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Integrating indigenous ecological knowledge and multi-spectral image classification for marine habitat mapping in Oceania

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ABSTRACT

This paper evaluates the usefulness of integrating indigenous ecological knowledge and remote sensing analyses to produce tropical marine habitat maps. Fishers from Roviana Lagoon, Solomon Islands, visually interpreted a Landsat-7 Enhanced Thematic Mapper (ETM+) multi-spectral satellite image to identify shallow-water marine environments. Their assessments were used to direct a supervised classification of the image and create habitat maps with indigenously defined habitat classes. Results show that these participatory remote sensing techniques produce accurate broad-scale marine habitat maps that can be useful to managers and decision makers. Participatory methods that draw from indigenous habitat definitions also have the potential benefit of generating new insights about socio-ecological processes and enhancing local acceptance and understanding of conservation projects by allowing stakeholders to actively contribute in management planning.

1. Introduction

In recent years, a resurgence of interest in "indigenous", or "local" ecological knowledge has emerged in the social and human sciences. This can be attributed to a growing number of decision makers and scientists who recognize the failure of top-down modernization approaches to development and environmental management that ignore local ecological understandings [1,2]. Those who advocate using indigenous ecological knowledge (IEK) for resource management argue that "hybrid" approaches need to be developed in environmental research, which integrate scientific techniques with local knowledge and practices [3–6]. Researchers from various disciplines have led efforts to combine IEK with remote sensing and geographic information system (GIS) technologies as these geo-spatial tools have become more accessible and cost effective. Studies of soil science [7], land use [8,9], resource management [10–12], and marine conservation [13–15] document how the combination of indigenous knowledge and GIS can provide more sensitive understandings of interwoven social–ecological systems, new epistemological frameworks for perceiving the natural world, and participation-oriented conservation and resource management.

To date, the use of indigenous knowledge in remote sensing has focused primarily on counter-mapping and indigenous cartography, in which marginalized local people lay claim to their land and sea territories through the production of maps [16]. More sophisticated analysis involving multi-spectral or hyper-spectral imagery is only in its infancy [17–20], particularly in tropical marine resource assessment and habitat mapping. Remote sensing has become a vital tool for marine scientists and coastal resource managers to assesses coastal and in-shore habitat characteristics and to track human-induced changes of coastal environments [21–25]. Still, the integration of IEK with remote sensing for these purposes has been limited.

In this paper, we evaluate empirically the usefulness of combining IEK and remote sensing for habitat mapping in tropical marine environments, drawing on our experience using participatory GIS to design marine protected areas (MPAs) in Roviana Lagoon, Solomon Islands [14,15]. First, we mapped shallow-water marine habitats by incorporating the visual assessments of local fishers into a supervised classification of Landsat-7 Enhanced Thematic Mapper (ETM+) multi-spectral satellite imagery. Through visual image interpretation, informants defined, identified, and delineated marine habitats on an image of the seascape surrounding their villages. These areas were used as training sites in image processing software to seed pixels and generate distinct habitat classes across the entire image. We then tested the classification accuracies of the resultant habitat map with independent reference data obtained from underwater visual surveys and assess the results.

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1.1. Study area

Approximately 12,000 people inhabit Roviana and the adjacent Vonavona lagoons and share a common cultural and linguistic heritage. Similar to much of island Melanesia, the population density is relatively low due to significant depopulation during the 18th and 19th centuries [26], although the region's current population growth rate is high [27]. The Roviana people live along the coastal strip and on barrier islands in hamlets ranging from 50 to over 1000 inhabitants, and the vast majority are subsistent horticultural-fishers who rely on shifting cultivation and fishing. Marine resources provide the bulk of the protein in their diet, and the marine environment plays a vital role in their daily lives [28]. Most households also engage intermittently with the cash economy and undertake small-scale commercial activities such as copra production, shell-diving, or the marketing of fish, shellfish, fruits, and vegetables. As logging operations continue to proliferate, many locals now find seasonal employment as laborers in the timber industry.

Roviana Lagoon extends 42 km along the southwest coast of New Georgia Island, Solomon Islands, from Munda to Kalena Bay, and has one of the largest and most ecologically diverse coastal lagoon ecosystems in the world (Fig. 1). Like Marovo Lagoon on the northeast side of the island, Roviana was formed by raised offshore coral islands that developed during the Pleistocene period due to sea-level changes and the accumulation of coral limestone, organic debris, and volcanic detritus [29]. Ranging from 3 to 6 km in width, the inner lagoon consists of small islets, pools, coral reefs, and intertidal reef flats that reach a maximum depth of approximately 40 m. Various marine habitats, including grass beds, mangroves, freshwater swamps, river estuaries, sand channels, shallow coral reefs, and outer reef drops dot the lagoon. The outer lagoon shorelines are abrupt, 200–500-m deep water drops, composed of rugged, notched limestone with many inlets, bays, carbonate sand beaches, and moats. New Georgia is a steep, rugged island of volcanic origin with an eroded crater at its center, which forms the backdrop of the lagoon. The interior part of the mainland is uninhabited and consists of thick montane and lowland rainforest. The coastal strip and offshore islands have undergone centuries of forest clearing and swidden agriculture, resulting in a patchwork of gardens, fallow plots, scrub lands, and stands of regenerating and mature forest. The region lies within the Bismarck-Solomon Seas eco-region, a large marine ecosystem that extends through the Solomon Islands, the north coast of Papua New Guinea, and the northern West Papua region. Regional marine biotopes are highly diverse, productive, and moderately undamaged by human activities, making this area one of the world's marine biodiversity hotspots [30,31].

In Roviana Lagoon and adjacent coastal areas, the use of and access to natural resources is managed through a traditional rights-based system which is commonly referred to as "customary sea tenure" (for an exhaustive description see [32]). Customary sea tenure is a situation where particular groups have informal or formal rights to coastal or marine areas and where these historical rights, at least in principle, are exclusionary, transferable, and enforceable [33]. A long history of inter-tribal marriage and common ancestry have resulted in close kinship ties among most of Roviana's inhabitants and thus villagers share rights to specific land and sea territories, sometimes referred to as "estates" or "tenure regimes". Today in Roviana Lagoon, groups of villages are organized into two main customary tenure regimes, Kalikoqu and Saikile, which are controlled by a centralized traditional authority (Fig. 1).

