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Comparing the information content of coral reef geomorphological and biological habitat maps, Amirantes Archipelago (Seychelles), Western Indian Ocean

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Abstract

Increasing the use of geomorphological map products in marine spatial planning has the potential to greatly enhance return on mapping investment as they are commonly two orders of magnitude cheaper to produce than biologically-focussed maps of benthic communities and shallow substrates. The efficacy of geomorphological maps derived from remotely sensed imagery as surrogates for habitat diversity is explored by comparing two map sets of the platform reefs and atolls of the Amirantes Archipelago (Seychelles), Western Indian Ocean. One mapping campaign utilised Compact Airborne Spectrographic Imagery (19 wavebands, 1 m spatial resolution) to classify 11 islands and associated reefs into 25 biological habitat classes while the other campaign used Landsat 7 þ ETM imagery (7 bands, 30 m spatial resolution) to generate maps of 14 geomorphic classes. The maps were compared across a range of characteristics, including habitat richness (number of classes mapped), diversity (ShannoneWeiner statistic) and thematic content (Cramer's V statistic). Between maps, a strong relationship was revealed for habitat richness (R2 ¼ 0.76), a moderate relationship for class diversity and evenness (R2 ¼ 0.63) and a variable relationship for thematic content, dependent on site complexity (V range 0.43 e0.93). Geomorphic maps emerged as robust predictors of the habitat richness in the Amirantes. Such maps therefore demonstrate high potential value for informing coastal management activities and conservation planning by drawing on information beyond their own thematic content and thus maximizing the return on mapping investment.

Keywords

content, biological, comparing, habitat, maps, amirantes, archipelago, information, seychelles, western, indian, ocean, coral, reef, geomorphological

Disciplines

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Comparing the information content of coral reef geomorphological and biological habitat maps, Amirantes Archipelago (Seychelles), Western Indian Ocean

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Abstract

Increasing the use of geomorphological map products in marine spatial planning has the potential to greatly enhance return on mapping investment as they are commonly two orders of magnitude cheaper to produce than biologically-focussed maps of benthic communities and shallow substrates. The efficacy of geomorphological maps, derived from remotely sensed imagery, as surrogates for habitat diversity is explored by comparing two map sets of the platform reefs and atolls of the Amirantes Archipelago (Seychelles), Western Indian Ocean. One mapping campaign utilised Compact Airborne Spectrographic Imagery (19 wavebands, 1m spatial resolution) to classify 11 islands and associated reefs into 25 biological habitat classes while the other campaign used Landsat 7+ ETM imagery (7 bands, 30m spatial resolution) to generate maps of 14 geomorphic classes. The maps were compared across a range of characteristics, including habitat richness (number of classes mapped), diversity (Shannon-Weiner statistic) and thematic content (Cramer's *V* statistic). Between maps, a strong relationship was revealed for habitat richness ($R^2 = 0.76$), a moderate relationship for class diversity and evenness ($R^2 = 0.63$) and a variable relationship for thematic content, dependent on site complexity (*V* range 0.43-0.93). Geomorphic maps emerged as robust predictors of the habitat richness in the Amirantes. Such maps therefore demonstrate high potential value for informing coastal management activities and conservation planning by drawing on information beyond their own thematic content and thus maximizing the return on mapping investment.

Key words: Remote sensing, CASI, Landsat, Millennium Coral Reef Mapping Project, Cramer's V statistic

Introduction

Digital habitat maps of reef systems derived from remotely sensed imagery are valuable sources of information for assessing regional biophysical status, comparing status within and between regions and monitoring changes in coastlines over time to guide coastal management and decision making (e.g. Lourie et al., 2004; Wabnitz et al., 2010, Hamel and Andréfouët, 2010). Information contained in habitat maps is particularly useful for marine spatial planning and, to this end, marine conservation practitioners are increasingly employing map products to evaluate candidate sites for protection (Roberts et al., 2003; Dalleau et al., 2010: Wilson et al., 2011). However, such maps offer a wide variety of information. This variation is determinedby the classification scheme applied, which itself depends on the application and the sensor used (Andréfouët, 2008). Hereafter, we use two notions: “geomorphological” and “biological habitats” to refer to different levels of detail contained in a map. The former describes islands only by reference to geomorphological qualitative units (e.g. landforms such as reef flat, spur and groove, fore-reef slope). The latter uses a combination of qualitative and quantitative information, such as percentage benthic cover, growth form of coral colonies, and reef rugosity indices to characterize “habitats” at, generally, a finer spatial scale.

