reefs may also have higher rates of disturbance: in addition to the main categories of disturbance that affect outer reefs (e.g. bleaching, cyclone damage, predation, overfishing), nearshore reefs are also subject to both acute and chronic disturbance from terrestrial discharge.

Acute pulses of freshwater discharge can cause mass mortality on reefs (Jokiel et al. 1993; van Woesik et al. 1995), while chronically elevated turbidity and nutrients may decrease reef resilience through reduced survivorship of coral recruits (Fabricius et al. 2003). Sedimentation in runoff from an open-cut gold mines (e.g. Misima Island, Papua New Guinea) can cause coral mortality through smothering, reduce tissue thickness and may be recorded as elevations in trace element to Ca ratios in *Porites* skeletal records (Barnes and Lough 1999; Fallon et al. 2002). Peaks or prolongued enrichment in *Porites* coral skeletal Ba/Ca can coincide with episodic release of sediments delivered to the nearshore and can therefore be used to assess recurrence frequency of significant land-based disturbance to coral reefs (McCulloch et al. 2003; Fleitmann et al. 2007; Jupiter et al. 2008).

Porites coral colonies distant from runoff and/or upwelling sources tend to have low baseline Ba/Ca with variability within the record related to differences in Ba incorporation into separate skeletal elements and seasonal availability of Ba (Allison 1996; Sinclair 1999). Results from the Kubulau *Porites* coral Ba/Ca records indicate that, as expected, the offshore areas around the Namena MPA are not influenced by terrestrial runoff from the mainland. The mean Ba/Ca concentration of the coral record collected near Namena MPA was similar to values recorded from inner-midshelf *Porites* colonies from the GBR at sites largely unaffected by river runoff (Jupiter et al. 2008). Prior to 1996, mean coral Ba/Ca values in the inshore Kubulau coral collected near Nasue MPA were also consistently low, indicating little terrestrial influence and sediment delivery to the nearshore from the Yanawai River. Sediment delivery from Yanawai River flood discharge was likely only substantially elevated over typically background levels during the period when the Mt. Kasi mine was operational (between 1996 and 1998) and immediately succeeding closure of the mine. The inshore coral Ba/Ca record does not indicate sharp peaks related to specific rainfall events, but rather prolonged enrichment of Ba/Ca. This has been observed previously in inshore corals where resuspension from strong tidal currents and release of Ba from sediments accumulated in the mangroves may have contributed to increases in coral Ba/Ca baseline values (Jupiter et al. 2008; Prouty et al. in prep). Based on these results, the relevant question to ask is, therefore: Is current day reef composition at nearshore reefs adjacent to the Yanawai River, including the Nasue MPA, shaped by the legacy of this disturbance or has there been substantial reef recovery?

Upon examining differences in reef fish communities between the Nasue and Namena region, and inside and adjacent to the Nasue MPA, it is evident that there must be certain drivers that have prevented recovery in reef fish abundance, biomass and species richness within the Nasue MPA. One obvious factor is likely longevity of protection: studies have shown that recovery of large-bodied food fish may take upwards of a decade (Jennings et al. 1998; Russ and Alcala 1998). As the Namena MPA has been protected for over 10 years and the Nasue MPA has only been established since 2005, the duration of closure is likely to be a strong factor explaining the difference in relative performance between MPAs in terms of fisheries effectiveness (Jupiter et al. 2010). However, it is particularly striking that the total fish abundance and biomass was greater at sites outside the Nasue MPA, which are farther away from the Yanawai River mouth. Coupled with results from the coral trace element data, one immediate assumption might be that the documented terrestrial disturbance experienced in the late 1990s on reefs proximate to the Yanawai River may have had lasting effects on benthic condition.

Disturbance that alters the composition and complexity of benthic habitat can have strong immediate and lagged effects on reef fish assemblages (Graham et al. 2006; Graham et al. 2007). On Fijian reefs, reductions in abundance of coral-feeding fish and small-bodied damselfish have been associated with declines in branching *Acropora* coral and coral-associated habitat complexity, respectively (Wilson et al. 2008). Furthermore, these habitat-associated reductions in availability of prey can be a more important driver of piscivore abundance than fishing pressure (Wilson et al. 2008). Yet, there was no significant difference between sites within (closer to runoff) or adjacent to the Nasue MPA in terms of cover of any of the benthic strata from the 2007 data. In addition, the 2009 forereef surveys failed to find any significant difference between Nasue closed and open areas in specific factors which may indicate recent disturbance (e.g. macroalgal cover, rubble) and/or play strong roles in structuring reef fish communities (e.g. live coral cover, presence of fast growing branching corals, reef complexity). Thus, if the benthos within Nasue MPA was affected by the runoff in 1998 which resulted in noted fish and coral kills inshore, the benthic community and reef structure has recovered substantially and should be able to support healthy reef fish communities. Although the coral cover around the Nasue region sites (pooled closed and open) was significantly lower and unconsolidated substrate was significantly higher than the Namena region, these differences are expected in natural inshore to offshore gradient, and based on the benthic composition and complexity data alone, the Nasue sites should be able to support healthy reef fish populations.

If the sites surveyed within the Nasue MPA were affected by large-scale disturbance from runoff in the late 1990s, part of the reason why the benthic communities may have been able to recover quickly is likely due to: (1) the cessation of mining operations which removed the potentially chronic sedimentation stress; and (2) the lack of large-scale agricultural activity in the region. Unlike the Macuata region of Vanua Levu, where a high proportion of land on lower slopes has been converted to sugarcane, only 1.4% of Kubulau District lands are under cultivation for agriculture and little if any nitrogen-based fertilizer is applied. Whereas in nutrient-rich waters, even low levels of sediment tend to form biologically mediated “marine snow” that can smother and kill coral recruits (Wolanski and Gibbs 1995; Fabricius et al. 2003), in waters with high turbidity but low nutrients, corals may adapt by altering their morphology or sloughing off particles through mucus production or tissue extension (Rogers 1990; Stafford-Smith and Ormond 1992).

