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Benthic mapping using local aerial photo interpretation and resident taxa inventories for designing marine protected areas

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SUMMARY

Given the frequent socioeconomic, political and concomitant ecological failures of science-driven marine protected area (MPA) programmes, it is now important to design MPAs by integrating natural and social science research more comprehensively. This study shows how indigenous peoples assisted in the design of MPAs by identifying marine substrates and related resident taxa on aerial photos, information which was then incorporated into a geographical information system (GIS) database, along with dive survey data. Two questions were asked: (1) Is indigenous ecological knowledge accurate enough for mapping the benthos and associated taxa? (2) Is such an approach an appropriate way for assisting in the biological and social design of MPAs in Oceania? Conventional quadrat field dive surveys were used to measure the accuracy of substrate identification by local informants and a visual survey was used to test hypotheses formulated from local knowledge regarding the spatial distribution and relative abundance of non-cryptic species within certain benthic habitats. Equivalence rates between indigenous aerial photo interpretations of dominant benthic substrates and *in situ* dive surveys were 75–85% for a moderately detailed classification scheme of the benthos, which included nine locally-defined abiotic and biotic benthic classes for the MPA seabed. Similarly, the taxa inventory showed a strong correspondence between the qualitative predictions of local fisherfolk and the quantitative analysis of non-cryptic species distribution, including their relative abundance and geophysical locations. Indigenous people's predictions about the presence or absence of fish in different benthic habitats corresponded 77% and 92% of the time (depending on scoring schema) with *in situ* visual measurements. These results demonstrate how incorporating local knowledge of benthic heterogeneity, existing biological communities, and particular spatio-temporal events of biological significance into a GIS database can corroborate the production of scientifically reliable base resource maps for designing MPAs in an environmentally and culturally sound fashion. This participatory approach was used to design and then establish MPAs in the Roviana and Vonavona region of the Western Solomon Islands. Under appropriate conditions, interdisciplinary work can complement the design of scientific fishery management and biodiversity conservation prescriptions for coastal Oceania.

Keywords: benthic mapping, geographical information systems (GIS), indigenous ecological knowledge, marine protected areas, Oceania, taxa inventories

INTRODUCTION

Benthic mapping is the crucial first step in identifying the characteristics of marine environments, leading toward the design and implementation of resource management plans such as marine protected areas (MPAs) (Cendrero 1989; Mumby & Harborne 1999; Roff *et al.* 2003; Stevens & Connolly 2004). Researchers have used a number of aerial and space-borne remote sensing techniques (Ahmad & Neil 1994; Sheppard *et al.* 1995; Mumby *et al.* 1997*a*; Green *et al.* 1998; Andréfouët *et al.* 2003; Purkis & Pasterkamp 2004), as well as other scientific methods (Schaffner *et al.* 1987; Carleton & Done 1995; Ardron 2002; Brown *et al.* 2002; Pickrill & Todd 2003; Jordan *et al.* 2005; Stevens 2005) for mapping benthic environments. These maps serve to catalogue habitat diversity and zonation, act as a proxy for identifying species diversity locally (Gray 1997; Ward *et al.* 1999) and identify sites that incorporate the ecological processes that support biodiversity, including the presence of exploitable species, vulnerable life stages and habitat inter-connectivity (Roberts *et al.* 2003).

Indigenous ecological knowledge can help habitat mapping because indigenous people develop a storehouse of practical environmental information through generations of human interaction with their environment. Social scientists are beginning to show the usefulness of indigenous ecological knowledge for mapping the seafloor and for applying such knowledge to participatory fisheries management (see Stoffle *et al.* 1994; Nietschmann 1995; Anuchiracheeva *et al.* 2003; Hughes *et al.* 2005). Interdisciplinary studies have validated the notion that indigenous ecological knowledge can enhance understanding of the marine benthos and associated biological processes (for example Poizat & Baran 1997; Aswani & Hamilton 2004*a*; Drew 2005; Silvano & Begossi 2005).

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This study presents a way to produce maps of the benthos and associated biological communities through generic aerial photography and the direct participation of local peoples. We show how indigenous peoples assisted in the design of MPAs by identifying marine substrates and related resident taxa on aerial photos, information which was then incorporated into a geographical information system (GIS) database, along with dive survey data. We employed conventional quadrat field-dive surveys to identify the dominant abiotic and/or biotic benthic features at each sampled site. This direct benthic measure was compared against the major benthic attributes identified by local informants at each site. To assess taxa, we compared a visual census to local knowledge regarding the spatial association and relative abundance of non-cryptic species within certain benthic communities.

We asked two questions: (1) is indigenous ecological knowledge for mapping the benthos and associated taxa scientifically reliable? (2) Is the present approach a valid way to assist in the biological and social design of marine protected areas in Oceania? We present data from Baraulu Village in the Roviana Lagoon, Solomon Islands to answer these questions. With our assistance, the Baraulu community established a no-take marine reserve (103 hectares) in 2002. This conservation site was chosen for its ecological and social importance through a combination of locally driven assessments (indigenous knowledge and attitudes, proximity to the village for monitoring and enforcement) and the research reported in this paper. We also incorporated indigenous ecological knowledge into conventional marine science methodology to identify critical life stages of susceptible species in the area (Aswani & Hamilton 2004*a*). For logistical and community-related reasons, ground truthing of local knowledge was conducted following the MPA's establishment. In addition, we included time series data (1994–2004) on human foraging activities into the GIS to examine spatio-temporal patterns of foraging effort, which was taken into consideration when designing the MPA (Aswani 1998; Aswani & Lauer 2006). Finally, we studied customary sea tenure (CST) in order to select a site in which there was minimal conflict over natural resources and sea boundaries (see Aswani 2002, 2005). In some instances, this approach to MPA design resulted in a trade-off between biological significance and social sustainability.

