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Mapping for coral reef conservation: comparing the value of participatory and remote sensing approaches

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Abstract. Detailed habitat maps are critical for conservation planning, yet for many coastal habitats only coarse-resolution maps are available. As the logistic and technological constraints of habitat mapping become increasingly tractable, habitat map comparisons are warranted. Here we compare two mapping approaches: local environmental knowledge (LEK) obtained from interviews; and remote sensing analysis (RS) of high spatial resolution satellite imagery (2.0 m pixel) using object-based image analysis. For a coral reef ecosystem, we compare the accuracy of these two approaches for mapping shallow seafloor habitats and contrast their characterization of habitat area and seascape connectivity. We also explore several implications for conservation planning. When evaluated using independent ground verification data, LEK-derived maps achieved a lower overall accuracy than RS-derived maps (LEK: 66%; RS: 76%). A comparison of mapped habitats found low overall agreement between LEK and RS maps. The RS map identified 5.4 times more habitat edges (the border between adjacent habitat classes) and 3.7–6.4 times greater seascape connectivity. Since the spatial arrangement of habitats affects many species (e.g., movement, predation risk), such discrepancies in landscape metrics are important to consider in conservation planning. Our results help identify strengths and weakness of both mapping approaches for conservation planning. Because RS provided a more accurate estimate of habitat distributions, it would be better for conservation planning for species sensitive to fine-spatial scale seascape patterns (e.g., habitat edges), whereas LEK is more cost effective and appropriate for mapping coarse habitat patterns. Goals for maps used in conservation should be identified early in their development.

Key words: coral triangle; habitat fragmentation; landscape ecology; landscape pattern indices; marine conservation; participatory GIS; Philippines; remote sensing; seascape; spatial planning; traditional ecological knowledge; WorldView-2.

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Introduction

Countries struggle toward meeting commitments to protect biodiversity (Convention on Biodiversity (CBD)) and endangered species (Convention on International Trade in Endangered Species (CITES)), in part because they lack information needed to make informed decisions (Schipper et al. 2008). Little or no information exists on the abundance and distribution of more than 11,000 assessed species (IUCN 2015). This lack of information is especially acute in marine systems (Hamel and Andréfouët 2010, Hansen et al. 2011). To address this information gap, there have been several global efforts to map species distributions, ecosystems, and habitats (e.g., FishBase (www.fishbase.org), Millennium Coral Reef Mapping Project (www.imars.marine.usf.edu/MC/)). Many such maps are created at a coarse or moderate resolution (>10 m resolution) and thus lack needed detailed habitat information (Andréfouët 2008, IUCN 2012, Roskov et al. 2015). Particularly lacking are high spatial resolution maps of benthic habitats, describing the seafloor's substrates and biotic communities.

The classification and spatial accuracy of maps influence the utility, accuracy, and cost of creation, as well as the representation of features on the map (Wulder et al. 2004, Roelfsema and Phinn 2013). In doing so, map accuracy impacts the management decisions made from maps (Gergel et al. 2007, Tulloch et al. 2013). All maps are generalizations of a spatially heterogeneous world and thus inherently contain some misclassification. Acceptable levels of overall map accuracies vary by ecosystem, and the level of detail required (e.g., more categories lower accuracies in general), but accuracy can be a low as 50–60% for coral reefs (Roelfsema and Phinn 2013). In situations where the overall map accuracy are high, the individual habitat category accuracy could be lower (e.g., coral classes in general have lower accuracy than bright sand). These differences in accuracy need to be considered when determining the purpose of the map (Roelfsema and Phinn 2013).

Although map errors are ubiquitous, they are often overlooked in conservation planning (Langford et al. 2006, Tulloch et al. 2013). Uncertainty in maps comes from many sources including incomplete sampling, measurement errors, processing errors, and a mismatch between the variability of the system and the spatial scale of the map (Gergel et al. 2007, Roelfsema and Phinn 2008, Thompson and Gergel 2008). Ultimately, classification errors impact not only the reported areal extent of any given habitat class, but also impact the perceived arrangement and connectivity among patches (Langford et al. 2006). Variations in perceived arrangement and connectivity of habitats therefore influence any products or decisions that are based on those maps (Gergel et al. 2007, Tulloch et al. 2013).

The effects of map errors on the design of protected area networks are of particular relevance for conserving biodiversity. Protected areas are an important part of conservation strategies because they can reduce the rate of biodiversity loss and can support surrounding, unprotected areas (Margules and Pressey 2000, Almany et al. 2013). As countries work to achieve conservation targets (e.g., CBD Aichi Biodiversity Target to half the loss of all natural habitats by 2020), the spatial extent of marine protected areas (MPAs) has grown at a rate of 4.6% (Wood et al. 2008) with over 1750 new MPAs created in the past 6 yr (Boonzaier 2014). But many existing MPAs were established without maps or based on maps with unknown errors (e.g., Hansen et al. 2011). Ignoring map accuracy in MPA design can lead to omissions of target features, and can reduce the likelihood that MPAs are fully meeting their objectives (Tulloch et al. 2013).

Quantifying the areal extent and spatial arrangement of habitats is important for prioritizing the locations of new MPAs (Grober-Dunsmore et al. 2007, Olds et al. 2012*a*). For example, the availability of suitable habitats influences the distribution and abundance of species (Jennings et al. 1996, Messmer et al. 2011). Where detailed information on species distributions is unavailable, there is empirical evidence that habitat maps can be used as effective surrogates (Margules and Pressey 2000). The arrangement of habitats in the seascape is also significant, particularly where habitat fragmentation is widespread. Habitat fragmentation can affect species by altering the number of suitable patches, increasing the distance between patches, and changing the amount of edge habitat within each patch (Saunders et al. 1991). For example, some species experience higher predation risk near habitat edges (Selgrath et al. 2007) and may benefit from MPAs incorporating locations with less edge habitat. As well, the density of habitat patches can affect the dispersal of organisms (Hovel and Wahle 2010) and influence metapopulation persistence (Bengtsson et al. 2003).

Several approaches have been developed to map the spatial composition and extent of marine habitats, including local environmental knowledge (LEK), remote sensing (RS), and in-water habitat surveys. Here, we focus on LEK and RS, which are two approaches that have the potential to produce contiguous maps of shallow marine habitats. One aspect of LEK, species and habitat distributions, can be applied to the creation of habitat maps by individuals or focus groups (e.g., Aswani and Lauer 2014). During mapping participants use their expert knowledge to draw maps freely or in combination with satellite or airborne imagery. LEK mapping (also called "participatory mapping") has great potential for improving conservation and management by increasing knowledge, complementing scientific measurements, and informing conservation strategies (Thornton and Scheer 2012). Yet the errors and biases in LEK are often unknown, and are important to document (Teixeira et al. 2013). For example, because LEK may focus on practical details (Foale 1998), abundant or visible habitats (Lauer and Aswani 2010), and familiar places (Lauer and Aswani 2008), LEK is rarely evenly distributed across a seascape.