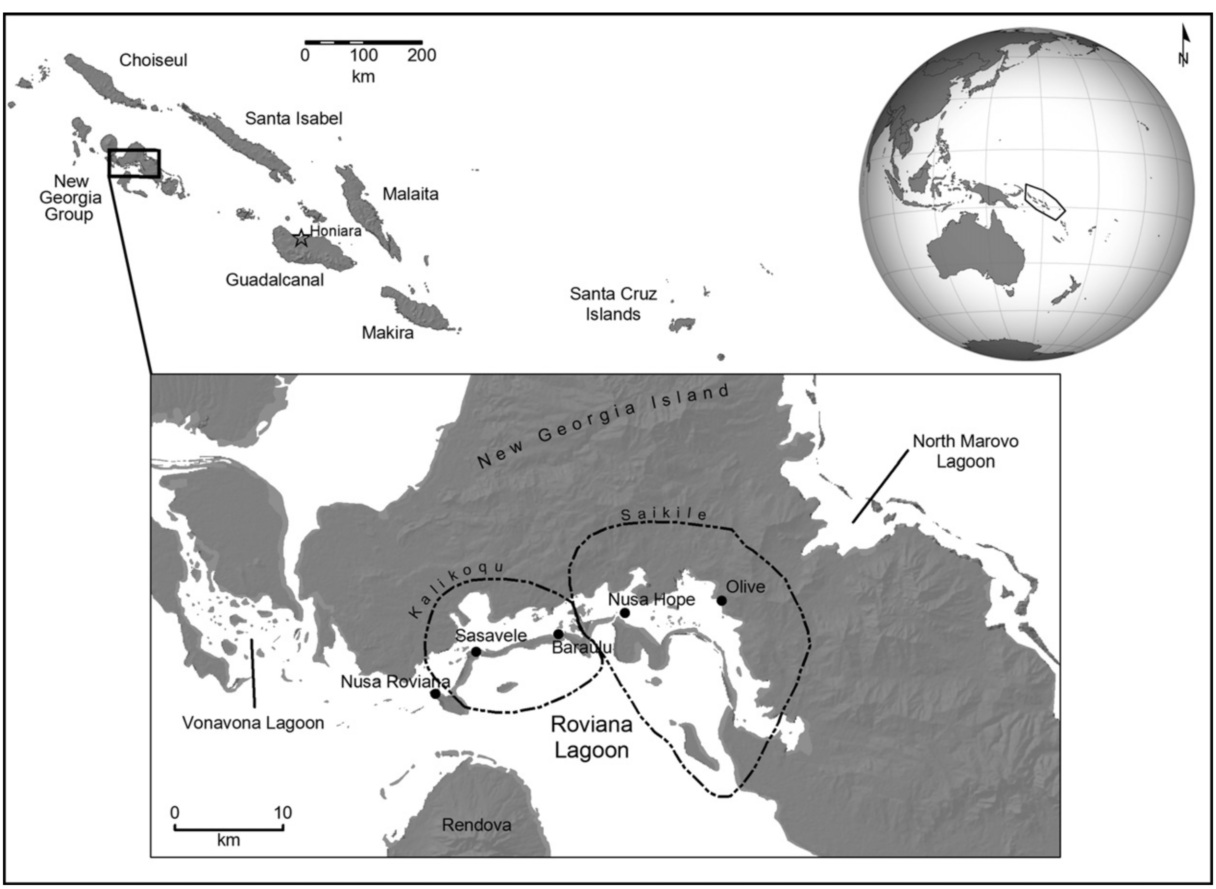

Fig. 1. The Solomon Islands with Roviana Lagoon inset. The two main customary sea tenure regimes are outlined with dashed-lines and labeled.

The boundaries of these territories are relatively well defined and local villages recognize land/sea space entitlements. Jurisdictional trusteeship over sea resources is confided in chiefs who are the heads of chiefly lineages. The chiefly lineages have recognized filial links that can be traced back through many generations to the founding ancestor or ancestors of the kin-based group who first claimed the land and sea areas. This centralized traditional leadership in tandem with all local entitlement holders exercise governance and management over use of and access to natural resources in the lagoon and the adjacent coastal areas within their respective customary land and sea estates. The traditional leaders form the backbone of the community-based management initiatives described below. Although customary sea tenure is found across Oceania, in Roviana Lagoon (as well as most of the Solomon Islands) it remains relatively intact and viable compared to the rest of the Pacific. Nevertheless, customary sea tenure, has not guaranteed the sustainable use of natural resources, as rapid population growth, rampant development pressures (logging and industrial fisheries), and substantial cultural and social change are increasingly threatening the ecology and social stability of the region.

1.2. Project background

With a growing population and a steadily dwindling marine resource base, Roviana community leaders recognized the impending ecological degradation of the lagoon and encouraged us to help them establish and sustain a community-based conservation and development initiative [34]. The aim of this ongoing program is to create a network of marine protected areas (MPAs) while also improving the basic infrastructure of the region. With varying degrees of success, 26 MPAs have been established in Roviana and Vonavona lagoons, most of which have been set up as permanent "no-take" zones. In addition, several small infrastructure projects, such as schools, clinics, and community halls, have been completed across the region.[1] To administer the project and manage the MPAs, traditional leaders from villages with MPAs founded a non-governmental organization (the Roviana Conservation Foundation or RCF) and elected a board of directors. Within each village, the traditional leadership appointed resource management committees to supervise and enforce the regulations of their respective MPAs. Our research team played an important advisory role in the formation of the NGO and establishment of the committees.