STUDY AREA

The Roviana Lagoon in the Western Solomon Islands (Appendix 1, see Supplementary material at http://www.ncl.ac.uk/icef/EC_Supplement.htm) is dominated by mangroves, seagrasses, sand banks, algal beds and coral reefs with various benthic characteristics. The lagoon lies within the Bismarck-Solomon Seas eco-region, which is considered one of the world's marine biodiversity hotspots (World Wildlife Fund South Sea Programme 2003). Baraulu Village and its adjoining land and sea territory lie at the intersection between the Kalikoqu and Saikile chieftain districts in the centre of the Roviana Lagoon. Over 600 people live in the village, many of whom reside in the provincial and national capitals intermittently. As with the rest of Roviana, local leaders exercise control over their own customary land and sea territories. Yet, community-based management has not assured the sustainable use of natural resources, even as the rising pressures of population and development threaten the ecology and social stability of this region. To address these problems, we established a marine conservation project at Baraulu in 1999, which was subsequently extended (2002) to cover neighbouring reefs within Baraulu and in other villages in the Roviana and Vonavona lagoons (Aswani & Hamilton 2004*b*).

METHODS

The initial step was to formulate a qualitative definition of benthic communities that incorporated both physical and biological components (Diaz *et al.* 2004). We drew on indigenous ecological knowledge because local habitat classification distinguishes between composite abiotic benthic substrates, biotic communities overlying the substrate and occupant species in a fashion similar to scientific marine habitat classifications for Solomon Islands coastal habitats (Stoddart 1969; Blaber & Milton 1990). Indigenous ecological knowledge was recorded through participant observation and interviews with fisherfolk. Open-ended and structured interviews were conducted with several hundred young (18–39 years of age), middle-aged (40–59 years), and elderly (>60 years) men and women from across the lagoon communities. We interviewed the general population through a random stratified sample, and we identified active and experienced fisherfolk using a snowball sample. Informants were asked to characterize (free list) the benthic characteristics of potential and existing MPA sites, including their associated benthic cover (substrate and morphology) and resident biotic communities. These data allowed for the formulation of a qualitative classification of benthic habitats commonly found in planned MPAs (Table 1). We then associated this indigenous ecological knowledge with locally named biophysical features, which established the spatial foundation for the ensuing GIS analysis (see Aswani & Lauer 2006).

Next, we used a large-format plotter to print a 60-cm by 120-cm hard-copy map of the planned Baraulu MPA with a scale of approximately 1:3500. The map was created using digitized and geo-rectified air photos as the real-world backdrop and with the boundary of the MPA site superimposed in a bright colour. The large-format, poster-sized map was the visual tool that was interpreted by local informants. Five informants, including both men and women, were selected to be the photo interpreters based on their knowledge of the marine environment and their overall fishing experience. Once the informants understood that the perspective of the photographs was from directly above, they began to interpret and identify the main reefs and predominant benthic characteristics. When a feature in a photograph was first identified, the group would think about

Table 1 Indigenous classification of habitats and associated benthic substrates and fish species found in the Baraulu MPA.

Local habitat classification	*Dominant abiotic substrates*	*Dominant biotic cover*	*Major resident fish species*
Kulikuliana (seagrass beds)	*Onone* (sand), *nelaka* (silt/sand), *patu horahoraka* (dead coral/stones)	*Kuli* (*Enhalus acoroides* seagrass), *kuli ngongoto* (various Cymodoceaceae and Hydrocharitaceae seagrasses), *tatalo, kakoto, omomo*, and *garagara* (*Halimeda* spp. and other macroalgae)	*Gohi* (*Sphyraena barracuda*), *lipa* (various Mugilidae spp.), *makoto lio* (*P. flavimarginatus*), *makoto noa* (*B. viridescens*), *mara* (various *Carangidae* spp.), *osanga* (*Lethrinus harak*), *ramusi* (*Lethrinus obsoletus*), *pakao* (*Parupeneus barberinus*), *tetego/medomedo* (*Siganus* spp.)
Sagauru Masa (shallow inner lagoon reef)	*Onone* (sand), *zalekoro* (rubble), *patu horahoraka* (dead coral/stones)	*Patupatu* (mixed live/dead corals), *patu voa* (*Porites* or massive corals), *patu pede* (*Acropora* spp. or sub-massive and branching corals), *huquru* (*Porites cylindrica* or branching corals), *nene siki* (digitate *Acropora* and other *Seriatopora* branching corals), *binu* (various hard corals), *toropae kiso* (*Fungia* spp. or mushroom corals), *ime* (*Caulerpa* spp. or macroalgae), *tatalo, kakoto, omomo*, and *garagara* (*Halimeda* spp. and other macroalgae), *laza keana* (various coralline algae), *lumulumutu* (various turf algae), *puha* (generic for sponges)	*Heheuku* (*Lutjanus gibbus*), *kulele* (*Lutjanus semicinctus*), *makoto lio* (*P. flavimarginatus*), *makoto noa* (*B. viridescens*), *mara* (various *Carangidae* spp.), *matalava* (*Monotaxis grandoculis*), *osanga* (*Lethrinus harak*), *odongo* (*Lutjanus fulvus*), *pakao* (*Parupeneus barberinus*), *pakopako* (*Choerodon anchorago*), *pazara* (generic for serranids), *ramusi* (*Lethrinus obsoletus*), *tarasi* (*Acanthurus auranticavus*)
Sagauru Lamana (mid-depth inner lagoon reef)	*Onone* (sand), *nelaka* (silt/sand), *zalekoro* (rubble), *patu horahoraka* (dead coral/stones)	*Patupatu* (mixed live/dead corals), *huquru* (*Porites cylindrica* or branching corals), *patu voa* (*Porites* or massive corals), *binu* (various hard corals), *toropae kiso* (*Fungia* spp. or mushroom corals), *laza keana* (various coralline algae), *puha* (generic for sponges)	*Heheuku* (*Lutjanus gibbus*), *mihu* (*Lethrinus olivaceous*), *pakopako* (*Choerodon anchorago*), *pipirikoho* (Various Haemulidae), *odongo* (*Lutjanus fulvus*), *sina* (*Lutjanus rivulatus*), *tarasi* (*Acanthurus auranticavus*), *topa* (*Bolbometopon muricatum*)
Bolebole (tidal sand bank)	*Onone* (sand), *zalekoro* (rubble), *nelaka* (silt/sand, sparsely distributed)	*Kuli ngongoto* (sparse cover), (Cymodoceaceae and Hydrocharitaceae sea grasses), *tatalo, kakoto, omomo*, and *garagara* (*Halimeda* spp. and other macroalgae), *ime* (*Caulerpa* spp. or macroalgae)	*Karapata* (*Lethrinus hypselopterus*), *mihu* (*Lethrinus olivaceous*), *osanga* (*Lethrinus harak*), *pakao* (*Parupeneus barberinus*), *suru* (*Lethrinus xanthochilus*)
Kopi (lagoon pool) and *karovoana* (reef channel)	*Zalekoro* (rubble), *onone* (sand), *nelaka* (silt/sand)	Corals may occur on the walls of the pool/channel, but these are generally composed of abiotic substrates	*Bebele lamana* (*Platax teira*), *mara* (various *Carangidae* spp.), *tarasi* (*Acanthurus auranticavus*), *vuhe* (*Pomacanthus sexstriatus*)