The second mapping approach is remote sensing (RS), which often uses computer algorithms to classify satellite or airborne imagery by assigning map classes to pixels with specific characteristics. RS has the potential to create spatially explicit maps over larger areas with more consistency in coverage than LEK (Lauer and Aswani 2008). However, mapping coral reef and seagrass habitats with RS has long been challenging because of the difficulty of differentiating underwater features that make up marine habitats due to water depth and clarity, the presence of different features within one pixel, and the spectral similarity of communities (e.g., coral and algae) (Mumby et al. 1998, Hochberg and Atkinson 2003, Leiper et al. 2012). Technological limitations have largely constrained the approach to identifying geomorphic characteristics (e.g., reef slopes, reef flats) rather than benthic communities, using moderate spatial resolution imagery (pixel sizes 10–100 m; e.g., Millennium Coral Reef Mapping Project) (Andréfouët 2008).

Recent advances in satellites capturing high spatial resolution imagery (pixel sizes 2–10 m) with spectral bands more suitable for marine applications (blue and/or green wavelength ranges, e.g., WorldView-2) have created new mapping possibilities, enabling the creation of benthic community maps of coral reefs at finer spatial scales (2–5 m) over large areas (>300 km^2) (Roelfsema et al. 2013*b*). To date, however, high spatial resolution mapping of coral systems exists in only a handful of areas (Hamel and Andréfouët 2010). One challenge can be the greater cost of high spatial resolution images and the technical expertise required for image processing. These constraints can be particularly limiting for organizations and agencies with limited technical capacity and funding.

Here, we extract and compare a suite of ecological characteristics from maps created using either LEK from coastal fishing communities or RS analysis of high spatial resolution satellite imagery. Our first goal was to understand how each mapping approach depicted the habitat distributions and seascape characteristics of the ecosystem. Our second goal was to explore the conservation implications and costs that influence which mapping approach is most appropriate for different situations.

Methods

Study site

We examine benthic marine habitats in a biodiversity hotspot in the central Philippines. The Philippines contains some of the most threatened coral reefs in the world (Burke et al. 2011), yet few of the coastal areas have been mapped in detail. The Danajon Bank (10°15′0″ N, 124°8′0″ E; Fig. 1) is one of only six double barrier reefs in the world. Lying at the center of evolution for marine species, the Danajon Bank includes a high diversity of corals, seagrass, and mangroves, and is home to over 200 threatened species (IUCN 2012). The distribution of biotic habitats in the Danajon Bank is influenced by low water clarity near the mainland island of Bohol (inner Danajon Bank) and higher water clarity in the more remote regions of the system (outer Danajon Bank). Anthropogenic pressures such as pollution and destructive fishing have led to widespread habitat degradation and the loss of species (Marcus et al. 2007, Lavides et al. 2010). The extent of marine mapping is so limited (Hansen et al. 2011) that the full extent, scale, and persistence of habitat damage in this ecosystem is challenging to quantify. To evaluate areas with differing habitat complexity and water clarity, our study area (500 km^2) spanned the inner and outer Danajon Bank.

Overview

We created and compared benthic habitat maps based on two mapping approaches: LEK and RS mapping. Both approaches involved field data collection, preprocessing of field and/or satellite image data, determination

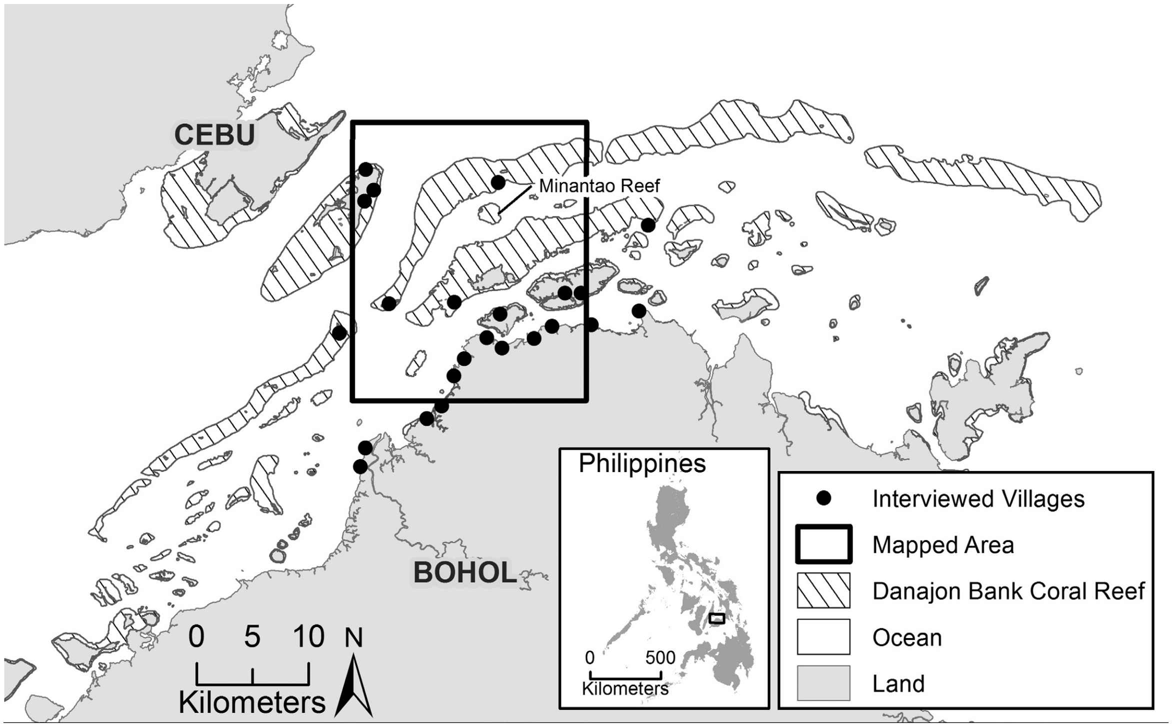

Fig. 1. The study area for which local environmental knowledge (LEK) and high spatial resolution remote sensing (RS) maps were created is located in the central Danajon Bank, Philippines. Villages where interviews took place were stratified by location in the ecosystem. Validation surveys took place at the Minantao Reef.

