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Abstract

A collaborative expedition between Khaled bin Sultan Living Oceans Foundation, Cambridge Coastal Research Unit and Seychelles Centre for Marine Research and Technology – Marine Parks Authority (SCMRT-MPA) was conducted to the southern Seychelles, western Indian Ocean, in January 2005. This resulted in a series of habitat maps of the reefs and reef islands of the Amirantes Archipelago, derived from remotely-sensed Compact Airborne Spectrographic Imager (CASI) data. The procedures used in map development, image processing techniques and field survey methods are outlined. Habitat classification, and regional-scale comparisons of relative habitat composition are described. The study demonstrates the use of remote sensing data to construct digital habitat maps for the comparison of regional habitat coverage, a key function for coastal management.

Keywords

seychelles, scheme, amirante, islands, island, habitat, development, classification, GeoQUEST

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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Development of a Regional Habitat Classification Scheme for the Amirante Islands, Seychelles

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Keywords: Remote sensing, Geographical Information Systems, coastal management, habitat.

Abstract—A collaborative expedition between Khaled bin Sultan Living Oceans Foundation, Cambridge Coastal Research Unit and Seychelles Centre for Marine Research and Technology – Marine Parks Authority (SCMRT-MPA) was conducted to the southern Seychelles, western Indian Ocean, in January 2005. This resulted in a series of habitat maps of the reefs and reef islands of the Amirantes Archipelago, derived from remotely-sensed Compact Airborne Spectrographic Imager (CASI) data. The procedures used in map development, image processing techniques and field survey methods are outlined. Habitat classification, and regional-scale comparisons of relative habitat composition are described. The study demonstrates the use of remote sensing data to construct digital habitat maps for the comparison of regional habitat coverage, a key function for coastal management.

INTRODUCTION

Surveys of coastal environments provide information on the distribution and abundance of shallow water benthic communities, as well as local topography and bathymetry. Standardised survey protocols permit assessment of regional biological diversity and ecological status, allow comparison of the status within and between ecoregions, and facilitate the detection of changes in coastal ecosystems relative to established baselines (English *et al.,* 1997). In the shallow water environments of the tropics and sub-tropics, standardised surveys can be applied to ecosystems

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such as coral reefs, seagrasses and mangroves, which collectively provide valuable ecological functions and services in the marine environment.

Remote sensing instruments provide a synoptic portrait of the Earth's surface by recording numerical information on the radiance measured in a series of picture elements (pixels) across a number of spectral bands (Green *et al.,* 2000). When mounted on an airborne platform, they sample habitat cover over extensive spatial ranges. The ability to survey detailed information from relatively large areas is particularly valuable at the coast because changing weather, locations which are inaccessible or difficult to access, and the logistical challenges of carrying out underwater fieldwork all compromise the ability to survey a representative sample of these shallow water environments directly. Remote sensing data benefit the mapping process by enabling accurate extrapolation of information to broader scales, providing information on areas not accessible in the field. In this way, cost savings can be achieved. Mumby *et al.,* (1999) found the combined use of remote sensing and field surveys to be a cost-effective means of acquiring meaningful survey data on the Caicos Bank when compared to a solely field-based approach.

Hierarchical classification schemes for coastal zone management

To map coastal habitats, it is necessary to represent spatially continuous and temporally dynamic benthic surfaces as discrete units. This requires some form of classification scheme. Habitat classification schemes play an important role in standardising the thematic content of regional benthic maps, facilitating their use as a common baseline against which regional subsets can be interpreted. In a spatial context, classes are assigned to homogenous patches of surface that differ in appearance from their surroundings but may vary widely in size, shape, type, relative heterogeneity and boundary characteristics (Forman and Godron, 1986). Ecological units can be divided hierarchically to accommodate user requirements. Top-level descriptions often identify geomorphological context, while lower tiers describe the relative cover of benthic organisms discriminated from ground-verified data (e.g. Mumby and Harborne, 1999). A hierarchical classification scheme that subsumes both geomorphological and ecological characteristics is systematic in structure with tier-level descriptors that cannot be used interchangeably. Geomorphological classes (e.g. fore-reef slope coral spur) can, therefore, be coupled with ecological ones (e.g. high cover of calcareous algae) within the same tier level.