the site from their personal experience, rather than focus intensely on the picture. Specifically, informants deduced from their cumulative fishing experience how each feature appeared in the photograph and then used the location cues in the photograph to locate specific benthic characteristics in relation to one another. The informants then selected the most knowledgeable person from their group and cooperatively drew the boundaries of abiotic and biotic substrates using a felt-tip marker directly on the photograph.

We initially focused on demarcating the predominant benthic abiotic and biotic substrates rather than on zoning the benthic habitat categories (Table 1), because it was easier for informants to conceptualize their marine habitats from the bottom-up at first. That is, the general habitat categories shared abiotic and biotic substrates as well as biological communities, thus making it initially harder for informants to delineate 'habitats' as discrete entities on the map but easy for them to delineate what was on the bottom. In addition, the broader habitat categories nested a number of biotic substrates of biological significance that we did not want to overlook (for example coral colonies). The resulting paper map, with the respective benthic types drawn on it by local informers, was scanned, and the image files were loaded into the GIS for geo-rectification. After geo-referencing, each of the boundaries was traced using on-screen digitizing techniques that created polygons (shape files) of each of the benthic substrates.

The next step was to test the correspondence between indigenous photo interpretation of major benthic features and the actual distribution of abiotic and biotic substrates in the area. We selected sample site locations by dividing up the MPA into 60-m × 60-m grid cells using GIS. We used a stratified random sample in which the number of samples collected for each general habitat type was based on its extent (as predetermined by our own rough estimations of habitat cover percentage). At each sampling location, a 1-m × 1-m metal frame was lowered into the water onto the seabed and flipped over three times during data recording to create a 2-m × 2-m survey area. Depth was measured directly below the centre of the 2-m × 2-m area, and a student researcher and local divers (free diving) measured on a pre-printed PVC slate only the dominant benthic cover in accordance with a modified version (to suit local conditions) of the Reef Check Survey Manual (Hodgson *et al.* 2003) and the Australian Institute of Marine Science (AIMS) manual for underwater research (English *et al.* 1997). Divers conducting the field dive surveys only recorded the dominant benthic cover within each quadrat to be consistent with local informants, who had only identified the presence or absence of dominant substrate or substrate bundles (of abiotic and/or biotic attributes) and did not estimate the percentage cover of all benthic classes within each polygon.

This simplified approach precluded a more elaborate classification of local benthic habitats using hierarchical cluster and similarity percentage analyses of the *in situ* survey data (Mumby *et al.* 1997*b*). To compare the two data sets, we used GIS to spatially display the substrate data collected in the marine science survey as one layer (points and their attributes), together with the layer (polygons and their attributes) created by the indigenous photo interpreters. Then we ran a spatial query that selected all of the points from the marine science survey layer found within each polygon of the indigenously defined dominant benthic attribute(s). The queries allowed us to add an attribute column to the benthic data set indicating which indigenously defined benthic types were associated with each survey site. This served as the basis for measuring the correspondence between local aerial photo interpretations of benthic types and dive survey results.

In our point-to-point comparison for the accuracy assessment, we compared the dominant abiotic and/or biotic benthic attributes (not entire habitats) identified by local informants and divers for each area. Accuracy was assessed as per cent correct (95% confidence intervals for chance correction) under two scoring schema. Under lenient scoring, partially correct answers were considered correct. Under strict scoring, partially correct answers were excluded, so comparisons were made only between unambiguously incorrect or correct answers. Because of language limitations, and because of the free-response format employed in acquiring local knowledge (rather than selection from a predetermined list), some Baraulu benthic categories corresponded with more than one benthic class collected during the ground-truthing survey. For example, *patupatu onone* is an accurate description of dive survey categories of sand with corals or rubble with corals. Because of these language limitations, the Tau statistic of Ma and Redmond (1995) could not be calculated (see also Mumby *et al.* 1997*b*). Therefore, chance correction for accuracy was estimated using a kappa statistic based on weighted survey standards (Fleiss *et al.* 1969), which may overestimate agreement above chance (Ma & Redmond 1995). Finally, after having conceptualized the general benthic characteristics from the bottom up, informants were better able to trace on the aerial photographs the rough extent of benthic habitats (mixed communities) within the MPA using the indigenous habitat categories (Table 1), for which rough percentage cover estimates were calculated.