Previous exercises have compared the geomorphological and biological habitat mapping capability of different sensors (Capolsini et al., 2003), the relationship between thematic richness and map accuracy (Mumby and Edwards, 2002; Andréfouët, 2008) and the relationship between mapped geomorphic richness and species richness (Andréfouët and Guzman, 2005). However, to our knowledge, there have been no quantitative assessments of the complementarities (or otherwise) between different thematic contents of coral reef habitat maps. Such assessments are potentially of great value because mapping the geomorphological units of a given coral reef is highly cost-effective, typically two orders of magnitude less costly than the traditional ecological ground survey methods required for biological habitat mapping (Wilson et al., 2011). If it is possible to estimate information on the biological habitat diversity from in a geomorphic layer, one could employ low cost geomorphological maps as proxies for habitat diversity and yield a greater return on mapping investment. The objective of this study is to test this hypothesis by empirically comparing two sets of maps from the Amirantes Archipelago, a group of platform reefs, sand cays and atolls that stretch over a distance of ~152 km (4^o52'S - 6^o14'S) along the Amirantes Ridge, Western Indian Ocean. The two map sets were produced independently by *i)* the Cambridge Coastal Research Unit, University of Cambridge, UK (Spencer et al., 2009) and *ii)* the Millennium Global Coral Reef Mapping Project (Andréfouët et al., 2006).

Methods

Site description

Of the seven reef types identified in the Seychelles by Stoddart (1984), three are present in the Amirantes Archipelago: platform reef, atoll and drowned atoll. The platform reefs are of three types that vary in complexity depending on platform elevation and variation in contemporary process environments (e.g. incident wave fields) (Spencer et al., 2009; Hamylton et al., 2011). Low complexity Type 1 systems are characterized by a reef surface entirely covered by intertidal sands and where the land areas are either extremely small (< 1% of total platform area; African Banks) or composed of mobile sand cays (Sand Cay, Etoile). Type 2 moderate complexity systems (Marie-Louise, Desnoeufs and Boudeuse) contain small islands (all < 0.8 km^2) characterised by low raised reef deposits, bedded calcareous sandstones and beachrock ridges which sit on the margins of more extensive but relatively shallow rock platforms. In Type 3 more complex systems (D'Arros and Poivre), platform surfaces have infilled to allow the development of large (>2 km^2) island areas. The three atolls (St. Joseph, Alphonse and St François/Bijoutier) are small by global standards (Stoddart, 1984). These systems – called here Type 4 - are characterised by wide reef-flats, shallow lagoons and poor lagoon-ocean exchange. The one drowned atoll in the island group is Desroches; detailed biological habitat mapping was not undertaken at this location and therefore no comparison of map content was possible. Overall, the islands on the western margin of the Bank support a restricted range of littoral habitats, whereas those in the east show a greater range of habitats, particularly in subaerial environments.

Mapping campaigns

Detailed descriptions of the image processing methods used for map production are reported elsewhere for both the geomorphological maps (Andréfouët et al., 2006) and the biological habitat maps (Spencer et al., 2009).

Since 2004, the Millennium Coral Reef Mapping Project (MCRMP) has examined more than 1600 Landsat 7 ETM+ satellite images (spatial resolution 30 m x 30 m; with 4 useful wavebands for the project) of coral reefs worldwide. The Project has generated, using segmentation and photo-interpretation techniques, a globally consistent hierarchical typology of 800 basic geomorphological classes that are subdivided into 5 hierarchical levels.

In January 2005, the Cambridge Coastal Research Unit conducted an airborne mapping campaign in which 110 flightlines of airborne hyperspectral CASI data were acquired (spatial resolution 1m x 1 m; 19 wavebands). After conversion to reflectance data, the imagery was pre-processed to correct for geometric error and the scattering and absorptive influence of the atmospheric and water column layers (Lyzenga 1981). Thereafter, a maximum likelihood classifier was applied to assign each image pixel to the most likely benthic cover class. Information from 910 ground-referencing points collected *in-situ* was employed to supervise and validate the classifications.