The success of the program can be attributed to the privileging of local knowledge and the support of practices and social institutions familiar to community members. The Roviana customary sea tenure system provides an indigenous cultural context within which the enforcement of marine closures and the development of a coastal resource management regime are embedded. Systematic study of customary sea tenure across the region has been vital for understanding the dynamics of ownership, political contest, and power disputes over natural resources [32].

We have assisted communities in selecting the locations of MPAs through a combination of locally driven assessments (e.g., proximity to the village) and information derived from our research. In our project, a strong emphasis has been placed on hybrid approaches or "hybrid science" [35] in order to generate needed socio-ecological data about the region that are used to inform and advise local leaders and communities about MPA site selection. For instance, IEK about locally identified habitats and biological events such as spawning aggregations has been combined with underwater visual census [UVC] surveys to study the distribution of marine habitats and the life-history characteristics of target species, as well as to identify vulnerable habitats and critical life stages of susceptible species across various areas of Roviana Lagoon [36]. Geo-spatial tools have played an integral role in helping to map local knowledge regarding the lagoon's ecology, to organize and analyze longitudinal data (1994–2004) on human fishing activities, and to pinpoint the location of fishing areas for examining spatial and temporal patterns of human fishing effort and yields (Fig. 2) [14]. Maps produced with these tools that display management zone boundary delineations have also served as important educational aids for the management program and for environmental education in general.

2. Methods

As part of our research and management effort, we have produced habitat maps of both coarse and fine-level habitat discrimination for inventorying coastal resources. Habitat maps serve as important tools for assessing and identifying representative areas of distinct habitats that are eligible for protection, as well as for providing data for socio-environmental change detection studies. To create habitat maps and study socio-ecological processes (e.g., changing sea tenure patterns and concomitant fishing activities), we have acquired a variety of current and historical remotely sensed data on the region, including government-donated black-and-white and color aerial photographs, multi-spectral Landsat satellite images, and multi-spectral IKONOS high-resolution satellite images. These were used in our participatory mapping of the lagoons.

In an effort to evaluate our participatory methods, we purchased a Landsat-7 ETM+, SLC-off mode scene (path 89, row 66) recorded on 2 May 2006. The ETM+ sensor provides image data from eight spectral bands and has an approximate scene size of 170×183 km. The visible and near-infrared (bands 1–5 and 7) have a spatial resolution of 30 m; band 8, a panchromatic band, is 15 m, and the thermal infrared (band 6) is 60 m. To perform our analysis, the Roviana Lagoon area was extracted as a subset image from the larger ETM+ scene, and clouds and cloud shadows were masked. The Scan Line Corrector (SLC) on the Landsat ETM+ satellite failed on 14 July 2003, and all image data collected after that date is in Scan Line Corrector (SLC)-off mode [37]. As a result, an estimated 22% of image data is lost, and data gaps appear in the image as white stripes. We calculated that the subset image of our study area had 15% data loss (approximately 15.83 km^2).

Because we had no accurate base map to use for geo-referencing, we collected 35 ground control points (GCPs) to register the image. Rooftops, WWII wreckage, and other features on the satellite image were identified on the ground as suitable GCPs, and data was taken using two Geoexplorer XT GPS receivers (rover and base

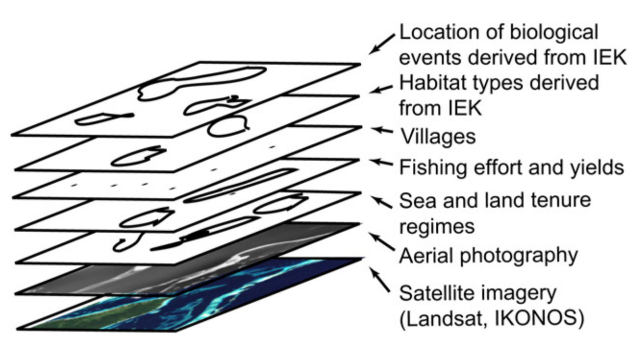

Fig. 2. Layers of information used to analyze socio-ecological processes and inform management decisions about Roviana Lagoon, Solomon Islands.

[1] The conservation, development, and education initiatives were offered to the local residents as integral components of a three-pronged approach to rural development rather than as trade-offs for their MPAs.

data). We performed differential correction on the GPS data using Pathfinder Office version 2.90 with a maximum error of <3.0 m. Then we geo-referenced the image using the nearest-neighbor re-sampling method that had a root mean square error (RMS is a measure of geo-referencing accuracy) of 12.9 m, well within the nominal pixel resolution of 30 m.

Following conventional remote sensing methods, we first classified the multi-spectral ETM+ image using an unsupervised training method [38,39]. This automated procedure requires little user input and involves running a statistical clustering algorithm (in this case the ISODATA algorithm) to derive dominant spectral clusters within an image [40]. In this way, the image processing software generates distinct classes by arbitrarily grouping similar pixels based on their reflectance values. Using ERDAS Imagine (version 8.7), we directed the computer to generate four classes (maximum iterations 10, 95% convergence threshold) so that we could compare these results with those produced through participatory methods.

2.1. Integrating indigenous habitat classifications

To place IEK at the center of a socio-ecological study of marine resource use and practice, we gathered information through "participatory image interpretation" to perform a supervised classification on our Landsat-7 ETM+ image of Roviana Lagoon. Classifying multi-spectral satellite images through supervised classification of spectral bands is a common technique for producing habitat maps of terrestrial, coastal, and marine environments [38,39]. Conventional supervised classification methods involve the assignment of pixels in an image to habitat types identified through field survey sampling. Instead of collecting *in situ* measurements to identify habitats, we assigned pixels to habitat classes based on visual image interpretations made by local fishers.