Thus, if the benthic habitat of Nasue MPA has either been resistant to sediment impact or recovered quickly and is similar to areas supporting healthier reef fish populations, there are likely other explanations for the low reef fish biomass and abundance within the MPA. One likely contributing factor is overfishing of Nasue MPA due to non-compliance of community rules. Signs of overfishing often included reduced biomass and abundance of targeted species (Jennings et al. 1999; Pet Soede et al. 2001). Because direct measures of illegal fishing within MPAs were unavailable, the targeted socioeconomic surveys provided valuable information on fishing pressure, both from the relative amount of infractions by local residents (Cinner et al. 2005) and perceived difference in amount of offences by local residents versus non-resource rights owners from outside of Kubulau District. Although the 2008 household surveys from Kubulau represented a smaller than desired sample size (because many heads of household were away earning income harvesting sugarcane in northern Vanua Levu), they indicated a strong perception that the large majority of non-compliance with MPA rules comes from poaching by external fishers. In support of these data, fishers from the adjacent Wailevu District to the north have been caught repeatedly inside Nasue MPA. Additionally, local fishers themselves have indicated multiple catch locations within the Nasue but not Namena MPA (Figure 13). The high incidence of both local and external poaching is most likely due to lack of awareness of MPA boundaries and rules and because the fishers cannot be seen from any of the Kubulau villages. In the tropical Western Pacific where communities are largely responsible for self-enforcement, the visibility of MPAs is one of the most important determinants of its success (Aswani and Hamilton 2004).

Conclusions and Recommendations

Assessing ecological change and the drivers of change on coral reefs is particularly difficult due to the complex nature of reef systems and unpredictable responses to multiple disturbances (Fabricius and De'ath 2004). By synthesizing interdisciplinary data from multiple sources, deductive logic can be used to decipher the most likely major drivers of effectiveness of MPAs. For example, had we only investigated coral core records and fish community data, we might have incorrectly assumed that mine runoff had lasting effects on benthic structure that continues to affect fish recruitment and habitable space. Furthermore, without conducting socioeconomic surveys, we would have only been able to guess at the extent of poaching: in reality, non-compliance is likely to be much more frequent than reported due to a reticence to admit to personal infractions. Future work should evaluate the percentage of fish from targeted species below minimum reproductive size across all study sites (e.g. Fabricius et al. 2005) in order to validate differences in recovery from fishing pressure between Nasue and Namena MPAs and differences in active fishing inside and adjacent to Nasue MPAs. Surveys could also be performed at higher replication, sampling more environmental variables, to rule out other factors which may have contributed to the differences in fish assemblages inside and outside the Nasue MPA.

Some recommendations to improve the effectiveness of Nasue MPA include:

- *Raise awareness of MPA rules and boundaries among residents of Kubulau District.* Following the endorsement and adoption of the Kubulau EBM plan (WCS 2009), rules and regulations were explained in each village and management posters, including maps of the current MPA and community tabu boundaries, were posted in every community hall. Follow-up activities are needed to ensure that all residents are aware of the rules and understand the consequences of non-compliance;

- *Raise awareness of enforcement protocol and options for legal punishment of offenders.* Protocols for enforcement of national laws and community management rules are detailed explicitly in the Kubulau EBM plan (WCS 2009). Follow-through depends largely on the pro-activity of the Kubulau Resource Management Committee (KRMC) and its subcommittee focused on resource management. To strengthen awareness of options for enforcement, the KRMC participated in a role-play exercise where four scenarios were presented and members were asked to evaluate whether management rules had been broken and, if so, what were the available options for punishment. However, at the same management implementation workshop, the KRMC ranked as high priority the need to obtain more skills for fisheries monitoring and infringement reporting, which will require ongoing training.

- *Raise awareness of MPA rules and boundaries among resource-rights owners living in adjacent districts.* At an intensive management planning workshop in February 2009, Kubulau leaders and participants suggested that much of the external poaching is being done by people originally from Kubulau who still retain traditional fishing rights within the qoliqoli but have since moved to other districts and therefore have not been educated about the recent management initiatives. KRMC resolved to: (1) visit neighboring districts to raise awareness of management rules for the qoliqoli and MPAs; and (2) produce and distribute fliers detailing MPA boundaries and rules to be posted at provincial offices, police stations and the regional fisheries department office in Savusavu.

- *Increase frequency and efficiency of enforcement patrols.* Because patrols require fuel, which may be costly, the KRMC has committed to developing and submitting grant proposals with conservation partners to acquire marine radios, which will help to identify the location of offenders, and fuel to operate the patrol boat. The KRMC will require assistance with grant proposal writing and development of a rotational schedule for patrols.

- *Shift the boundary of the Nasue MPA away from the border with Wailevu.* At the February 2009 management planning meeting, a suggestion was proposed to shift the boundaries of Nasue MPA further south so that it would be at least partially visible from shore. The residents of Kubulau seemed initially resistant to the idea because they felt it might encourage more poachers to cross the border from Wailevu District if the area is declared open again to fishing. However, given that re-configuration options for the MPA network will be presented back to the community which optimize fisheries benefits while minimizing costs to fishers (Adams et al. 2010), it may be worthwhile to broach the topic again given the degree of poaching in the area.

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