For the species inventory, we mapped resident taxa and associated biological events of significance by interviewing fisherfolk and mapping the seascape as they conceptualized their marine environment (i.e. indigenously defined and named sites that are associated mainly with fishing). Baraulu fisherfolk guided us in a small boat around the perimeter of each named area, which might or might not correspond with the boundaries of particular marine biotopes (for example seagrass beds) mapped earlier for their intrinsic benthic qualities. We recorded (and ranked) the presence and distribution of common fish species and the locations of spawning, nursery, burrowing and aggregating sites for particular species within each recognized ground and associated benthic habitats. The spatial extent of the area (represented as polygons) and the location of particular biological characteristics (represented usually as points) collected with the global positioning system (GPS) receivers were consolidated into a large file and imported into our GIS database as a layer.

To test working hypotheses formulated from local knowledge regarding fish species distribution and relative abundance across the locally defined benthic habitats (Table 1) within the Baraulu MPA, we conducted visual counts. We selected 11 locally identified species that were easily recognizable during visual surveys (non-cryptic species) (Lieske & Meyers 2002), including species belonging to the Lutjanidae, Lethrinidae, Mullidae, Balistidae, Acanthuridae and Labridae families (Table 2). Each sample inside the MPA consisted of one static seven-minute fish survey from the surface, during which the selected fish species were observed within a radius of five metres. Relative abundance measures were calculated for all species in each general habitat type (Table 2) to compare their distributions across the MPA regardless of habitat size (rough cover percentage). Finally, to determine whether the Baraulu participants were significantly better than chance-guessing at which fish species were present in which areas, fish observations were matched with local speculation. Statistical concurrence between fish observations with local knowledge for four habitats and 11 non-cryptic species of fish was investigated using a 4 × 11 matrix of 44 cells. Four indigenously defined habitats (mid-depth reefs, shallow reefs, seagrass beds and sand) were matched to the MPA general habitats. Channel (or mid-depth sand) was

Table 2 Relative abundances (% of total samples for one habitat where this species was present) of fishes for each habitat type.

Fish species	*Shallow sand*	*Mid depth sand*	*Shallow reefs*	*Mid depth reefs*	*Seagrass beds*
Heheuku	0	0	37	45	0
Kulele	0	0	20	14	0
Makoto lio	0	0	31	5	8
Makoto noa	0	0	10	14	0
Matalava	0	0	31	5	0
Odongo	0	0	35	55	8
Osanga	17	7	59	0	75
Pakao	0	0	45	9	58
Pakopako	0	0	49	64	17
Ramusi	0	0	22	5	17
Tarasi	0	0	43	41	8

excluded from the analysis as unrepresentative because almost no fish count was generated from this area owing to poor water visibility.

For statistical testing, the Baraulu prediction of the presence versus absence of a specific species in a specific habitat was assigned a probability of 0.5 because the natural abundance of 'fish present' and 'fish not present' approached 50–50 (fish present in 21 of 44 opportunities, or 48%). A sign test was used to determine statistical significance (Keppel 1991; Howell 2002), with the significance threshold set at $p < 0.05$. To ensure the reliability of the findings, two scoring schemas were used. The count-everything scoring schema included all 44 fish cells multiplied by the number of habitat cells in the comparison. The unambiguous-only scoring method included only fish-by-habitat cells with either zero sightings or more than 10% sightings. This removal of sightings of < 10% ($n = 7$, $n = 37$ remaining for comparisons) was conducted to ensure that one or two stray fish did not create an artificial overestimation or underestimation of local knowledge.

RESULTS

The interview data showed that fisherfolk divided the ocean into named sites that represent biophysical resource exploitation areas, geomorphological features that allow or bar people from navigating, and cultural and historical markers that define the seascapes (*sagauru* or generic for 'reef'). Next, fisherfolk identified fishing grounds (*habuhabuana*) that are nested within the larger indigenously named and demarcated biophysical sites. Fishing grounds, in turn, are composed of one or more areas or floating spots (*alealeana*), in which people actually fish (for example a reef outcrop). Beneath this cultural construction of the seascape, informants identified biological events of significance and one or more of the 16 locally recognized marine habitats, including mid-depth reefs (*sagauru lamana*), shallow reefs (*sagauru masa*), tidal sand banks (*bolebole*) and seagrass beds (*kulikuliana*). Finally,

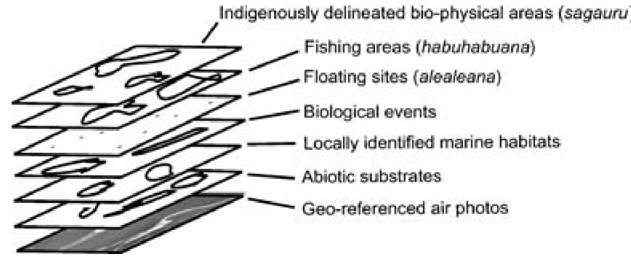

Figure 1 Roviana hierarchical cognition of the seascape as represented by layers (or themes) in the GIS.

informants distinguished the composite benthic substrates of each locally defined habitat (found in the MPA designated areas), which reasonably resembled the abiotic and biotic group codes detailed in the Reef Check and AIMS manuals (Table 1). The indigenous hierarchical cognition of the seascape was represented by layers (or themes) in the GIS (Fig. 1).