Fundamental to our approach was the use of Roviana indigenous environmental categories to define habitat classes. The development of a methodology for defining habitat classes or types is a crucial step in the habitat mapping process. Remote sensing specialists and marine scientists propose a variety of classification schemes that define habitats based on *ad hoc* definitions, geomorphology, and biotic assemblages or communities [39,41]. Whatever rationale is selected, it is stressed that no absolutely correct method of habitat classification exists and that the overriding goal should be to devise a classification system "that reflects the major habitat types in the area of interest as faithfully as possible" [39: 134]. We chose to map major indigenously defined habitats for three key reasons: (1) Roviana IEK consists of a rich and sophisticated system of habitat classifications that has an internal logic to distinguish classes based on geomorphology, abiotic substrates, and benthic assemblages of plant and animal species; (2) the Roviana IEK classification system is interpretable in marine science terms; and (3) to encourage local participation in the resource management program and MPA design.

2.2. Roviana marine habitat classifications

Roviana understandings of the environment are organized around the concept of *pepeso*. Like other societies in Oceania, land and sea environments are considered subgroups of the same category rather than ontologically distinct components. *Pepeso* could be translated literally as "soil" or "ground", but as a conceptual category it includes the open sea out to the midpoint in the channel separating New Georgia from Rendova, as well as barrier islands, passages, inner lagoons, and the New Georgia mainland [32,42]. As in many non-Western societies, the *pepeso* concept blurs the distinction between natural and social environments [43,44]. As the basic element of the Roviana tenurial system of ownership, each *pepeso* consists of a named land and sea "estate" delineated by *voloso* (boundaries) and owned by a particular *butubutu* (kin-based group). As noted above, Roviana is divided into a number of *pepeso*, with Kalikoqu and Saikile being the major land/chiefly divisions. Within each *pepeso*, four major ecological zones are identified: *lamana* (open sea) *vuragare* or *toba* (barrier islands, open-sea facing intertidal zones, and reef drops), *poana* or *koqu* (inner lagoon), and *tutupeka* (mainland) (Fig. 3).

In this paper, we focus on the *poana* area because it encompasses the greatest number of marine habitats and was the main focus of the resource management initiative. The *poana* is comprised of a heterogeneous patchwork of ecological habitats. Among various biotopes and ecotones, Roviana fishers recognize and classify the following major marine ecological categories (approximate English equivalents in parentheses): *bolebole* (intertidal sand banks), *holapana* or *sangava* (lagoon passages), *kopi* (lagoon pools), *kulikuliana* (grass beds), *nunusa* (lagoon islands), *sada ovuku* (river mouths), *sagauru* (generic for reef), and *teqoteqo* (reef drops).[2]

While conducting participatory image interpretation exercises (discussed in more detail below) our groups of informants collectively decided that the four most comprehensive, recognizable and visually interpretable marine habitat classes on the Landsat image were *bolebole* (intertidal sand banks), *kopi* (pools), *kulikuliana* (grass beds), and *sagauru* (reefs) (Table 1). Informants across all participating villages easily recognized these general categories even though within these habitat categories informants also recognize a variety of minor, smaller-scale ecological zones or habitats. These minor habitat classifications vary from village to village as the micro-habitat changes. Nonetheless, informants from villages across Roviana Lagoon commonly use these four generic categories to describe the local environment. As the English equivalents express, the four generic categories generally correspond with gross scientific classification of habitat types. The exception is the *kopi* habitat. It is the most heterogeneous when compared to gross scientific categories as it tends include lagoon pools and reef channels which marine scientists would commonly designate as distinct habitat types.

In some ways *sagauru* constitute the most fundamental "habitat" type for Roviana fishers. The *sagauru* are productive lagoon habitats and receive a high percentage of overall fishing effort relative to other inner lagoon habitats. As an ecological habitat class, it could be translated as "reef" areas with various characteristics (e.g., shallow, deep, protruding, etc.). Roviana people are cognizant of this biophysical variation and have specific classifications for it which include *sagauru lamana* (inner lagoon mid-depth reefs), *sagauru masa* (inner lagoon shallow reefs), *sagauru ruata* (outer lagoon deep water reefs), and *miho sagauru* (cape reefs). In addition to these biophysical characteristics of the *sagauru* category, it also employed to designate important navigational markers that are visible underneath the water's surface. Fishing grounds are also referenced in terms of *sagauru*. Specific fishing areas within the *sagauru* are referred to as *habuhabuana*, which are the sites where fish tend to aggregate or are considered the areas where fish most likely can be taken. A spatially more specific fishing ground category, *alealeana*, refers to anchor-dropping points within a *habuhabuana*. Most *sagauru*, along with *nunusa* (island) and *miho* (cape), have specific names and are owned by specific kin-based groups. Thus, these are not simply ecological categories but *socio*-ecological in that they have histories. These histories, which are expressed through everyday storytelling, may involve a *sagauru's* fishing productivity over time, the evolution of its ownership, or maybe navigational mishaps that have occurred there.

[2] Note that the Roviana people employ additional categories for terrestrial, coastal, and aquatic habitats (see [42]).

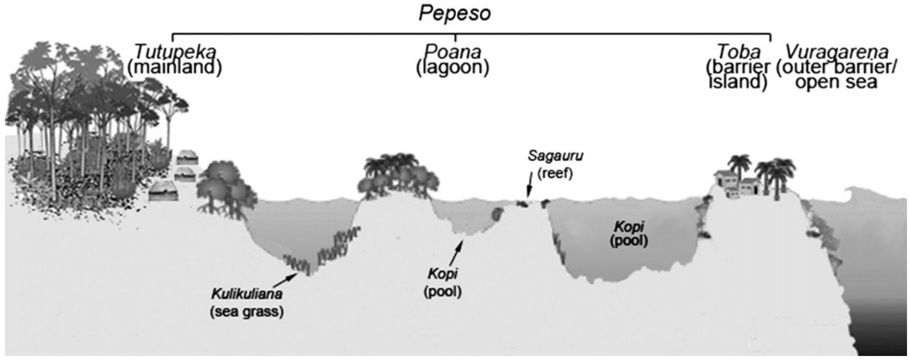

Fig. 3. Cross-section schematic of a generalized Roviana *pepeso*, showing local environmental classifications and their approximate English equivalents.