of appropriate benthic community class divisions, and map creation. The LEK approach used participatory mapping to delineate habitats incorporating SPOT-5 satellite image as a basemap, whereas the RS approach classified two WorldView-2 satellite images using the full spectral characteristics of the different bands that make up the imagery within an object-based classification. Mapped classes were based on a composite of the ecological relevance of habitats as well as technological constraints in distinguishing among complex coral reef habitats which often occur as heterogeneous, highly mixed mosaics (Capolsini et al. 2003). For RS and LEK mapping approaches we define benthic habitats to include abiotic substrates (e.g., sand) and biotic communities (e.g., coral) growing on the seafloor. Habitat classes used here comprised a mix of five benthic cover types (coral, rubble, sand, seagrass, and algae). Although germane to reef health and conservation, we excluded mangroves from comparisons because the LEK mapping method used here focused solely on fishing grounds, rarely located in mangrove habitats (See LEK Data Collection). Deep sea water, clouds, and land were also excluded.

Benthic community map creation

Local environmental knowledge mapping approach.—1. LEK field data collection.—LEK comprises the integrated and situated knowledge, practices, and beliefs of communities and resource users regarding the local environment and their relationship with it (Berkes 2012, McMillen et al. 2014). To map LEK of benthic habitats we conducted participatory mapping interviews in the local language, Cebuano. We interviewed 249 fishers from 20 villages between July 2010 and April 2011. Villages were randomly selected and were stratified by their location (e.g., mainland, large islands, cays) to include geographically contrasting parts of the reef system. We asked fishers to identify their current fishing grounds in a 20 by 25 km area and to describe the habitats therein (Appendix S1: Fig. S1). To make the maps as spatially precise as possible, we drew habitat boundaries over a georeferenced SPOT-5 satellite image (4 bands: green, red, NIR, MIR; 10 × 10 m pixel size), which was the highest resolution image available at the time interviews were conducted. The high spatial resolution WorldView-2 images used for the RS mapping (see below) were not available at the time of the LEK fieldwork. This integration of technology (similar to aerial photography interpretation) allowed fishers to orient their drawings to geographic features in the seascape and to incorporate the texture and color of the image into their mapping (Morgan et al. 2010). Since many respondents were unfamiliar with satellite images and maps, we oriented fishers to the map and confirmed their ability to identify locations and features on the map before collecting any data. We offered respondents a list of nine habitat classes with photos to help standardize responses, although some fishers provided four other habitat categories (e.g., bato (Cebuano for rocks, but a term used to classify both coral and rubble); taganas (Cebuano for deep areas that are adjacent to the reef slope)).

2. *LEK-based classification*.— We created a map representing fishers' cumulative LEK by layering habitat maps from all respondents into one map showing the most commonly identified habitat (Appendix S1: Fig. S1). To achieve this, we first digitized the maps drawn during each interview using heads-up digitizing in ArcGIS 10.1 (Environmental Systems Research Institute, Redlands, California, USA). We then calculated the number of respondents that identified a given habitat at each location on the map (i.e., in each grid cell; Appendix S1: Fig. S1). The final habitat class included the habitats which were reported by the highest and second highest number of respondents (e.g., if seven fishers reported "Coral" and six fishers reported "Rubble" the habitat class for that location would be "Coral/Rubble" (Appendix S2: Table S1). Calculations used ArcGIS 10.1 and R 2.15.2 (package: Raster) (Hijmans and Etten 2014, R Core Team 2014). We modified existing R commands in the Raster package to calculate the habitats reported by the highest and second highest number of fishers. R scripts for conducting this analysis are included in Supplement S1.

We made four alterations to the LEK data: (1) we simplified LEK habitat classes by combining rare habitat classes (<200 ha) with ecologically similar classes; (2) we merged all polygons smaller than 100 m^2 with neighboring polygons; (3) we filled small gaps in coverage (<1.5 ha) with neighboring polygons; and (4) we assigned larger gaps to a "No Data" category. Gaps in the LEK maps occurred because fishers mapped their fishing grounds, but not the surrounding areas.

Remote sensing mapping approach.—1. RS field calibration data.—To create the RS map, we conducted benthic cover (seafloor) field surveys using two methods. First, we undertook georeferenced point intercept transects (English et al. 1997). For 11 sites we recorded habitat cover types at 0.5 m intervals on 20-m-long transects (n = 2070 points with six transects at most sites (range 3–8). We distributed the transects across as many habitats as possible at each site, allowing us to obtain a representative sample of the habitats. Second, we conducted georeferenced spot-check surveys, by placing a viewing bucket in the water to estimate the percent cover benthic cover types (n = 2357 points). Survey locations were chosen to cover a diverse and representative subset of habitats found in the Danajon Bank. The combination of methods was a compromise between the higher accuracy of point intercept transects and the larger sample area achievable through spot-check surveys (Roelfsema and Phinn 2008).

2. *RS image acquisition and preprocessing.*— To cover the full extent of the study area, we acquired two WorldView-2 images (05/10/2010 and 20/04/2012) from the Digital Globe archive. These images were selected for having the lowest cloud cover and the shortest time lag. The WorldView-2 sensor has eight multispectral bands (coastal, blue, green, yellow, red, NIR, MIR1 and MIR 2) with a 2 × 2 m pixel size. We initially created a RS map using a pixel-based classification of the same SPOT-5 satellite image as the LEK mapping, but after obtaining map accuracies <50% we switched to the WorldView-2 images used here. The WorldView-2 images were radiometrically and geometrically corrected by DigitalGlobe with a stated accuracy of 5 m (www.digitalglobe.com). The two images were dark pixel corrected (Jensen 2005) and joined to form an

almost seamless mosaic. We used WorldView-2 imagery because past studies have shown that they are suitable to create habitats maps using object-based image analysis (Phinn et al. 2012, Roelfsema et al. 2013*b*). All image preprocessing was conducted using ENVI 5.0 (Exelis Visual Information Solutions, Boulder, Colorado) and ArcGIS 10.1 software.

3. *RS-based classification.*—We used object-based image analysis (Blaschke 2010) for the RS classification of the WorldView-2 mosaic following the same approach as explained in detail in Phinn et al. (2012) and Roelfsema et al. (2013*b*). This technique classifies the image into maps with increasing detail, resulting in a hierarchical classification. Where pixel-based classification assigns a class to each individual pixel, object-based image analysis segments the image in groups of pixel with same color and texture and then assigns a label to each segment following predefined decision rules. Decision rules for classifying images are included in Supplement S1. These decision rules are based on the segments' color, texture, and contextual relationships. Contextual relationships can include: other hierarchical levels (e.g., geomorphology can influence benthic habitat classes) or spatial proximities to other classes (Mumby et al. 1998). The RS method we used is well suited to classifying high spatial resolution imagery, because pixel variance is grouped into image-objects approximating real features (Blaschke 2010).