Results from point-to-point comparison between the ground-truthed quadrat field dive surveys and the data derived from local photo interpreters showed a high correspondence rate. In spite of limitations of polygon areas versus spot comparisons and some differences in how environmental categories were cognized locally and by our team, the agreement between local estimates and the quadrat field dive survey was between 75 and 85% across the two scoring schema. Lenient scoring included all data ($n = 137$) by counting partially-correct answers as correct. Agreement by lenient scoring was $112/137 \times 100 = 81.8\%$ (chance-corrected: 78.2%, 95% CI = 73.8–82.6%). Strict scoring consisted of removing the partially correct guesses (such as substrate correctly identified but missing features or bundled with additional features) ($n = 137–33$ or $n = 104$), thus only counting the unambiguous incorrect or correct answers resulted in $79/104 \times 100 = 76.0\%$ agreement (chance-corrected: 70.2%, 95% CI = 61.9–78.6%) (Table 3).

Generally, Baraulu informants had a high accuracy rate of interpretation for rock and silt substrates, had reasonable proficiency for identifying sand, rubble and hard corals, and were less proficient at distinguishing soft corals and algal beds (Table 3). In sum, Baraulu photo interpreters demarcated the predominant abiotic and biotic substrates on the aerial photographs of the MPA with a moderately comprehensive benthic classification that included bundled and individual substrates (Fig. 2), which corresponded well with our identification of dominant attributes recorded during the quadrat field dive surveys.

The general extent of benthic habitats as defined and delineated (polygons) by local informants (i.e. combinations of the substrate classes illustrated in Fig. 2; Table 1) included *nelaka* or silt (*karovoana* or reef channels) 40%; *patupatu-onone, huquru* and *pede*, or substrates predominated by a mix of dead and live coral colonies (mainly *Porites* and *Acropora*), and sand and coral gravel (*sagauru masa* and *sagauru lamana*,

Table 3 Point-to-point comparison between quadrat dive field survey results and indigenous aerial photo interpretation of dominant benthic substrates in the Baraulu MPA.

Predominant benthic cover	*Lenient scoring schema (including partials)*					*Strict scoring schema (excluding partials)*				
	(n = 137)	*Full + partial equivalence*		*No equivalence*		*(n = 107)*	*Full equivalence (unambiguous)*		*No equivalence*	
Hard coral (HC)	11	6	54.5%	5	45.5%	11	6	54.5%	5	45.5%
Soft coral (SC)	3	0	0.0%	3	100.0%	3	0	0.0%	3	100.0%
NI Algae (NIA)	3	1	33.3%	2	66.7%	2	0	0.0%	2	100.0%
Rubble (RB)	7	5	71.4%	2	28.6%	2	0	0.0%	2	100.0%
Rubble (RB)/hard corals (HC)	14	10	71.4%	4	28.6%	14	10	71.4%	4	28.6%
Rock (RC) /hard corals (HC)	11	9	81.8%	2	18.2%	10	8	80.0%	2	20.0%
Dead coral (DC)	–	–	–	–	–	–	–	–	–	–
Sand (SD)	19	17	89.5%	2	10.5%	7	5	71.4%	2	28.6%
Sand (SD)/hard corals (HC)	9	8	88.9%	1	10.1%	9	8	88.9%	1	10.1%
Silt (SI)	48	46	95.8%	2	4.2%	42	40	95.2%	2	4.8%
Seagrass (SG)	12	10	83.3%	2	16.7%	4	2	50.0%	2	50.0%
Total	137	112	81.8%	25	18.2%	104	79	76.0%	25	24.0%