Many coastal mapping strategies employ coarse mapping at the regional scale, augmented by finer resolution maps at locations of specific interest (e.g. Borstadt *et al.,* 1997). Despite the potential use of habitat classification schemes in regional comparisons, most coastal habitat mapping has been conducted on an *ad hoc* basis and displays little consistency in terminology. This limits the interpretation of map products, particularly where regional comparisons would be of value. The use of digital habitat maps derived from remotely-sensed imagery is also limited by these difficulties as they range considerably in resolution.

Habitat maps are commonly compiled from vector data, which partition an area in such a way that each location falls into a polygon assigned a value that is assumed to be homogenous for all locations within that polygon. Although this imposes a discrete data structure on communities that often present themselves as a continuum of changing densities, such data formats lend themselves well to analysis within Geographical Information Systems (GIS) (Burrough and McDonnell, 1998). Such an approach to data storage provides a computationally efficient means by which to carry out statistical analyses on landscape-scale datasets, e.g. extracting coverage values for the different habitats.

STUDY AREA

The Amirantes Archipelago, which lies SW of the extensive, shallow water Seychelles Bank in the western Indian Ocean, comprises a group of

(i.)

Figure 1. (i.) Location of the Seychelles Islands, western Indian Ocean.

(ii.)

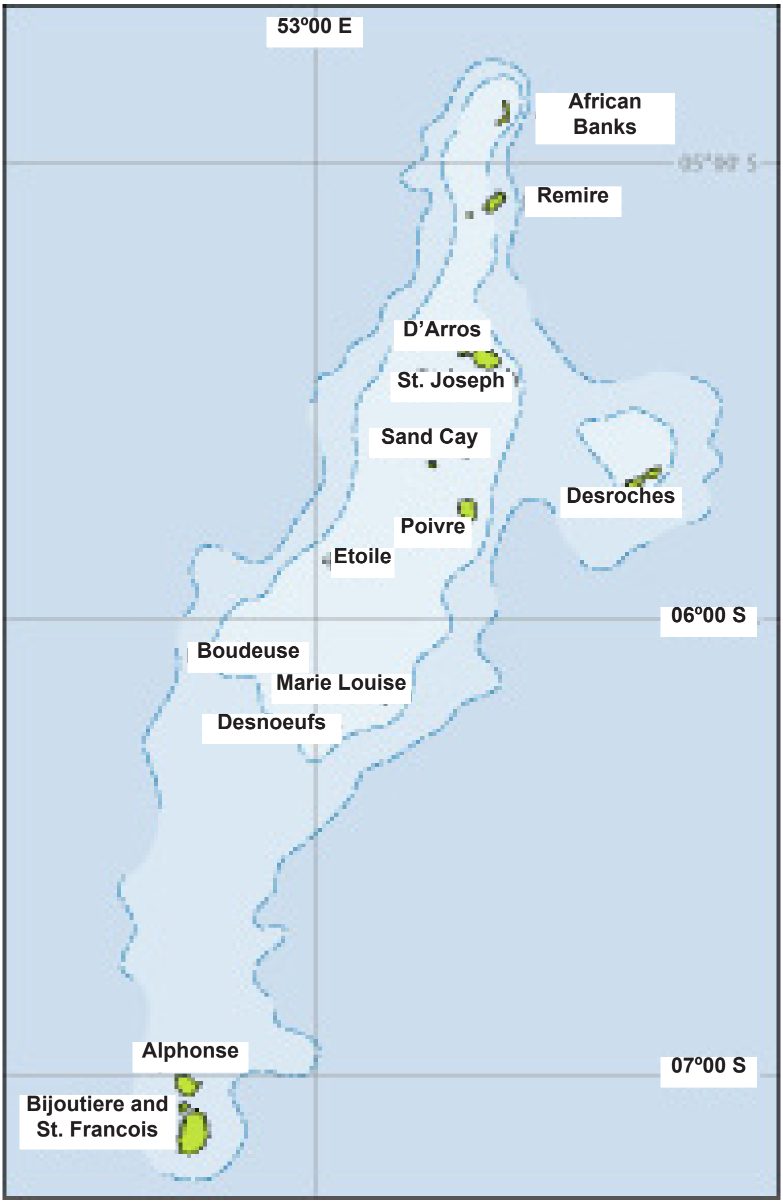

Figure 1. (ii.) The Islands of the Amirantes Bank, Seychelles.