The satellite mapping and airborne hyperspectral mapping identified 14 geomorphological classes and 25 biological habitat classes respectively (Table 1).

Table 1. Classification schemes employed for mapping geomorphology (column 1) and biological habitats (column 2) and of the reefs and islands of the Amirantes Archipelago.

Map Comparison Methods

Three different metrics were employed to compare the geomorphological and biological habitat maps for eleven islands: 1) the richness or number of classes mapped per island; 2) the Shannon-Weiner statistic; and 3) the Cramer's *V* statistic.

Richness of reef features (number of classes mapped)

The number of classes mapped was recorded from both the geomorphological and biological habitat maps as a measure of richness of reef features. The relationship between the richness of the geomorphological maps and the biological habitat maps was modelled by performing 10 iterative regressions, each time omitting one island site to calibrate a power model between the two as follows:

$$n_b = h\, n_g^{j} \qquad \text{Equation 1}$$

Where: n_b = number of biological habitat classes mapped using the CASI sensor

n_g = number of geomorphological classes mapped using the Landsat sensor

h = slope factor determined for 10 islands

j = power factor determined for 10 islands.

For each iteration, this model was applied to the one remaining island to predict the number of habitat classes mapped given the number of geomorphic classes mapped. As a measure of the overall validity of this approach, the 11 modelled values of habitat richness were then compared to the actual values via a linear regression and the significance of this relationship was established via a t-test.

Habitat and geomorphic diversity (Shannon-Weiner statistic)

The Shannon-Weiner statistic is commonly employed to link coral reef geological and ecological diversity (e.g. Aronson, 2007). To incorporate both diversity and evenness (in terms of the relative area covered by each map class), the Shannon-Weiner statistic, *H’*, was calculated for each island map as follows:

$$H' = \sum_{i}^{b} \sum_{i}^{g} (p_i \ln p_i) \qquad \text{Equation 2}$$

where subscripts *b* and *g* denote summing across the biological habitat and geomorphological habitat classes respectively and p_i is the proportion of total mapped area covered by each class. The 11 values of Shannon-Weiner statistic were compared across the two island map sets via a linear regression, using the iterative approach employed for the number of classes (richness) comparison with the omission of one island in each regression. As with the class richness comparison, the 11 modelled values of Shannon-Weiner diversity were then compared to the actual values via a linear regression as a measure of the overall accuracy of this approach and the significance of this relationship was established via a t-test.

Similarity between habitat and geomorphic maps (Cramer’s *V* statistic)

Cramer's *V* statistic was calculated to quantitatively compare the geomorphological and biological habitat maps at each site because it is a simple, widely used and effective measure of similarity in the spatial content of maps (Cramer, 1999; Rees, 2008). It incorporates thematic content into a single measure of map association, scaled between 0 (no association) and 1 (identical), comparing the deviation of class membership distribution of both maps from an expected random distribution using chi-square methods:

$$V = \sqrt{\frac{\chi^2}{N(\min(b, g) - 1)}} \qquad \text{Equation 3}$$

Where χ^2 is the chi square distribution of the contingency matrix, *N* is the total area mapped and min (*b*, *g*) is the minimum value of its arguments (i.e. the minimum number of classes mapped by either map set of *b* or *g* classes).

$$\chi^2 = \sum_{i=1}^{b} \sum_{j=1}^{g} \frac{(c_{ij} - c_{ij}^*)^2}{c_{ij}^*} \qquad \text{Equation 4}$$

Where c_{ij} and c_{ij}* are the observed and expected map contingency matrices respectively.

Results

The spatial configurations and limits of the main island zones were in good agreement (Figure 1).

Figure 1. The Amirantes Ridge (centre) with the two map sets of the reefs and islands of the Amirantes Archipelago (see inset box for location). For each inset box, the habitat map is displayed in colour and the geomorphological polygon limits are overlaid on top in red. The spatial extent of the maps varies because of the different sensors employed in their production and the different size of the units that were the focus of the geomorphological and biological habitat mapping campaigns (Table 1).

Across the set of 11 islands tested, strong and significant power relationships were consistently revealed between the number of geomorphological classes mapped (n_g) and biological habitat classes mapped (n_h), with an R^2 ranging from 0.81 – 0.92 and t-test were significant in all cases at the $p<0.002$ level (Table 2). The overall linear regression of modelled and actual number of classes across the 11 islands was also strong ($R^2=0.76$) and significant (t statistic = 4.96, $p<0.001$), suggesting that the geomorphological maps served as a reliable predictor of biological habitat richness (Figure 2a).