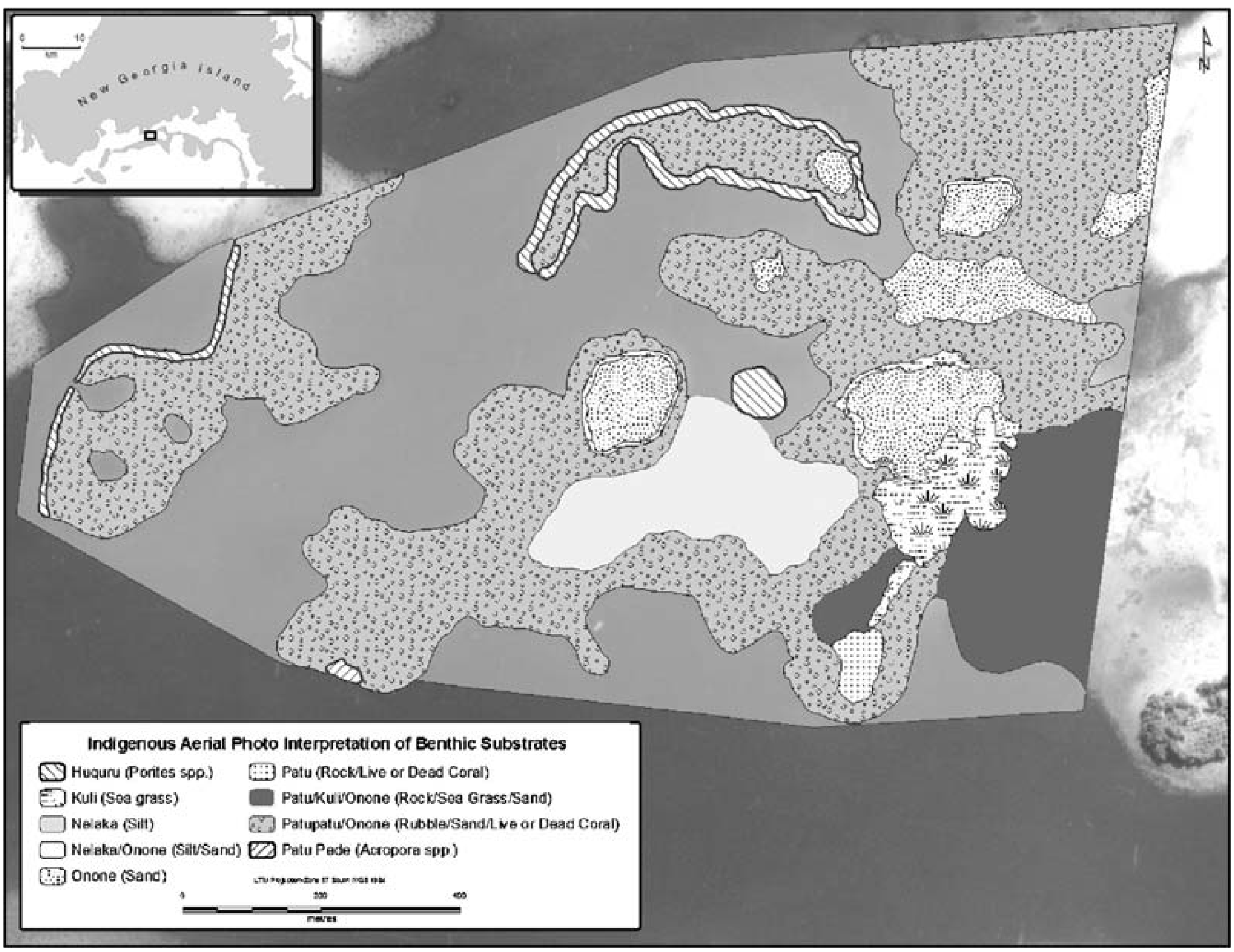

Figure 2 Informants' demarcation of predominant abiotic and biotic substrates on the aerial photographs of the Baraulu MPA.

or shallow and mid-depth inner-lagoon reefs) 41%; *kuli* and *patu-kuli-onone*, or seagrass and seagrass mixed with sand and dispersed dead and live corals (*kulikuliana* or seagrass beds) 8.3%; and *onone* and *onone-nelaka*, or sand and sand mixed with silt (*bolebole* or tidal sandbanks) 11%. These habitat cover percentages corresponded reasonably well with our estimates of general habitat types, which indicate 30% cover for reef channels, 49% cover for shallow and mid-depth inner-lagoon reefs, 8% cover for seagrasses, and 14% cover for shallow and mid-depth sandbanks. The informants were not able to identify algal beds, as these occur across most benthic substrates and are difficult to distinguish in the aerial photographs, except for some spots where an informant remembered *Caulerpa* species harvest areas.

For the species inventory, local informants spatially demarcated the Baraulu MPA into seven main indigenously delineated biophysical areas using their own cultural construction of the seascape. Nested within each of these areas, fisherfolk tended to identify 17 fishing zones and 31 floating spots. For each area, they provided inventories of fish commonly found and indicated significant biological resources. The geo-referenced zones identified by the indigenous informants showed *Porites cylindrica* (*huquru*) and *Acropora* spp. (*pede*) coral colonies (coral heads), bumphead parrotfish (*Bolbometopon muricatum* [*topa*]) burrowing and nursery sites (Fig. 3, areas 1 and 2), and paddletail snapper (*Lutjanus gibbus* [*heheuku*]) spawning aggregation sites (Fig. 3, area 3).

The visual survey results corresponded well with indigenous accounts of the spatial distribution and relative abundance of the non-cryptic species sampled within the MPA. The visual survey results showed that some fish species had a clear preference for certain habitat types (value% $>=$ 50%; Table 2). For instance, *odongo* (*Lutjanus fulvus*) and *pakopako* (*Choerodon anchorago*) were associated with mid-depth reefs (55% and 64%, respectively), *osanga* (*Lethrinus harak*) was associated with shallow reefs (59%) and more clearly with seagrass beds (75%), and *pakao* (*Parupeneus barberinus*) was associated with seagrass beds (58%). Other species, such as *heheuku* (*Lutjanus gibbus*) and *tarasi* (*Acanthurus auranticavus*), were more evenly distributed across all MPA benthic habitats (L. Geelen, unpublished data 2003). When these measurements were compared with the predictions of the indigenous people, they correctly predicted fish presence versus fish absence per habitat in 34 of the 44 fish × habitat cells (4 habitats × 11 fish). This 77% accuracy was statistically significant (sign test, $n = 44$, $p < 0.0004$). Some habitat × fish species data were ambiguous, in that fish species were observed in less than 10% of measurement periods, which may indicate stray fish or may simply be an underestimation of the natural abundance. When only unambiguous data were considered ($0 < x < 10\%$ data not considered), the Baraulu people were correct in 34 of 37 opportunities. This 92% accuracy was statistically significant (sign test, $n = 37$, $p < 0.000001$). These findings show that Baraulu fisherfolk know which fish species live in which benthic region.

DISCUSSION

How reliable was indigenous ecological knowledge for mapping the benthos and associated taxa? Equivalence between indigenous aerial photo interpretations of dominant benthic substrates and *in situ* quadrat field dive surveys was 75–85% for a moderately detailed classification scheme of the benthos, which included nine locally defined abiotic and biotic benthic classes for the MPA seabed. The ranges reported by more conventional space-borne (for example Landsat and IKONOS) habitat mapping techniques provide an accuracy of 12–74% using five substrate classes (Joyce *et al.* 2002), 77% for a 4–5 substrate class schema and 53% for a 13-class classification (Andréfouët *et al.* 2003), 70% for coarse classification and 40% for a more precise mapping classification (Mumby *et al.* 1999), and 72–86% for major biological cover identification (Cochran-Marquez 2005). While the present study did not seek to measure entire habitat classes (as reported by most of the above studies), the high equivalence rates between local knowledge and direct ground-truth mapping for benthic abiotic and/or biotic attributes is promising.

This contention is only strengthened by a limitation of the present study, the age (1984, 20 years old) and coarse spectral resolution of the black-and-white aerial photographs, which did not reveal the present-day environmental conditions, resolve currently salient environmental features, nor precisely differentiate the reflectance disparities between coral rubble and sand banks, for example. These old, low spectral resolution, black-and-white photographs seem dated compared with modern imaging techniques, yet the photos were sufficient for the local people to use the general landmarks in visualizing environmental regions of interest and then to provide reasonably accurate descriptions of the dominant benthic substrate and the presence or absence of specific taxa. If recently-acquired, high-resolution, multi-spectral or hyper-spectral imagery were employed, combined with better one-to-one correspondence between local language and direct-survey truth-mapping categorizations, it is reasonable to believe that local Roviana photo interpreters could identify benthic communities with even higher accuracy and reliability.