2.3. Participatory image interpretation methods

We developed our participatory techniques after noticing how villagers were fascinated by satellite images and aerial photographs of their lagoon environment. As villagers looked over our shoulders at our computer screens, they would comment on different aspects of the lagoon environment by interpreting the imagery. Taking these experiences as our cue, we gathered a group of five men and women from Baraulu Village who were considered knowledgeable fishers and had them interpret a Landsat image displayed on a large screen by an LCD data projector. To enhance visual interpretation of submerged or partially submerged aquatic habitats, we displayed a true-color image (spectral bands three, two, and one) of the lagoon. We helped the group orient themselves to and gain perspective on the satellite image by encouraging them to recognize, identify, and name villages, islands, and other physical or cultural features in the image. Once the informants understood that the perspective of the image was from directly above, they identified and discriminated marine habitats across the seascape.

As mentioned earlier, the group collectively decided that the four most recognizable and visually interpretable marine habitat classes on the Landsat image were *bolebole* (intertidal sand banks), *kopi* (pools), *kulikuliana* (grass beds), and *sagauru* (reefs) (Fig. 3). We then asked the informants to point out the areas across the lagoon where they could positively identify each of the habitat classes. The group began by focusing on areas in the adjacent fishing grounds contained within the *pepeso* associated with their village and delineated homogeneous patches of those habitats. They suggested that in order to create a more accurate map we should make visits to other villages because each community would tend to have more in-depth knowledge of their respective fishing grounds and *pepeso*.

To simplify the image interpretation process and to avoid having to transport computers, power generators, and other equipment to each village, we printed and laminated a large-format paper copy of the lagoon (2 ft $\times$ 5 ft) so that informants could draw directly on the image as they made their visual assessments of habitats. We organized meetings in the villages of Olive, Nusa Hope, Sasavele, and

Table 1
Indigenous classification of habitats and associated abiotic substrates, biotic cover, and major occupant species found at Roviana Lagoon (approximate English equivalents and/or Latin binomial counterparts within parentheses)

Indigenous category	Dominant abiotic substrates	Dominant biotic cover	Major occupant fish species
Bolebole (sand bank)	*Onone* (sand) *Zalekoro* (rubble)	*Kuli ngongoto* [sparse cover] (Cymodoceaceae and Hydrocharitaceae sea grasses)	*Mihu* (*Lethrinus olivaceous*) *Suru* (*Lethrinus xanthochilus*) *Karapata* (*Lethrinus hypselopterus*) *Osanga* (*Lethrinus harak*)
Kopi (lagoon pools and reef passages)	*Zalekoro* (rubble) *Onone* (sand) *Nelaka* (silt/sand)	Corals may occur on the walls of the pool, but these are generally composed of abiotic substrates	*Mara* (various *Carangidae* spp.) *Bebele lamana* (*Platax teira*) *Vuhe* (*Pomacanthus sexstriatus*) *Pipirikoho* (various Haemulidae) *Tangiri* (*Scomberomorus commerson*) *Gohi* (*Sphyraena barracuda*) *Makoto noa* (*Balistoides viridescens*) *Makoto lio* (*Pseudobalistes flavimarginatus*)
Kulikuliana (seagrass beds)	*Nelaka* (silt/sand) *Onone* (sand) *Patu* (dead coral/stones)	*Kuli* (*Enhalus acoroides*) *Kuli ngongoto* (various Cymodoceaceae and Hydrocharitaceae sea grasses)	*Gohi* (*Sphyraena barracuda*) *Mara* (various *Carangidae* spp.) *Osanga* (*Lethrinius harak*) *Tetego/Medomedo* (*Siganus* spp.) *Lipa* (various *Mugilidae* spp.)
Sagauru (shallow and mid-depth inner lagoon reef)	*Zalekoro* (rubble) *Onone* (sand) *Patu* (dead coral/stones) *Nelaka* (silt/sand)	*Patu voa* (Porites corals) *Patu pede* (*Acropora* spp. or submassive corals) *Huquru* (*Porites cylindrica* or branching corals) *Binu* (various hard corals) *Ime* (*Caulerpa* or macro algae) *Tatalo* (*Halimeda* spp.) *Laza keana* (coralline algae) *Puha* (generic for sponges)	*Heheoku* (*Lutjanus gibbus*) *Odongo* (*Lutjanus fulvus*) *Pakopako* (*Choerodon anchorago*) *Ramusi* (*Lethrinus obsoletus*) *Pazara* (generic for Serranids) *Mara* (various *Carangidae* spp.) *Mihu* (*Lethrinus olivaceous*) *Sina* (*Lutjanus rivulatus*) *Pipirikoho* (various Haemulidae) *Topa* (*Bolbometopon muricatum*) *Matalava* (*Monotaxis grandoculis*)