We classified the image mosaic using three hierarchical levels of image-objects: reef, geomorphic, and benthic community using a 4 m^2 minimum mapping unit. The reef level distinguished reef, land, deepwater, and clouds; whereas the geomorphic level classified reef slope, inner reef flat, outer reef flat, mangroves, re-planted mangroves, deepwater, mainland, terrestrial islands, cays, and clouds (Appendix S2: Table S2) (Roelfsema et al. 2013*b*). The benthic community level segregated the final image into 17 classes. Object-based image analysis was conducted using eCognition 8.4 (Trimble, Sunnyvale, California, USA). To make the RS and LEK approaches directly comparable, we clipped the RS map to the smaller area of the LEK map (Appendix S2: Table S2).

Comparisons of LEK- and RS-based approaches

We evaluated the results of both mapping approaches in five ways: (1) a quantitative map validation based on independent habitat surveys; (2) a quantitative assessment of the agreement between the maps; (3) a qualitative comparison of the maps; (4) a quantitative assessment of how each map characterized seascape characteristics; and (5) a comparison of mapping costs.

Quantitative map validation.—1. Field validation data.—Independent manta tow survey data (English et al. 1997) was used to assess the accuracy of the maps for a subset of the study area. These surveys took place at a 4 km^2 reef (Minantao) located near the center of the map (Appendix S1: Fig. S2). Although a validation survey that sampled many parts of the study area would have been preferred, due to limited resources the validation survey was only available for this subset of the mapped area. The independent validation data were considered representative for the whole study area. The manta tow survey documented four major habitats: "Coral", "Seagrass", "Rubble", and "Sand", the same as used for the major habitat classes in the LEK- or RS-based maps. "Patchy Coral," also documented by the surveys, was not included in the accuracy assessment because we were not able to assign these manta tow points to a dominant habitat class in the maps. We also excluded manta tow points located in "Deepwater" on the maps. Because more manta tow points fell into "Deepwater" areas on the LEK map, there were 19 fewer manta tow points for evaluating the LEK map.

2. *Accuracy assessment.*—For each map, we compared the field validation to the mapped habitat classes. An error matrix was created from the reference and mapped data, to calculate the overall map and individual class accuracies (Congalton 1991). Overall accuracy (the percentage of points that were classified correctly) estimates the overall reliability of the classification. Producer and user accuracy were calculated for the individual map classes. Producer's accuracy (error of commission) is the probability that a point on a map is correctly categorized by the classification scheme; while the user's accuracy (error of omission) estimates the probability that the class assigned to a point on the map accurately represents what is on the ground. Overall map and individual map class accuracies can be influenced by the size of the area mapped, the habitat complexity, the number of habitat classes, and the

mapping approach (Roelfsema and Phinn 2013). As approximately 60% accuracy is the standard for marine remote sensing maps (Roelfsema and Phinn 2013), we considered anything higher than 60% agreement to indicate a good fit.

The reference data were opportunistically collected for another project using the manta tow technique (Panes and Nellas 1997), hence not all habitat classes were surveyed that were also present in the LEK or RS habitat maps (e.g., a "Sand/Seagrass" class was mapped using LEK and RS approaches, but was not included in the Manta Tow survey). Thus, we simplified the mapped habitat classes to match the validation survey classes, which focused on major habitat classes. This led us to have two sets of maps: the original maps and map incorporating the major habitat classes (i.e., corresponding to the validation survey habitat classes). Unless otherwise stated, analyses were conducted on the major habitat class map.

Quantitative map agreement.—To assess agreement between the LEK and RS maps, we sampled the mapping categories for both maps at 1000 randomly sampled points. Points were restricted to shallow areas where benthic habitats were categorized by both mapping approaches. We used the sampled values to create a summary matrix, which included the overall agreement and the per-category agreements. We took this approach because we assumed neither map represented "the truth" (Morgan and Gergel 2013). The quantitative map comparison was conducted twice: once with the major habitat classes used in the manta tow survey; and once using the original habitat classes. For the later comparison, we considered "matches" to include agreement between any of the habitats mapped at a location (e.g., "Seagrass" was considered to match "Sand/Seagrass"). We found that this method was the most concordant way to address the fact that the habitat classes in the LEK map and the RS map were not identical.

Qualitative visual assessment.—To further understand the maps, we documented qualitative differences between the mapping approaches, including geographic variations in benthic habitat distributions, and the local areas where habitats were not successfully mapped. This was especially important to assess areas that were not part of the validation.

Seascape characteristics assessment.—We evaluated how the LEK and RS mapping approaches quantified three seascape characteristics: habitat abundance; heterogeneity; and connectivity. The two mapping approaches covered the same 20 × 25 km area. However, the final versions of the RS and LEK maps classified benthic habitats in a slightly different area (e.g., the LEK map had gaps where no respondents mapped habitats; see *Results*). To account for this difference, we used metrics of seascape characteristics that were standardized by the area (ha) where habitats were classified.

Habitat abundance was quantified by evaluating the percent of the seascape (aka landscape) covered by each habitat class. Here, we defined "seascape" to include the area (ha) of a map where benthic habitats were classified, and to exclude deepwater, land, mangroves, and unclassified areas. Heterogeneity was measured using two landscape indices: Patch Area and Edge Density. Patch Area measures the mean size of habitat patches in the seascape, whereas Edge Density measures the linear length of edge (in meters) per ha. We defined an edge as the border between two adjacent habitat classes and did not distinguish natural and anthropogenic habitat edges. We chose Edge Density because habitat edges can influence species distributions and survival rates (Selgrath et al. 2007).

To quantify the seascape's structural connectivity (the physical attributes of the seascape, which theoretically influence the ability of species to disperse; hereafter "connectivity") (Calabrese and Fagan 2004, Grober-Dunsmore et al. 2008), we used Patch Density (number of habitat patches per 100 ha) and Near-Neighbor Distance (the shortest distance between two patches of the same habitat class). Theoretically, connectivity increases with Patch Density, due to the greater ability of individuals to disperse through a seascape. The actual connectivity depends on the species of interest. A smaller Near-Neighbor distance suggests higher connectivity in the seascape. Landscape metrics were calculated in Fragstats3 (McGarigal et al. 2012) and R (2.15.2).