The visual fish census showed a strong correspondence between the qualitative deductions of the indigenous informants and our quantitative analysis of non-cryptic species' general habitat distribution and relative abundance. While indigenous ecological knowledge regarding particular biological events such as spawning aggregations (Fig. 3) was not ground truthed (with the exception of information regarding bumphead parrotfish [*Bolbometopon muricatum*] nursery areas; see Aswani & Hamilton 2004*a*), the present empirical findings support the scientific validity of indigenous ecological knowledge. In short, local people can determine fish distributions at least as accurately as direct scientific observation, and possibly more accurately if seasonal or dynamic events were included. This knowledge is crucial in building MPAs sensitive to local needs and local ecological concerns, two basic principles that are vital to fostering sustainable MPAs.

Documenting indigenous ecological knowledge for producing resource base maps can yield reliable research results because indigenous peoples can accurately identify benthic substrates and the associated biological communities

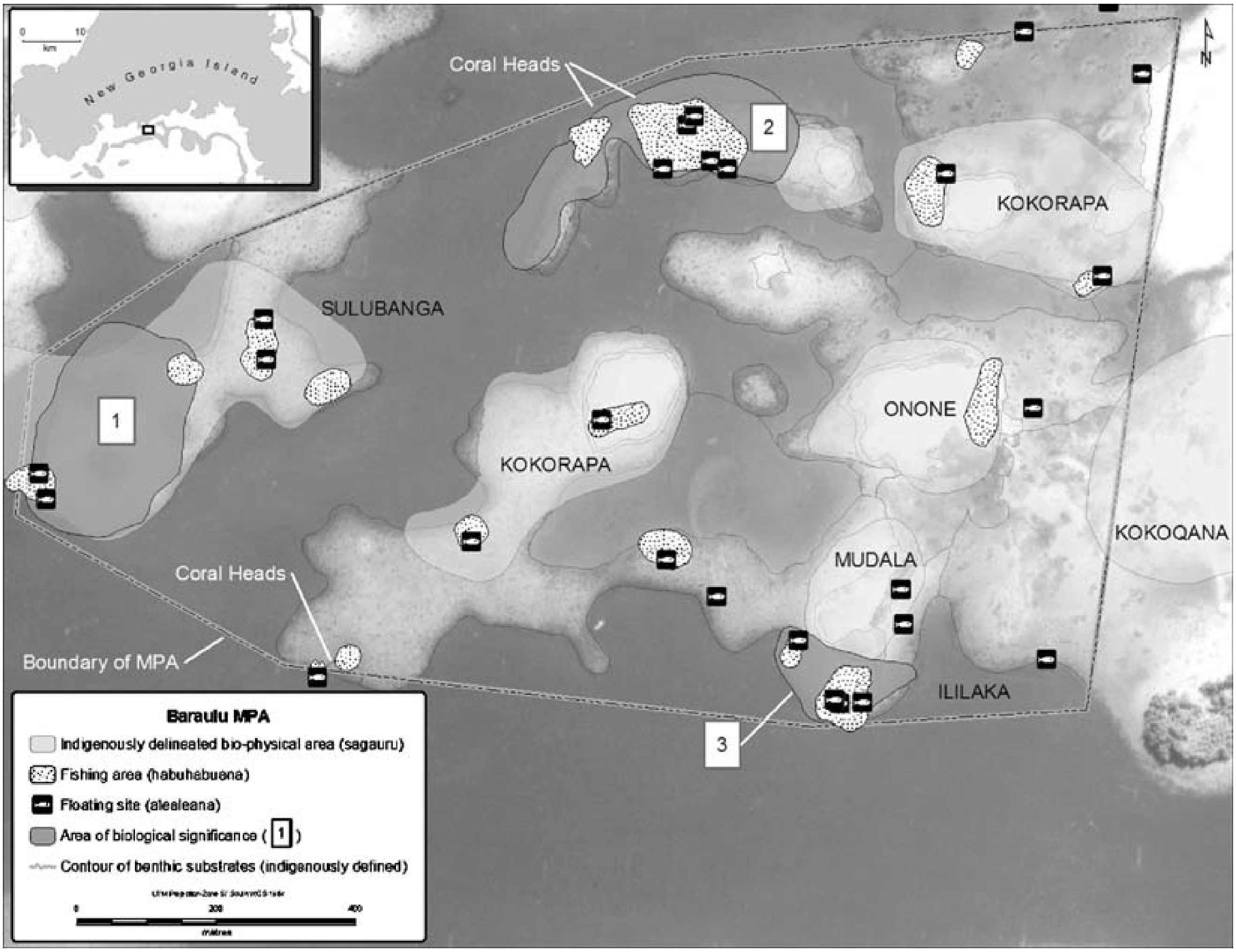

Figure 3 Indigenous map of the Baraulu MPA seascape. The numbered areas are ecologically important events/ characteristics. Note that for display purposes, the *sagauru* layer was placed underneath the *alealeana* and *habuhabuana* layers.

in heterogeneous marine environments. In contrast to scientists, local photo interpreters employ more inductive reasoning to assess aerial photographs. To make their visual interpretations, the local interpreters drew not only from the image, but also from their repertoire of highly specific and detailed local environmental knowledge concerning the location and quality of benthic regions. Although remote-sensing experts create imagery keys for visual interpretation through extensive *in situ* observations, they must classify benthic habitats by deduction from the tones, shapes, sizes, patterns, textures, shadows and the association of features in the imagery. Scientists do not have the same level of knowledge of benthic habitats that they map and thus do not learn their specific locations, characteristics and extent, but structured interviews with local peoples can provide reliable answers.