The linear regressions of the Shannon-Weiner statistic, H', encompassing map content and evenness across each island, were moderately strong, with an R^2 ranging from 0.54 – 0.71. The overall regression of the modelled and actual Shannon was moderately strong (R^2 0.66) and significant (t statistic = 3.65, $p<0.008$), indicating that the geomorphological maps were also a moderately reliable predictor of this statistic.

The Cramer's *V* statistic, however, indicated a wide range of association between the map products for the islands assessed (V = 0.43 - 0.93). Such variability in association appears to be related to the simplicity of island structure, with, for example, simple Type 1 islands (e.g. Etoile and Sand Cay) showing a greater degree of association between biological habitat and geomorphological maps than the more complex Type 3 platform reefs and Type 4 atolls.

Table 2. Results of the map set comparisons by island type (see text for discussion and Figure 2 for location) for the number of classes (n), Shannon-Weiner index (H') and Cramer's *V* statistic (*V*). Subscript *h* denotes habitat map and subscript *g* denotes the geomorphological map.

Figure 2. A plot of a) the actual number of habitat and predicted number of habitat classes mapped on the basis of the geomorphological maps, and b) the actual and predicted Shannon-Weiner statistics associated with both the biological habitat and geomorphological maps.

Discussion

This study formally tests the hypothesis that simple, inexpensive geomorphological maps can be used in place of biological habitat maps when conservation planning is focused on habitat richness and diversity (e.g. Roberts et al., 2002; Gray, 1997). In the reef systems of the Amirantes Archipelago, it is possible to infer biological habitat characteristics in the form of three metrics (richness, diversity, Cramer's *V*) from the application of a simple statistical adjustment to geomorphological maps. The strongest associations were between the number of geomorphological classes and biological habitat classes mapped These relationships were likely underpinned by the laterally extensive nature of the reef platforms and atolls of the Amirantes Archipelago, which provide a shallow surface that supports multiple habitats, such as seagrass beds, coral patches and further reef development. This relationship was weaker among the lower complexity Type 1 landforms composed of dynamic sedimentary accumulations such as sand cays where where overwash by waves and high mobility has limited succession beyond salt-tolerant species capable of surviving in nutrient poor sediments (e.g. Sand Cay and Etoile). This relationship was strongest in the more developed Type 3 platform reefs (e.g. D'Arros and Poivre) where a succession through to terrestrial habitats has taken place through sedimentary lithification and subsequent development of subaerial beachrock foundations that protect the island margin. Island stability and elevation therefore appears to be a key control, an important component of which is the establishment of vegetation, which binds sediments with root systems, protects surfaces and encourages deposition of windblown sediments and wave overwash sediments by greatly increasing surface roughness (Stoddart and Steers, 1977).

With the incorporation of areal considerations using the Shannon-Weiner statistic, the strength of the overall relationship between the habitat and geomorphic maps was slightly reduced (overall $R^2=0.66$, $p<0.008$). The lower complexity landforms comprised of sand accumulations stabilised by seagrass (e.g. African Banks and Sand Cay) tended to exhibit stronger relationships between habitat and geomorphic diversity as measured with the Shannon-Weiner statistic. Weaker relationships existed in this regard between the Type 3 platform reefs (e.g. D'Arros and Poivre) where subaerial landforms have developed through infilling, likely because of a greater relative rate of addition of habitat diversity per unit geomorphic diversity (e.g. one large "land on reef" class in the geomorphological map equates to 7 additional terrestrial habitat classes, see Table 1). Thus, while larger geomorphic landform units mapped may appear relatively consistent, as their areas increase they allow greater biological differentiation between windward v. leeward and island margin v. island interior environments.