Cost estimation.—Since cost can be a substantial determinant of mapping feasibility, we compared the costs of the two mapping approaches. Fieldwork for both approaches was a subset of other projects. Therefore, we estimated the number of hours that would be needed for directly working on the mapping for those who were already familiar with a site and with existing expertise in field work and object-based image analysis. We assumed a small NGO or government agency in a developing country conducted field surveys. For this research project, the satellite imagery was donated, and we obtained a discounted license for the object-based image analysis software (eCognition). Thus, for the cost estimate, we used the standard costs of these items if obtained without discounts, and we assumed NGOs would use qGIS (a free GIS software; QGIS Development Team, Open Source Geospatial Foundation Project).

Results

Summary of LEK- and RS-based map creation

We created 20 × 25 km habitat maps of the study area (Fig. 2) and we found that both mapping approaches were able to characterize the coral reef habitats accurately. This assessment was based on the quantitative map assessment for the Minantao Reef (Fig. 1; Appendix S1: Fig. S2), for which the validation resulted in acceptable level of accuracy (>60%; Roelfsema and Phinn 2013). Overall the RS map performed better than the LEK map, although each mapping approach had various strengths and weaknesses, detailed below and summarized in Table 1.

Within the 20 × 25 km study area, both maps included habitats that were not evaluated (e.g., land) and had some locations that were left unclassified. The RS map had gaps due to cloud cover. The LEK map had gaps at locations where no respondents identified habitats. As a result, the total amount of classified shallow habitat differed slightly for each map. The LEK map classified 22% (10,902 ha) of the 50,000 ha study area as benthic habitats, whereas the RS map classified 28% (13,865 ha).

On average LEK habitat patches were five times as large as RS habitat patches (Table 1), indicating that the RS approach provided higher spatial precision for habitat locations. The LEK approach produced maps with 18 habitat classes (Appendix S2: Table S1; see *Methods* for details). The RS approach produced maps with 16 benthic habitats (Appendix S2: Table S2; see *Methods* for details).

Comparisons of LEK- and RS-based approaches

Quantitative map validation.—For the accuracy assessments of each mapping approach, the RS map outperformed the LEK map (LEK = 66%; RS overall accuracy = 76%; Table 2). Both mapping approaches exceeded the minimum mapping standard of 60% (Roelfsema and Phinn 2013). The LEK map correctly identified all "Rubble" (producer's accuracy = 100%), but failed to capture other habitat classes. The high LEK accuracy of "Rubble" suggests that this class was over-mapped with the LEK approach. In the area where validation surveys took place, "Sand" and "Seagrass" were not included in the LEK maps, although they were mapped elsewhere. When we assessed the accuracy of the RS map, we found that "Rubble" and "Seagrass" were mapped more consistently than "Coral" and "Sand. " For both LEK and RS approaches, it was difficult to assess "Coral" as only one "Coral" reference point overlapped the LEK map and only five "Coral" reference points overlapped the RS map (Table 2; Appendix S1: Fig. S2).

Quantitative map agreement between LEK and RS.—The comparative agreement between the two mapping approaches showed that maps had 37% overall agreement when using the major habitat classes (Appendix S2: Table S3a; Appendix S3: Fig. S3). When we instead compared the maps using the original classes (Appendix S3: Fig. S4), the map agreement was higher (62%; Appendix S2: Table S3b). Among the two mapping approaches there was wide range in agreement between various classes. For example, "Seagrass" was mapped inconsistently between the two maps.

Qualitative visual assessment.—A visual overview of the two mapping approaches reveals that the maps are fairly different. Their differences were most pronounced in the outer reef where the LEK primarily mapped "Rubble" whereas the RS primarily mapped "Seagrass" (Fig. 2; Appendix S3: Fig. S4). When considering qualitative differences between the maps, there were various strengths of each mapping method (Fig. 2; Table 1). The RS map was able to pick up much finer-scale detail in the study area. In