carbonate islands and islets extending over a distance of ~152 km, from 4°52'S (African Banks) to 6°14'S (Desnoeufs) (Fig. 1). The majority of the islands are coral reef platforms at sea level with varying degrees of subaerial sand cay and coral island development. They have evolved over the last 6,000 years since the post-glacial sea level approached its

Table 1. Aerial coverage of CASI data.

Number of islands surveyed	13
Area flown	268 sq kms
Flight lines flown	110 lines
Data volume (raw)	65 Gbytes
Data volume processed (estimated)	150 Gbytes

present level on the Amirantes Bank (Stoddart, 1984). The Amirantes Bank is an elongate structure, measuring approximately 180 km by 35 km, deepest in its centre (up to ~70 m) with a marginal rim 11-27 m deep. With the exception of the islands of Etoile and Boudeuse, the reef platforms lie towards the eastern margin of the Bank. The atolls of Alphonse and Bijoutier/St François which form the Alphonse Group are approximately 95 km further south. Of the 14 islands, 13 were mapped, the exception being Desroches, a shallow submerged atoll, 19-21 km in diameter, lying 16 km to the east of the Amirantes Bank.

The climate of the western Indian Ocean is humid and tropical, with mean monthly temperatures always >20°C and an annual rainfall >700 mm. Seasonal and inter-annual climatic variability is determined by i) the SE Asian Monsoon and the associated seasonal reversal of winds; ii) monsoon-related movements of the Inter-Tropical Convergence Zone (ITCZ); iii) changes in the position and intensity of the South Indian Ocean subtropical high pressure; and iv) variations in ocean circulation and sea surface temperature.

The surface ocean circulation of the western Indian Ocean is characterised by a subtropical, anti-cyclonic gyre to the south (between 40–15°S) and reversing monsoon gyres north of 10°S. The northern boundary of the subtropical gyre is formed by the South Equatorial Current (SEC). During the northern hemisphere summer the SEC is displaced northwards as far as 6°S, and thus into the region of the Amirantes Archipelago, with typical current speeds of 0.25 m s^{-1} and an estimated transport rate of 50 Sv (where 1 sverdrup (Sv) = 10^6 m^3 s^{-1}). These climatic patterns influence both the structural form and surface communities of the reefs of the Amirantes, which display notable leeward-windward contrasts in reef platform development (Spencer *et al.*, 2009).

METHODS

The primary aim of this collaborative expedition was to use a Compact Airborne Spectrographic Imager (CASI) remote sensor onboard a seaplane to conduct large-scale mapping of the reefs and islands of the Amirantes Bank. The sites comprised laterally extensive shallow water landforms, which were ideally suited to airborne mapping. Concurrent field surveys were conducted alongside the airborne surveys. Data were collected on the terrestrial and marine habitats. Results from the CASI image processing provided the first detailed maps of the distribution of shallow marine habitats for each of these locations.

Airborne remote sensing surveys

Airborne remote sensing data were acquired over 13 islands in the Amirantes (Table 1). Reflectance data were recorded between 430-850 nm using a CASI sensor. The sensor was calibrated to measure radiance in 19 spectral bands at a pixel size of 1 m^2, yielding continuous data layers for the area. Synoptic coverage was acquired by following a predetermined flight pattern over each island at an altitude of 1,000 m. This generated a series of parallel flight lines, each 512 m wide, which could be geo-corrected and processed. A landscape scale, ranging between 0.005 and 10 km, in spatial extent was employed in the analyses, encompassing both intra-reef and reef system landforms (Perry *et al.,* 2008).