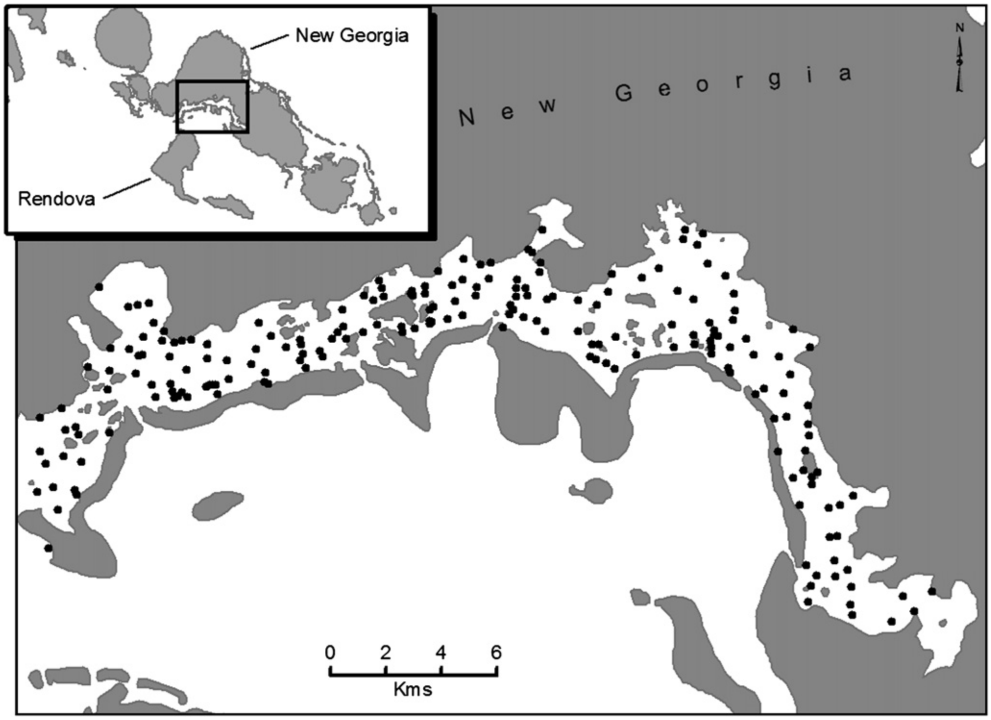

Fig. 4. Roviana Lagoon study area showing the locations of dive-survey sampling sites used for accuracy assessments.

Nusa Roviana and selected, through purposive sampling, villagers, both men and women, who were considered knowledgeable fishers. We then followed the procedures outlined above and had the group pinpoint the location of the largest, most discernable patches of each of the four main indigenously defined habitats. They would then select the most knowledgeable person and co-operatively draw boundaries around these habitat patches directly on the laminated image. Depending upon the surrounding ecology, the villagers identified 5–10 representative sites for each of the major habitat types around their villages.

The local informants spent between 60 and 90 min performing their image interpretations of the area within the vicinity of their villages and the respective *pepeso*. Once the interpretations were completed, we photographed the image with a 5-megapixel digital camera set to its highest resolution, and several photographs were taken to ensure that the drawings and labels made by the group were recorded. After completing the exercises with the informants, we downloaded the digital photographs from the camera to a computer. We geo-referenced the digital photographs through image-to-image registration with the previously geo-referenced Landsat image, ensuring that the average RMS error was below the size of one pixel (30 m).

To perform the supervised classification, we identified training samples on the image within the habitat patches delineated by the groups of informants. Using image processing software (ERDAS Imagine version 8.7), between 10 and 30 training sites per class were seeded on the image, and the maximum likelihood decision rule was used to assign every pixel within the image to distinct classes. Working iteratively, the classes were subsequently merged at the thematic class level to represent the four primary, indigenously defined habitats of Roviana Lagoon.

To increase the thematic accuracy of our habitat maps and improve visual interpretation it would have been desirable to conduct water column correction techniques. Water depth has been shown to significantly affect remotely sensed measurements when trying to derive quantitative information about underwater habitats [45–47]. Remote sensing practitioners have addressed this problem by developing depth-invariant bottom indexing methods that compensate for water depth effects [39]. Although these techniques have proven useful in many contexts they are ineffective when water properties such as clarity and turbidity are inconsistent across an image. Patches of turbid water, for example, cause significant spectral confusion and pose a major limitation of depth-invariant processing methods. Because our image of Roviana had significant areas of patchy turbidity we chose not to perform depth-invariant processing.

2.4. Marine field survey

We assessed the thematic accuracy of the habitat map by surveying 50 field sites per habitat class (200 total) (Fig. 4). The geographic coordinates of the sample sites were selected by random stratified sampling and loaded into a Trimble Geoexplorer XT GPS receiver. Using the GPS receiver, a researcher and two Roviana divers navigated to each of the predetermined field site locations and assessed the underwater habitats around the boat at each sampling location. Efforts were made to ensure that an area equivalent to the size of a Landsat pixel (900 m^2) was as homogeneous as possible. If the divers determined that the sample site was located on the edge of a habitat, the sample site was relocated to a nearby site with more homogeneity, and a new GPS fix of the position was recorded.[3] We used GIS to compare the independent dive-survey data

[3] As part of our broader survey, we collected additional data. To do this, a 1-m × 1-m metal frame was lowered onto the seabed and flipped over three times during data recording to create a 2^2 survey area (a 2-m by 2-m frame would be too large to carry on a canoe). Data for each sample were recorded on a pre-printed PVC slate. Indigenously defined categories of substrate and dominant benthic habitat were recorded right underneath the centre of the 2-m × 2-m area. Depth soundings were taken using a Speedtech 400-kHz, hand-held depth sounder. Other observations included time of day, weather (sunny, partly cloudy, cloudy/overcast, rainy), vertical underwater visibility, and the presence and condition of certain coral families.

with the classified image. In this way we could test the accuracy of the habitat maps using the standard measures of comparison in remote sensing: producer accuracy, user accuracy, and kappa statistic [39].

3. Results

The unsupervised classification of the satellite image produced a map with an overall thematic accuracy of 39.0%. All four classes were confused by the unsupervised clustering, and we had little confidence in assigning them to specific habitat types.

The supervised classification generated from participatory techniques had an overall thematic accuracy of 64.5% and a kappa statistic of 0.53 (Table 2). The probability that a pixel classified on the image corresponded with *in situ* measurements, a statistic known as "user accuracy", varied between 53% and 79.6%. The probability that a categorized pixel was correctly classified, known as "producer accuracy", varied between 52% and 86%. *Kulikuliana* and *sagauru* had the lowest user and producer accuracies, which suggested that some misclassification was occurring for these habitat types. Classifications of *kopi* and *bolebole* had high user and producer accuracies, and thus we had more confidence in these classifications. The supervised classification indicates that Roviana Lagoon's unmasked area[4] (103.2 km^2) consists of 7.11% *bolebole* habitat, 37% *kopi*, 23.46% *kulikuliana*, and 32.42% *sagauru* (see Table 3 and Fig. 5). Roviana IEK about these local habitats provides a synopsis of dominant habitats in Roviana Lagoon (Table 1).