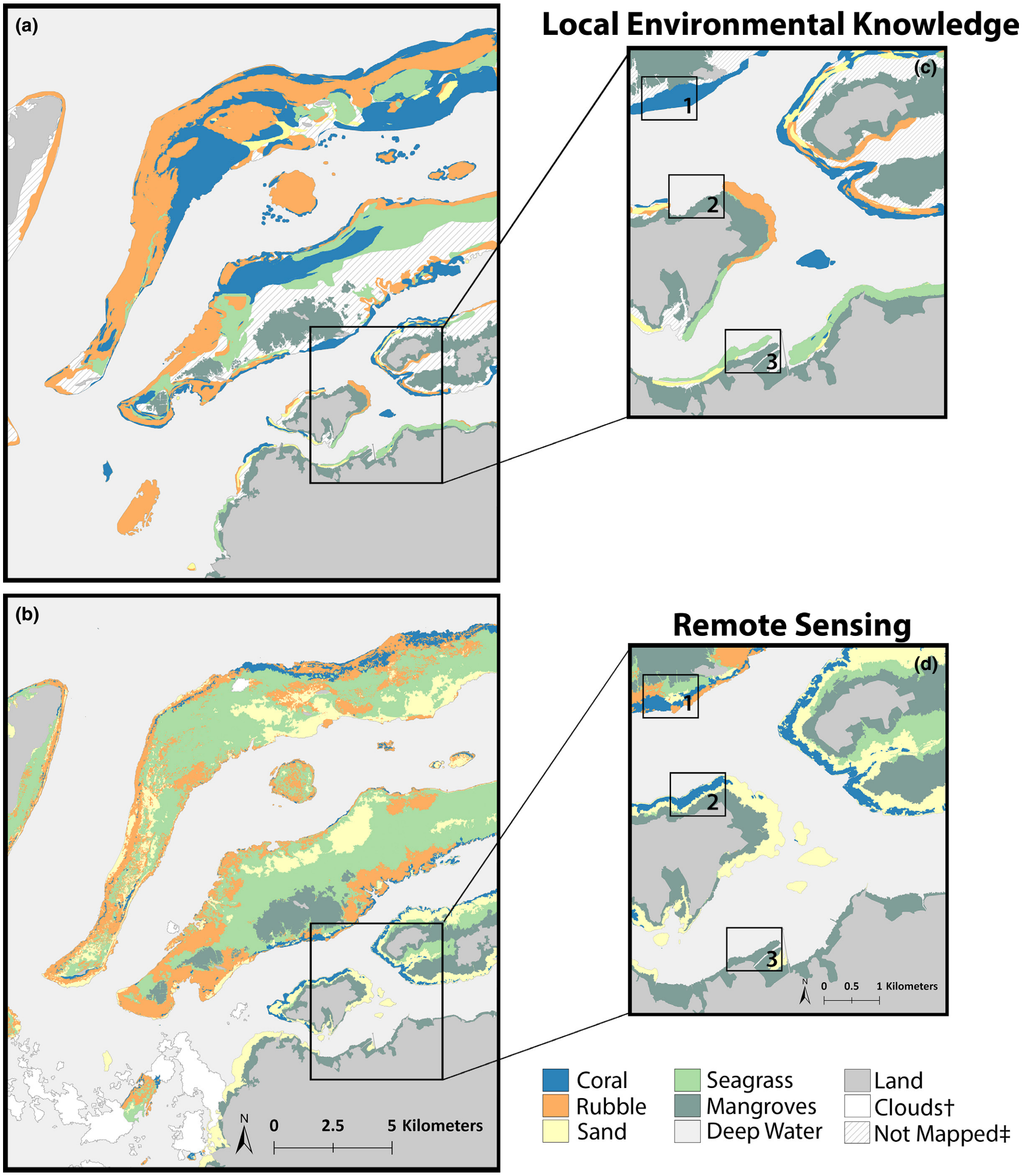

Fig. 2. Maps of major habitat classes for: (a) local environmental knowledge (LEK) and (b) high spatial resolution remote sensing (RS) habitat maps of benthic habitats in the Danajon Bank, Philippines. Close-up examples demonstrate differences in benthic habitat maps made using (c) LEK and (d) RS. In some areas: the LEK approach shows less detail than the RS map (c1 & d1); the LEK approach missed habitats that the RS approach captured (c2 & d2); or the LEK approach mapped habitats that the RS maps missed (c3 & d3). † = classes unique to LEK map; ‡ = classes unique to RS map.

Table 1. Summary table of findings for comparison of local environmental knowledge (LEK) and high-resolution remote sensing (RS) mapping approaches.

Metric	Mapping approach		Comment
	LEK	RS	
Overall map accuracy	66%	76%	Accuracy higher than the required 60% for both approaches.
Class accuracies	Over classifying ″Rubble″; under classifying ″Sand″ and ″Seagrass″.	Higher accuracies then LEK for ″Rubble″ and ″Seagrass″.	The remote sensing map had higher class accuracies and did a more consistent job of mapping habitats.
Quantitative map agreement			Maps have a 37% agreement for major habitat classes. Agreement varies between habitat classes. Map agreement is higher (62%) when evaluating original habitat classes.
Qualitative map agreement	Missed habitats where no respondents fished. Better at classifying habitats in turbid waters.	Mapped finer detail of habitat arrangements.	Each approach has different strengths.
Habitat distribution	″Rubble″ and ″Coral″ dominated.	″Seagrass″ dominated.	Different habitats dominated each map.
Landscape indices			
Patch area (ha, mean ± SE)	8.8 ± 2.5	1.7 ± 0.4	The remote sensing approach identifies smaller habitat patches.
Edge density (length of edges/m^2)	9.5	51.4	Remote sensing provides more detail about habitat edges.
Connectivity			
Near-neighbor distance (m; area mean ± SE)	37.6 ± 5.1	10.3 ± 0.9	Remote sensing maps depict 3.7 to 6.4 higher connectivity due to a shorter distance between habitat patches and a higher density of habitat patches.
Patch density (no. patches/100 ha)	2.4	15.4	
Cost			
Donated images and software	$7,718	$10,188	Remote sensing maps are more expensive and requires greater technical skill, but some costs can be offset.
Purchased images and software	$9,343	$47,688	

locations where respondents did not fish, the LEK map had no data, whereas the RS map was able to identify habitats. In inner areas with relatively turbid waters, the RS map missed seagrass beds that were mapped using the LEK method.

Seascape characteristics assessment.—When evaluating how the two mapping approaches characterized major habitat distributions, both the maps showed that habitats covered a different proportion of the seascape and were distributed in different ways (Table 1; Appendix S3: Fig. S3). Measures of habitat heterogeneity showed that ″Rubble″ and ″Coral″ dominated the LEK map, covering 44% and 34% of the LEK seascape, respectively. In contrast ″Seagrass″ dominated the RS map, covering 48% of the RS seascape. The RS approach found low ″Coral″ cover (6%), whereas the LEK approach showed higher ″Coral″ cover (34%). In the original RS map (i.e., the map that was not simplified to match the validation survey categories), there was a lower percent cover of categories containing coral (Appendix S3: Fig. S5).

The two mapping approaches characterized the seascape as having quite different habitat heterogeneity and connectivity (Fig. 3). The RS map depicted greater complexity in the spatial arrangement of benthic habitats, as characterized by having six times more habitat patches

Table 2. Confusion matrices comparing independent habitat survey data from manta tows with the (a) local environmental knowledge (LEK) and (b) remote sensing (RS) maps at the Minantao Reef. Boldface type indicates class agreement between the map and the reference data.

	Reference habitats				
Characteristic	Coral	Rubble	Sand	Seagrass	Total
(a) LEK Map					
Habitats					
Coral	**0**	0	1	0	1
Rubble	1	**121**	23	37	182
Sand	0	0	**0**	0	0
Seagrass	0	0	0	**0**	0
Total	1	121	24	37	183
Accuracy					
Producer's accuracy	0%	100%	0%	0%	
User's accuracy	0%	66%	0%	0%	
Overall accuracy					66%
(b) RS Map					
Habitats					
Coral	**1**	2	0	0	3
Rubble	3	**117**	12	3	135
Sand	1	2	**2**	1	6
Seagrass		12	13	**33**	58
Total	5	133	27	37	202
Accuracy					
Producer's accuracy	20%	88%	7%	89%	
User's accuracy	33%	87%	33%	57%	
Overall accuracy					76%

Note: We excluded reference (manta tow) points located in "Deepwater" on the maps. Since more reference points fell into "Deepwater" areas on the LEK map, there were 19 fewer manta tow points for evaluating the LEK map (LEK n = 183; RS n = 202).

(Table 1). The RS approach distinguished approximately four times as many edges between adjacent habitats (Table 1). The finer resolution of the RS map was thus better at documenting the full extent of habitat edges. Habitat connectivity was five times higher with the RS approach than in the LEK map when measured using Patch Density (Table 1) and four times higher in the RS map when measured using Near-Neighbor Distance (Table 1). Note that a higher Near-Neighbor Distance indicates a higher distance between similar patches and lower connectivity. Thus, the RS approach suggested higher structural connectivity in the seascape and indicated that species (e.g., fish, crustaceans) traveling across the seascape could travel shorter distances between patches of the same type of habitat (e.g., between two "Coral" patches).