Association between the thematic content of the map products, as measured by Cramer's *V* statistic, was variable (*V* 0.43 - 0.93), with a stronger association where less classes were mapped (Table 2). The correspondence between the habitat and geomorphic maps reduced as the complexity of the islands increased, such that the average Cramer's *V* associated with an upward transition in complexity of reef islands was ranked as follows: reef platform Type 1 (0.84), reef platform Type 2 (0.71), reef platform Type 3 (0.64) and Type 4 atolls (0.49). Thematic richness may contribute to the dissimilarity between the two map sets for a number of reasons, including the greater opportunity for classification error and subsequent thematic mis-registration and the differing influence of spectral mixing of endmember classes in spatially heterogeneous areas between the two image resolutions (Steele et al., 1998; Mumby and Edwards, 2002). This limitation should be borne in mind by managers intending to compare the spatial distribution of the thematic content of these different map types.

Conclusion

This study has demonstrated strong relationships between habitat and geomorphic richness, as measured by the number of classes mapped; moderately strong and positive relationships with the incorporation of the area of habitat classes mapped through the Shannon-Weiner statistic and variable relationships in relation to the spatial and thematic map content as measured by Cramer's *V*. To further investigate relationships between biological and geomorphological maps of reef islands, similar comparisons are needed between the products of the Millennium Global Coral Reef Mapping Project and available satellite and airborne remote sensing products, both in areas subject to different sea level, tectonic and climatic histories and across biogeographic provinces with gradients of biological diversity. Potential case studies where similar remote sensing campaigns have been conducted include, but are not limited to, Panama (Benfield et al., 2007), the Red Sea (Rowlands et. al., 2012), Zanzibar (Knudby and Nordland, 2011), New Caledonia (Andréfouët et al., 2009b) and the Coral Triangle (Bertels et al., 2008). If strong relationships between geomorphological richness and biological habitats appear consistent between different coral reef settings, this will translate into clear management advantages, an outcome that is particularly pertinent given the global scope of the Millennium Coral Reef Mapping Project and the application of its products for conservation planning (e.g. Dalleau et al., 2010: Wilson et al., 2011, Allnut et al., 2012). These management advantages include (i) the provision of information on habitat characteristics where none may previously have existed; (ii) the identification of areas of high geomorphic diversity, which are also likely to harbor high biological habitat and species diversity; and (iii) the maximization of returns on investment in regional-scale biodiversity marine conservation planning.

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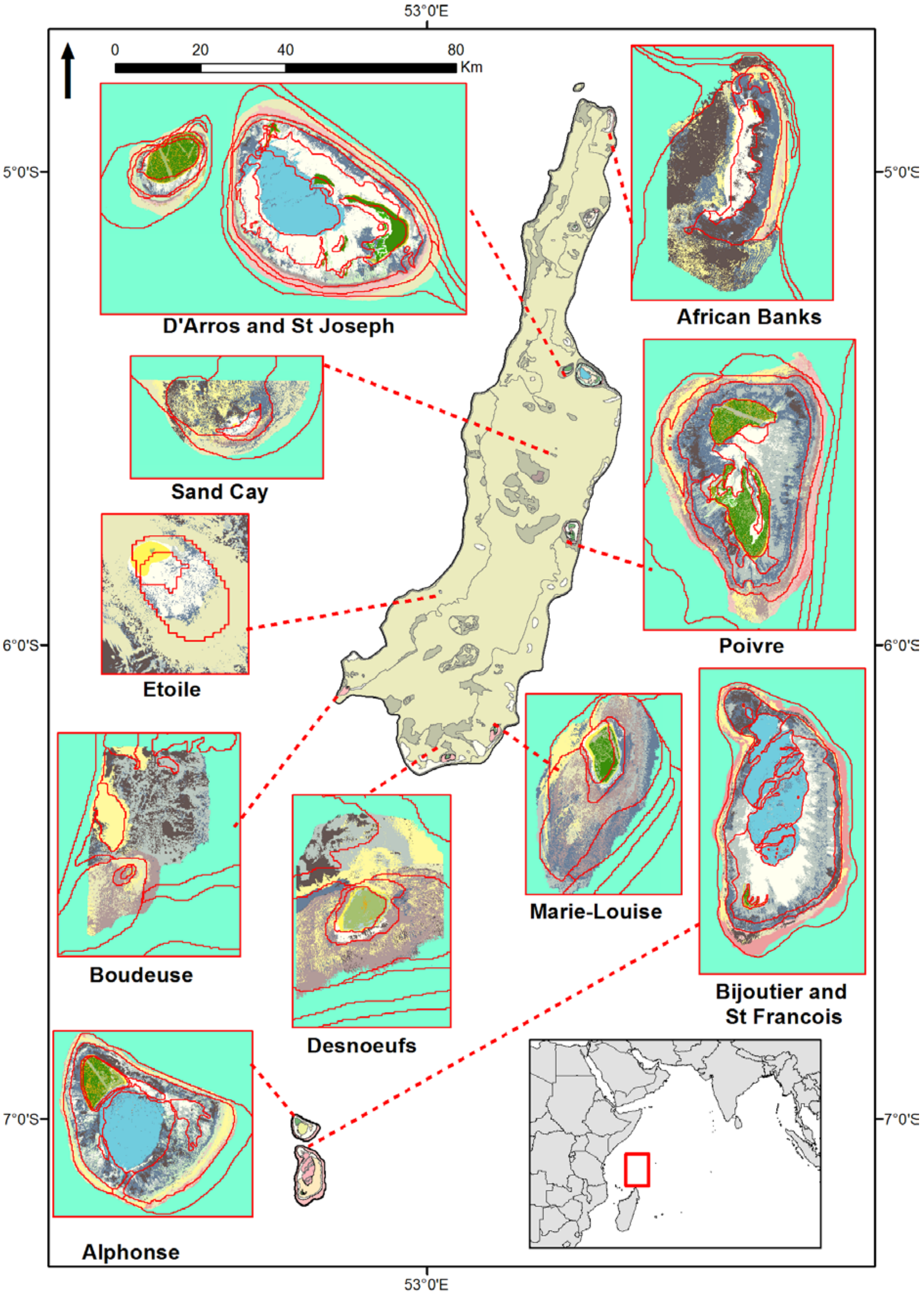