Table 2
Accuracy assessment of supervised classification of marine habitats at Roviana Lagoon, Western Province, Solomon Islands

Indigenous map data	Reference data				Total	User accuracy (%)
	Bolebole	Kopi	Kulikuliana	Sagauru		
Bolebole	29	0	6	2	37	78.38
Kopi	1	43	2	8	54	79.63
Kulikuliana	7	1	31	14	53	58.49
Sagauru	13	6	11	26	56	46.43
Total	50	50	50	50	200	
Producer accuracy (%)	58.0	86.0	62.0	52.0		

Overall % accuracy ¼ 64.50, kappa statistic ¼ 0.53.
Informant's visual assessments were used for supervised classification of spectral bands.

4. Discussion

The Roviana research suggests that participatory remote sensing methods are an accurate means for producing broad-scale marine habitat maps. Measured accuracies are within the suggested range (~60% to ~90%) when the maps are to be used to inventory resources for management planning [39]. Relatively low user and producer accuracies in the *kulikuliana* and *sagauru* classes indicated that moderate misclassification occurred, while *kopi* and *bolebole* were classified reasonably well.

There are a variety of explanations why *sagauru* and *kulikuliana* were more often misclassified than *kopi* and *bolebole*. First, it may be due to differences in reflectance values of reefs under different water depths and the uneven water clarity across the Roviana Lagoon. As mentioned early, we did not perform water column correction techniques due to varying amounts of lagoon water turbidity. In several sections of the lagoon, rivers with high sediment loads empty into sheltered bays. There is a significant difference in water clarity between these bays and more hydrologically open sections of the lagoons that do not receive turbid river water. Since sea grass and reefs tend to have similar spectral signatures, classification of these habitat classes are more susceptible to error caused by variable water clarity. Another possible explanation for misclassification could involve Roviana ecological classifications of these habitats. For this study, Roviana informants aggregated several more specific reef categories into the broader, generic *sagauru* habitat category. Roviana people discriminate between *sagauru ruata* (outer lagoon deep water reefs), *miho sagauru* (cape reefs), *sagauru lamana* (inner lagoon mid-depth reefs), and *sagauru masa* (inner lagoon shallow reefs). Notice that the last two indigenous classifications are depth-dependent. By lumping together *sagauru lamana* with *sagauru masa* into one generic category of *sagauru* a certain amount of spectral confusion is bound to occur because deeper inner lagoon reefs would tend to have darker spectral signatures and shallower reefs would tend to have lighter ones. A third reason for misclassification of *sagauru* and *kulikuliana* habitats may be their inherent heterogeneity. Our previous studies of habitats at finer descriptive scales show that these habitat types are highly variable in their ecological characteristics with patchiness and complexity as the norm [15].

Overall, the results of our study suggest that hybrid approaches that combine IEK and science can produce accurate outputs that are useful to decision makers and managers. Nevertheless, commonly held assumptions about indigenous ecological knowledge continue to impede its integration with science. Many development practitioners, decision makers, and scientists are committed to definitions of indigenous ecological knowledge that brackets it from global or scientific knowledge and portrays it as a self-contained, homogeneous system of "folk beliefs". Defined as narrow, limited in scope, and culturally bound, indigenous knowledge tends to be contrasted with and separated from scientific knowledge—the assumption being that science produces knowledge through a specific, empirically driven method of measurement, guided by abstract ideas, and that it is context-free and universally applicable.

A growing body of evidence reveals how the distinction between scientific and indigenous knowledge is unfounded and impedes the integration of local people's perspectives into resource management and conservation initiatives [48,49]. All knowledge systems are heterogeneous, linked temporally and spatially, and share historical sequences of change [35,50]. The people of Roviana Lagoon, for example, have been in sustained contact with wider social and economic systems since at least the 18th century [51]. Likewise, philosophers of science have long abandoned the separation of science from non-science methodologies [52]. The sharp separation and distinction of science from local knowledge discourages hybrid approaches such as participatory remote sensing while encouraging problematic conservation and resource management interventions that are top-down and expert-led.

This study details how local perspectives and knowledge systems are rich and diverse sources of ecological information. But this diversity of knowledge is specific to place and context, and generalization and comparison can be problematic. As a result,

Table 3
Total (unmasked) area and percent cover of habitat coverages at Roviana Lagoon, Western Province, Solomon Islands derived from participatory remote sensing methods

Class	Area (ha)	Percent cover
Bolebole	734.51	7.1
Kopi	3863.14	37.4
Kulikuliana	2421.64	23.5
Sagauru	3304.18	32.0
Total[a]	103,23.47	100

[a] Total lagoon area 121,81.68 ha (includes dataless and masked areas).

[4] The total area of the lagoon is approximately 18% larger than this figure because cloudy and cloud–shadowed areas and areas lacking image data were masked from the image.