Cost estimation.—Based on our cost estimation, the RS map was approximately one and a half times as expensive to produce for this project when images were donated and software was available from existing licenses (total cost: $7,718 LEK and $10,188 RS; Table 3). When imagery and software would need to be purchased, we estimate that the RS map would be five times more expensive then the LEK map (total cost: $9,343 LEK and $47,688 RS; Table 3). Ideally the software could be used for several projects. The primary cost for the LEK map was time (83%), whereas the primary cost of the RS method was the high spatial resolution satellite images and software (79%).

Discussion

Large coral reef systems have rarely been mapped using high spatial resolution satellite imagery (Roelfsema et al. 2013*b*). Thus, this study, by mapping a 500 km^2 area, provides a rare quantitative assessment of the accuracy and seascape characteristics of RS and LEK mapping at this scale. The accuracy of the RS map, similar to the accuracy of other studies

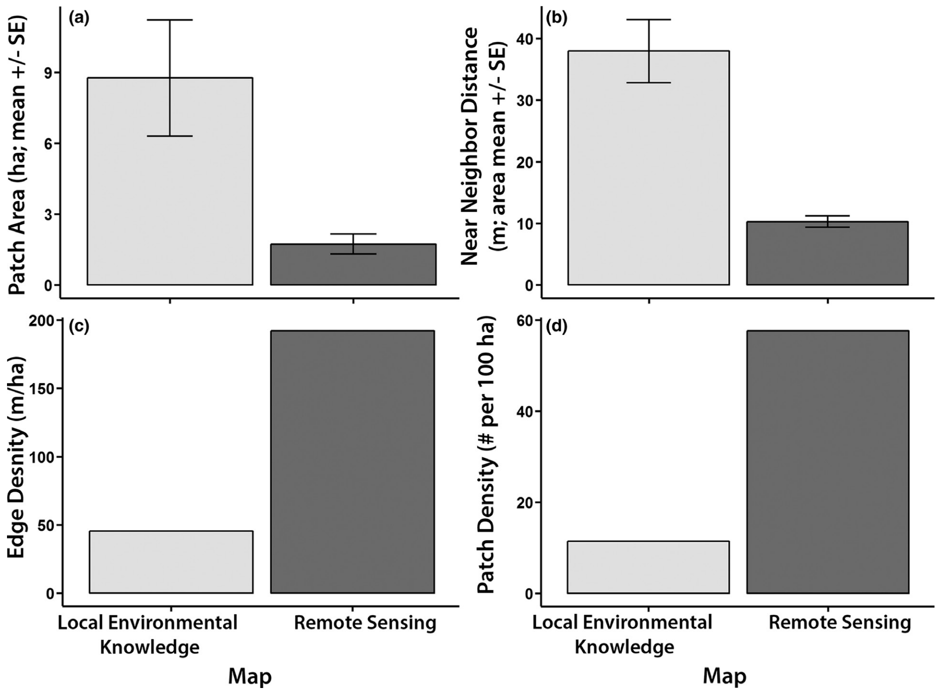

Fig. 3. Contrasting estimates of seascape characteristics of the Danajon Bank, Philippines based on maps created using local environmental knowledge (LEK) and classification of high spatial resolution remote sensing (RS) of WorldView-2 images. The seascape estimates used here incorporate information from all habitat classes. (a) Area of habitat patches; (b) Distance between a habitat patch and the nearest patch of the same habitat class; (c) Density of habitat edges (the borders between two different types of habitat); (d) Density of habitat patches.

(Roelfsema et al. 2013*a,b*), provides evidence that this object-based mapping approach can be successfully applied in a new region (South-East Asia). The RS mapping approach used here was originally developed for the Western Pacific (Lyons et al. 2012, Phinn et al. 2012, Roelfsema et al. 2013*b*). Furthermore, this study demonstrates that although the remote sensing specialist is not familiar with the reefs in the study area, accurate and reliable RS maps can be created through the presence of: expert knowledge; sufficient field data; high spatial resolution imagery; and existing rulesets developed for other reefs (Roelfsema et al. 2013*b*).

Our detailed evaluation of LEK and RS approaches enabled us to test the often implicit assumption that RS maps are more accurate than LEK maps. We show that the RS approach was indeed more accurate, but both methods met the 60% standard for overall accuracy (Roelfsema and Phinn 2013). Our LEK map was in a similar overall accuracy range as coral reef habitat maps produced by other studies, including moderate spatial resolution RS maps (e.g., Landsat-7, with overall accuracies ranging from 48% (9 classes) to 77% (4 classes) (Capolsini et al. 2003) and as other LEK maps (65%) (Lauer and Aswani 2008). Thus, both mapping approaches used here have suitable accuracy for conservation applications. High accuracy and high spatial resolution benthic mapping are particularly important for threatened areas, such as the Danajon Bank, because such maps can support the conservation of threatened ecosystems. Having quantified the accuracy and other characteristics of two mapping approaches, we discuss the implications of using each in conservation planning, and effects of the biases and limitations present in each method.

Conservation applications of LEK and RS maps

For conservation planning that considers connectivity and species movement, our research suggests that the best mapping approach will

Table 3. Estimated costs (USD) using local environmental knowledge (LEK) and remote sensing (RS) approaches for mapping benthic community habitats.

		LEK			RS		
Task	Cost per hour	Person-hours	Other costs	Total cost	Person-hours	Other costs	Total cost
Establishing contacts, Identifying field sites	6	40	$100	$340	20	$100	$220
Field surveys (Interviews, Habitat surveys)	6	315	$400	$2,290	160	$700	$1,660
Validation surveys	6	48	$300	$588	48	$300	$588
Data entry (Including digitizing)	6	100		$600	40		$240
Obtaining advice from previous studies (R code, Classification rules; Technician)	20	40		$800	24		$480
Data processing & Map creation (Technician)	20	80		$1,600	200		$4,000
Supervision, Data processing & Map creation (research associate/professor)	150	10		$1,500	20		$3,000
Total cost, without images or software		633	$800	$7,718	512	$1,100	$10,188
Satellite images			$1,625	$1,625†		$17,500	$17,500†
Software		$0	$0	$0‡		$20,000	$20,000§
Total cost		1,266	$2,425	$9,343	512	$38,600	$47,688

Note: The LEK costs assume an existing NGO has established community contacts and staff skilled with ecological and LEK fieldwork. The RS costs assume that the technician has technical expertise in object-based image analysis.