Local knowledge is important for other reasons. Abiotic and biotic habitat classifications inferred from aerial or space-borne images are quite often used as surrogates for determining species diversity and distribution in particular locales (see Gray 1997; Ward *et al.* 1999). However, Stevens and Connolly (2004, p. 352) demonstrated that inferring biological diversity and distribution from abiotic surrogates can result in both false homogeneity errors and false heterogeneity errors. Also, biological events such as spawning aggregations cannot be gathered from abiotic and/or biotic surrogates, and also often cannot be identified from *in situ* random sampling during underwater visual surveys. This problem can be circumvented by incorporating local knowledge of benthic heterogeneity, existing biological communities, and particular spatio-temporal events of biological significance into the production of base resource maps, knowledge that can be geo-referenced and entered into a GIS. If needed, this information can be assessed easily through various rapid ecological survey techniques. Integration of indigenous ecological knowledge into benthic mapping may bridge the divide between the 'physical' (benthic substrate) and 'biological' (associated species) components (Diaz *et al.* 2004) of scientific benthos maps.

The present study demonstrated success in local aerial photo interpretation and associated taxa identification in spite of some limitations. The local informants interpreted aerial photographs and drew polygons on a map to describe benthic regions, while the visual measurements were obtained based on quadrat point sampling. While map overlays are powerful and highly instructive, a one-to-one geophysical correspondence between measurements from the indigenous informants and those from the scientific team would greatly aid in making inferences based on inferential statistics. Hence, future studies should incorporate a one-to-one geophysical correspondence between scientific measurements of fish, benthic substrates, and other environmental variables and the geo-rectified locations described by indigenous peoples. In addition, the present study was limited by some conceptual issues. For instance, while the scientific descriptions of substrates included discrete categories (such as silt and hard coral) for which the Roviana language has one-to-one equivalents (Table 1), the local language is also rich in word phrases that bundle substrates and associated biotic covers into single categories (such as *patupatu-onone* and *nelaka-onone*). While some in-field adjustments may be necessary to fully capture the phenomena of interest, our current investigations are striving to create cross-language mapping a priori, allowing an objective scoring schema to reveal the most honest estimation of indigenous knowledge. The results generated by this study only provide an assessment of the dominant benthic abiotic and biotic substrates and the predominant fish species identified at each indigenously defined habitat (qualitatively). Informants did not clearly define the dominant geomorphology for most areas and quantified the percentage cover of abiotic and biotic attributes for each traced polygon. These outlined methods provide an understanding of the benthic substrate and associated biological communities known to local informants, not a multi-level hierarchical model of habitats that incorporate various geomorphological, bathymetric, benthic and community structure complexities. The present methodology is flexible and could easily be modified in future studies to embrace fuller habitat descriptions.

Overall, how appropriate is the research strategy presented in this paper for assisting in the biological and social design of MPAs in Oceania? In biological terms, given the dearth of biological baseline data in many Pacific Island nations (Johannes 1998), incorporating indigenous ecological knowledge is an effective, low-cost strategy for producing base resource maps during the planning phase of MPA implementation. The geo-spatial referencing of local knowledge can serve to spatially identify habitat diversity, or lack thereof, to delineate bio-geographical representation when habitat zonation is done on a large scale, and to identify vulnerable habitats and life stages, conceptualized as the association between habitat structure and species size and distribution, as well as sites of rare and/or endangered species and areas of exploited species (Roberts & Hawkins 2000; Botsford *et al.* 2003; Roberts *et al.* 2003).

In social terms, there is a potential trade-off between scientific rigour and local participation, but careful planning can ameliorate this trade-off. Given that scientific studies are increasingly being designed for biodiversity management and conservation purposes, it is imperative to incorporate the concerns, interests and knowledge of local peoples into a project's research design. Such participation not only produces scientifically acceptable data, but also aids in bridging the divide between indigenous and western environmental knowledge. Benthic mapping by means of participatory GIS can also produce maps of local habitats and conservation areas that represent indigenously cognized and delineated natural and social seascapes. In the Roviana case, the hard-copy maps (produced after the MPAs were established) were invaluable because local people could easily recognize the areas under protection, and the habitats and species that were targeted for management and conservation. The inclusion of local cultural knowledge and ecological values enhanced local participation in community-based fisheries management.

CONCLUSIONS

Local knowledge is not offered as an absolute substitute for conventional scientific methods for mapping marine habitats, but rather as a way of integrating local knowledge and participation into the scientific process of MPA design and designation. Under the right conditions, local non-governmental organization coordinators, community members, government officials and researchers can effectively use these field methods over a short period of time (2–3 weeks of fieldwork) and with only minimal technical training. The techniques combined with more accessible GIS contribute to the design of culturally appropriate and environmentally sound MPAs (Aswani & Lauer 2006).

Local knowledge may stretch over longer time frames than presently conducted investigations, and thus may assist scientists in assessment of modern imagery or dynamic ecological events. The next challenge is to assess the environmental health and transformation of benthic habitats and associated marine communities (such as fish stocks) in the region by mapping their changes across the lifetime of local fisherfolk using methods similar to those outlined in this paper. These dynamic maps from local knowledge may provide a baseline for appreciating the natural variability over time, which is a crucial consideration when evaluating long-term and short-term MPA efficacy.

We have demonstrated how combining anthropological fieldwork with spatial tools and marine science methods can improve the design of fishery management and biodiversity conservation initiatives for part of coastal Oceania. Given the profound role of humans in environmental change in this region, empirical support for the inclusion of social science research and local inputs to the design of MPAs is timely. The present study developed methods that were intentionally stakeholder-driven, interdisciplinary, and applicable on the ground.

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