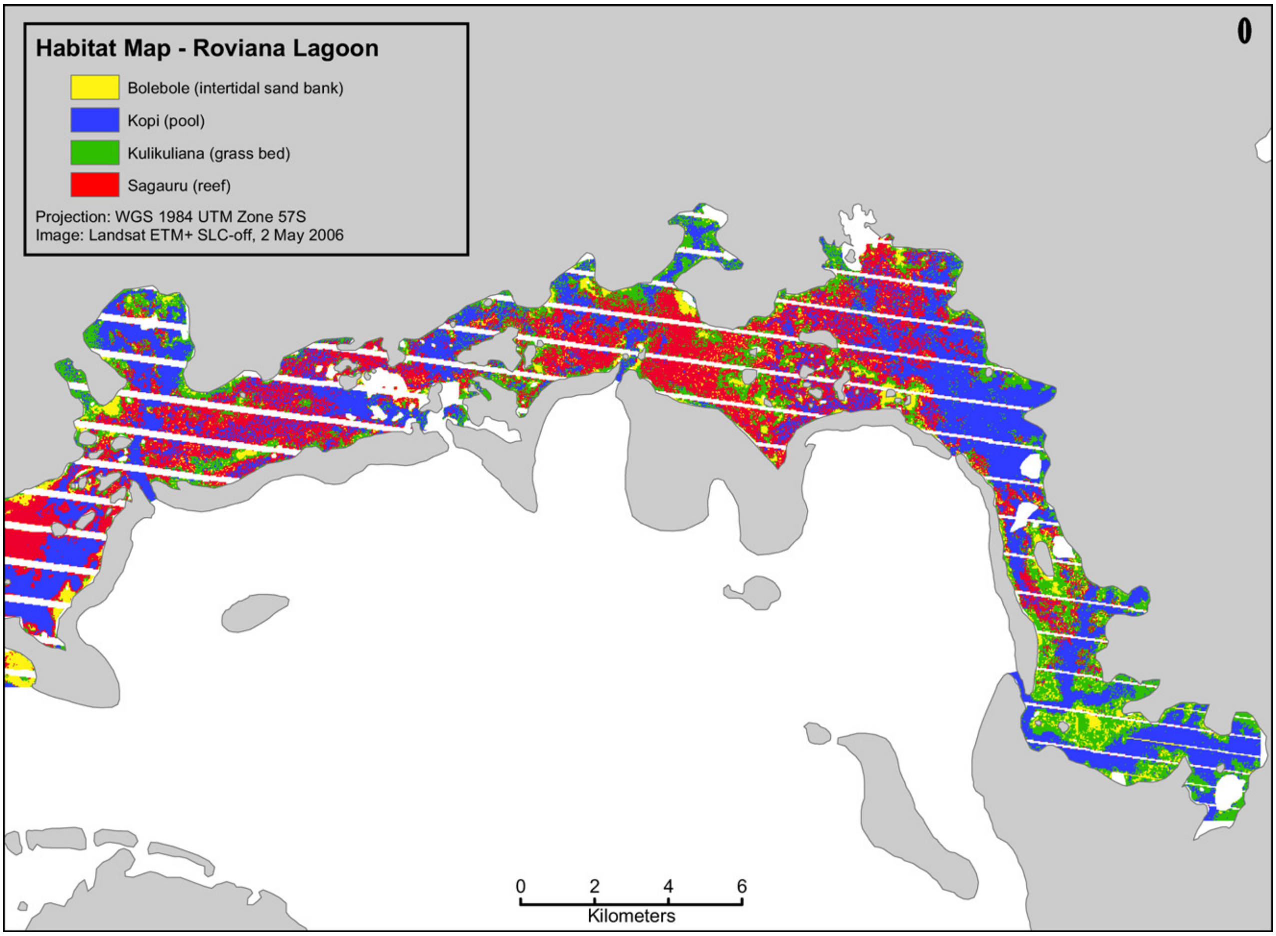

Fig. 5. Four-class habitat map produced by integrating indigenous ecological knowledge with supervised classification techniques at Roviana Lagoon, Solomon Islands. (Note: The white stripes are data gaps produced by the Landsat-7 ETM+ SLC-off sensor.)

participatory remote sensing may potentially produce outputs that are not interpretable to natural scientists because the categories employed by local people will reflect their specific engagement with a specific ecosystem. In Roviana, local marine habitat categories tend to correspond with marine science habitat classifications [29,53], which facilitates cross-fertilization and comparison. In other socio-ecological contexts, this may not be the case.

Although the coarse habitat maps produced through participatory remote sensing may not be comparable to standard marine science surveys, participatory techniques have the potential of revealing new perspectives on environmental processes. In soil science, for example, the principles of indigenous soil classifications have been applied to generate morphological classifications schemes useful for management purposes [54]. In Roviana, the concept of *pepeso* blurs the distinction between the social and natural worlds, a conceptualization of socio-ecological processes that has been widely reported in the ethnographic literature [43]. Many scholars concerned with global climate change are now formulating frameworks that incorporate this idea [55].[5] Considering these and other insights gained through integrating local concepts into ecological studies, participatory remote sensing represents a technique that encourages mutual exchange between scientific and indigenous knowledge.

[5] The idea that we have now entered a new geological era, referred to as the *anthropocene* [55], indicates how the broader research community acknowledges the anthropogenic characteristics of the current global environmental system.

5. Conclusion

This article adds to a growing literature documenting hybrid applications that integrate indigenous knowledge and scientific approaches for research and management purposes [3,6]. It also shows that participatory remote sensing methods can achieve outputs useful to coastal managers for assessing marine resources and designing MPAs. Although coastal and marine habitat maps generated through remote sensing applications are an important method for assessing coastal resources, producing resource inventories, and tracking changes to coastal environments, the potential for combining IEK with remote sensing applications in coastal areas has rarely been explored. We have shown that in coastal ecosystems, fisher-horticulturalists have IEK that can be integrated into a supervised classification analysis to produce broad-scale habitat maps with levels of accuracy in the middle of published ranges (64.5%). The additional element of local participation provides further impetus to employ hybrid methodologies such as the one outlined here. Much recent research now indicates how participation significantly improves the implementation, sustainability, and local acceptance of development projects, conservation schemes, and resource management initiatives. Hybrid approaches, particularly those involving geo-spatial tools, show great promise as relevant and effective methods.

Indeed, while participatory remote sensing in certain contexts can produce reliable results, the approach has a potential drawback—the difficulty of comparing the results with standardized environmental science survey data. This difficulty, however, is often counterbalanced by the inherent potential that indigenous knowledge has for providing novel insights into socio-ecological processes and for helping in the development of culturally acceptable conservation schemes. Clearly, participatory remote sensing may not be appropriate in all socio-ecological contexts, and resource managers and researchers should be cognizant of IEK's heterogeneity both within communities and across different societies. In the Roviana case, the knowledge of local fishers is particularly well suited for participatory remote sensing, but the IEK of societies engaged in other forms of subsistence or embedded within different social-ecological contexts may not produce equally reliable results.

Despite the increasing use of IEK in scientific research and management, few methods have been developed that integrate IEK with remote sensing analyses. Participatory remote sensing is a step in this direction. Although not always appropriate, these methods can help bridge the gap between scientists and local people and encourage the sustainable and socially acceptable management of coastal or other ecosystems.

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