† Images for this project were donated through Planet Action grants, but these are the estimated image costs for SPOT-5 and WorldView-2.

‡ If free software, qGIS and R, are used for the project.

§ If eCognition is used and an independent license is purchased.

depend on the sensitivity of fish or invertebrate species to seascape patterns. At the individual level, the distribution of habitats, combined with species behavior, can facilitate or impede the movement of organisms (Grober-Dunsmore et al. 2007). For example, individuals traveling across exposed habitats (e.g., sand, deepwater) may have a higher predation risk (Selgrath et al. 2007) and may avoid crossing open areas (Hovel and Wahle 2010). When suitable patches are far apart their low connectivity can reduce ecological resilience by impeding the movement of mobile organisms with important ecological functions (e.g., roving herbivorous fish) (Nyström and Folke 2001, Olds et al. 2012*a*). At the population level, connectivity between habitats can enhance the performance of MPAs by supporting higher biomass of piscivores and herbivores than found at isolated locations (Olds et al. 2012*b*, but see Edgar et al. 2014). Since RS was better at mapping habitat edges and small patches, it could be most suitable for species with short movement ranges or high predation risk at edges. When important species have wider home ranges or are not impacted by edge effects then both maps have the potential to provide insight into conservation of biodiversity and species.

The map comparison presented here demonstrates that there are several situations where RS maps are most suitable. When conservation programs aim to assess habitat changes due to protection or anthropogenic impacts, consistency is essential for identifying change (Scopélitis et al. 2009, Roelfsema et al. 2013*a*). Thus, the more automated RS approach would be preferred because it offers finer spatial resolution and spatial consistency and is less subjective in comparison to manual interpretation. In addition, the RS approach is repeatable over short time scales (e.g., 1 yr or less), which may be difficult with the LEK approach (e.g., research fatigue) (Reed 2008). Finer resolution benthic habitat maps (e.g., <10 m), such as those derived from high spatial resolution imagery, may also be better suited for species with strong habitat associations. Fine-spatial scale habitat variations (5–20 m) have been the most important predictors of reef fish community composition (Knudby et al. 2010, but see Mellin et al. 2010). Finally, conservation initiatives that target marine species sensitive to edge effects should incorporate RS maps when possible because the RS approach was much better at capturing habitat edges which can influence species distributions at small-scales (e.g., <5 m) (Selgrath et al. 2007).

Our findings determined that LEK maps can well represent coarse habitat patterns, in addition to having benefits that extend beyond the maps themselves. In Tanzanian and U.S. Virgin Island coral reefs, some functional groups of fish are more abundant at coral reefs near seagrass beds (Grober-Dunsmore et al. 2008, Berkström et al. 2013). Such general habitat patterns occur at scales coarse enough (e.g., 750 m) to be captured by the LEK-derived maps created here and therefore do not require the more detailed maps provided by high spatial resolution RS. Beyond map characteristics, LEK maps have the benefit of involving communities as active participants in conservation programs, which can lead to the greater success of conservation programs (Reed 2008, Pajaro 2010, Thornton and Scheer 2012). Furthermore, we estimate the LEK approach to cost substantially less than the RS approach, making it a financially practical mapping approach.

Accounting for biases and limitations of maps

Both mapping approaches used here can be improved by accounting for two factors: sampling bias and knowledge/technological limitations. First, both LEK and RS field survey approaches rely on the observer (resource users or field biologists) identifying the dominant habitat. Observer bias toward a particular resource (e.g., coral) can influence observations and survey results that underlie maps (Roelfsema and Phinn 2008) and LEK mapping may have a systematic offset from scientific observations (Aswani and Lauer 2014). When there are biases in LEK mapping of habitats (e.g., over-mapping "Rubble" as seen here), RS mapping can create maps with higher accuracy. Alternatively, LEK biases could also be accounted for in mapping procedures (e.g., by using local habitat classifications; Lauer and Aswani 2008). For RS mapping, field biologists can avail of techniques that minimize observer bias (e.g., standardization between observers; English et al. 1997). When habitats are rare, such as the "Coral" habitat class in this study, validation surveys could utilize methods for sampling rare species to ensure that there is a high sample of rare habitat classes in the validation survey.

Accounting for the knowledge and/or technological limitations of the mapping approaches used here is a second factor which can improve map accuracy. Here, we accounted for the limits of fishers' spatial precision by providing respondents with a map that incorporated a satellite image. As fishers' knowledge is limited to places that fishers visit (Lauer and Aswani 2008, Roelfsema et al. 2013*a*), we addressed this limitation by constraining mapping to fishing grounds. However, this restriction caused areas where fishers do not fish (e.g., mangroves) to be under-mapped. Future projects could address this limitation by asking fishers to map habitats in their fishing grounds *and* the surrounding areas, or by providing respondents with a grid of data points on a map (Roelfsema and Phinn 2008). Here, we found that offshore areas (further from villages) appeared to be mapped less accurately, and such lower accuracies have been found to occur in areas that fishers rarely visit (Lauer and Aswani 2008). In contrast, RS technologies are limited by factors such as the precision of calibration surveys, spectral resolution, water clarity, and water depth (Mumby et al. 1997). By creating a high-accuracy map using a mix of calibration survey methods (with high and moderate precision), we created a RS map with high accuracy. This demonstrates that a practical approach to calibration surveys can yield maps with high value for conservation, even in large areas with variable water clarity.

Conclusions

Both LEK and RS maps are valuable tools for meeting the growing need for improved marine habitat maps. By creating detailed maps of benthic habitats for the Danajon Bank coral reef, we developed valuable assets for species conservation and spatial planning in the center of marine biodiversity and identified guidelines for future conservation mapping. We suggest that programs carefully consider the specific goals and uses for maps, as well as the resources available, when deciding upon the most suitable approach. For projects requiring high spatial precision or high habitat accuracy, the RS method would be the best option. When resources are limited or objectives dictate it, LEK mapping can provide a viable alternative to RS and has the added benefit of engaging stakeholders. There is also the possibility of enhancing both maps by combining them into one (e.g., LEK in nearshore or deeper areas with turbid water and RS in shallow offshore areas with clear water) (Ban et al. 2009, Roelfsema et al. 2009). Drawing on the strengths of each approach has the potential to improve conservation efforts in ways that range from confidence in reserve design (Tulloch et al. 2013) to more accurate evaluations of restoration and conservation targets (Gergel et al. 2007). Overall, both mapping approaches, apart or together, have the potential to aid informed decision making to achieve conservation targets.

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Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1325/supinfo