Figure 1. The Amirantes Ridge (centre) with the two map sets of the reefs and islands of the Amirantes Archipelago (see inset box for location). For each inset box, the habitat map is displayed in colour and the geomorphological polygon limits are overlaid on top in red. The spatial extent of the maps varies because of the different sensors employed in their production and the different size of the units that are the focus of geomorphological and habitat mapping campaigns (Table 1).

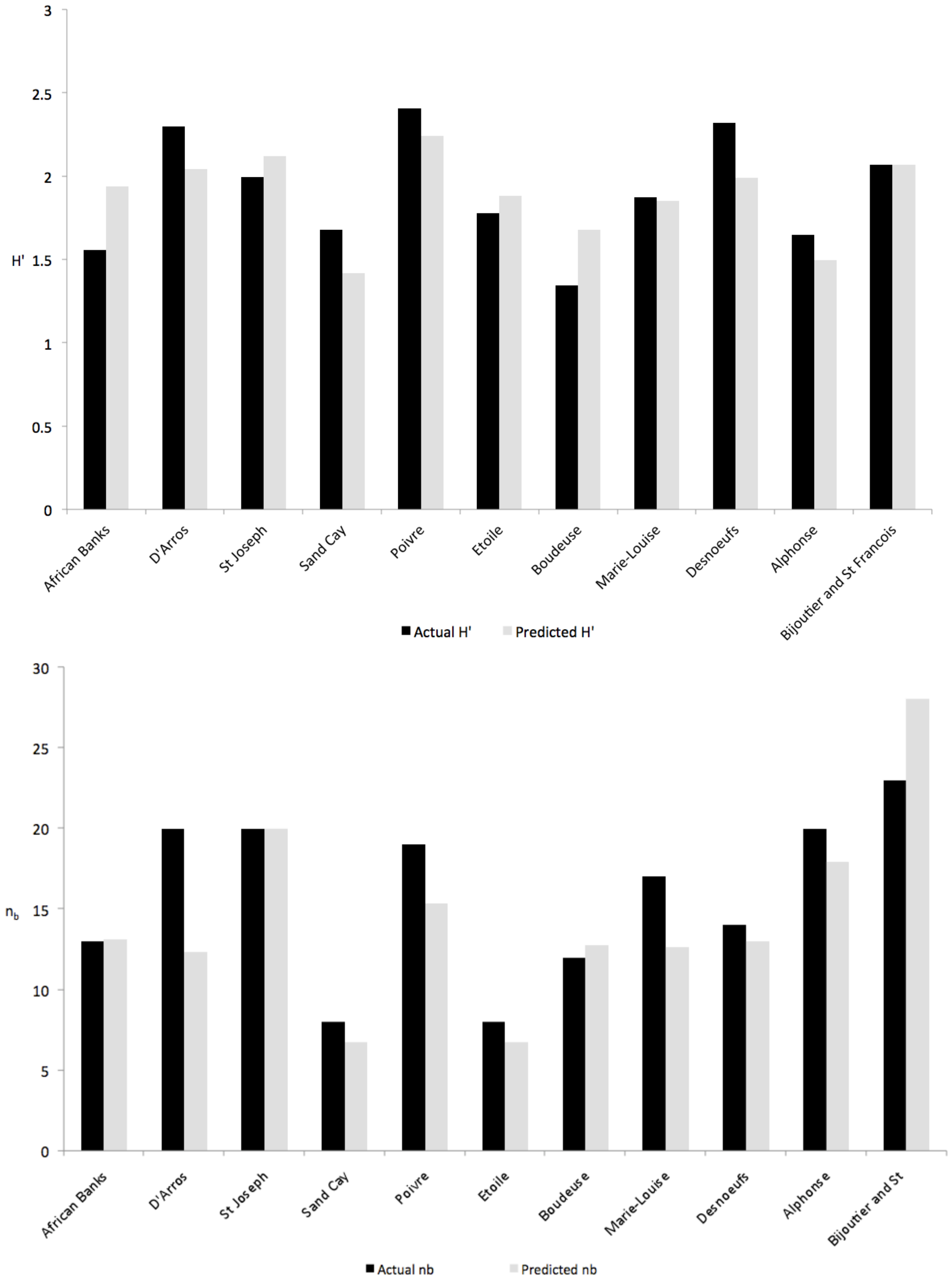

Figure 2. A plot of a) the actual number of habitat and predicted number of habitat classes mapped on the basis of the geomorphic maps, and b) the actual and predicted Shannon-Weiner statistics associated with both the habitat and geomorphic maps.

List of Tables

Habitat Maps	Geomorphological maps
Coconut woodland	Land on reef
Other trees and shrubs	Reef flat
Herbs and grasses	Shallow lagoonal terrace
Saline pond	Enclosed lagoon with constructions
Cleared bare ground	Enclosed lagoon or basin
Buildings and other structures	Faro reef flat
Littoral hedge	Shallow lagoonal terrace with constructions
Mangrove woodland	Shallow lagoon with constructions
Coral sandstone raised reef	Subtidal reef flat
Beach sand	Shallow lagoon
Coral boulders	Shallow terrace
Beachrock	Pass
Rock pavement	Forereef
Reef-flat sand	Deep terrace
Low density seagrass macroalgae	
Medium density seagrass	
High density seagrass	
Lagoon patch reef	
Lagoon sand	
Coral rubble with coralline algae	
Forereef slope coral spurs with coralline algae	
Rocky forereef slope	
Forereef slope sand	
Forereef slope rubble and sand	
Forereef slope with coral	

Table 1. Classification schemes employed for mapping geomorphology (column 1) and biological habitats (column 2) and of the reefs and islands of the Amirantes Archipelago.

Location	Island type	N_h	N_g	R^2 (N)	H'_h	H'_g	R^2 (H')	V
African Banks	1	13	4	0.88	1.56	1.06	0.71	0.67
Sand Cay	1	8	2	0.81	1.65	0.25	0.65	0.93
Etoile	1	8	2	0.81	1.34	0.45	0.63	0.91
Boudeuse	2	12	3	0.86	1.68	0.23	0.58	0.53
Marie-Louise	2	17	4	0.87	1.87	0.94	0.63	0.89
Desnoeufs	2	14	4	0.87	1.78	0.98	0.66	0.71
D'Arros	3	20	4	0.92	2.4	1.84	0.62	0.79
Poivre	3	19	4	0.9	2.32	1.3	0.54	0.49
St Joseph	4	20	6	0.86	2.07	1.71	0.64	0.43
Alphonse	4	20	6	0.86	2.3	1.41	0.63	0.55
Bijoutier/ St Francois	4	23	7	0.87	1.99	1.46	0.65	0.49

Table 2. Results of the map set comparisons by island type (see text for discussion and Figure 2 for location) for the number of classes (N), Shannon-Weiner index (H') and Cramer's *V* statistic (*V*). Subscript *h* denotes habitat map and subscript *g* denotes the geomorphological map.