Ground-referencing

Ground-referencing was conducted in the terrestrial and marine environments at eight of the islands. Over 1,500 ground-reference points were recorded; locations were marked with hand-held GPS units (horizontal accuracy of ±10 m). In shallow water, ground-referencing was conducted from the surface using a glass-bottomed bucket lowered over the side

Table 2. Two-tier classification scheme for the marine habitats of the Amirantes Islands.

First tier	Second tier
1. Terrestrial vegetation: Trees and shrubs	1.1 Coconut woodland 1.2 Other trees and shrubs
2. Herbs and grasses 3. Saline ponds 4. Cleared/bare ground 5. Littoral hedge 6. Mangrove woodland	
7. Coarse beach material & rocks	7.1 Coral sandstone/raised reef 7.2 Coral boulders 7.3 Beachrock
8. Beach sand 9. Rock pavement 10. Reef-flat sand	
11. Seagrass	11.1 Low density seagrass/macroalgae 11.2 Medium density seagrass 11.3 High density seagrass
12. Lagoon patch reef 13. Lagoon sand	
14. Fore-reef slope (not sand)	14.1 Coral rubble with coralline algae 14.2 Fore-reef slope coral spurs with coralline algae 14.3 Rocky fore-reef slope 14.4 Fore-reef slope (rubble and sand) 14.5 Fore-reef slope with coral
15. Fore-reef slope sand	

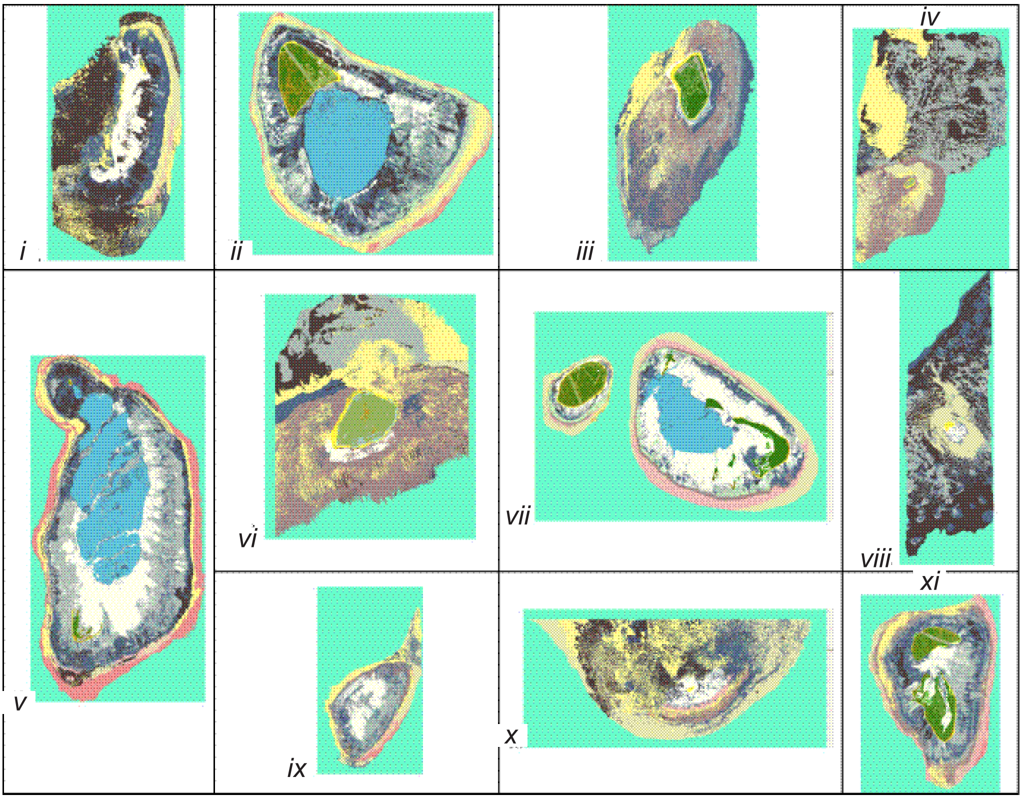

Figure 2. Habitat maps of the Amirantes Islands: i. African Banks, ii. Alphonse, iii. Marie-Louise, iv. Boudeuse, v. Bijoutier & St François, vi. Desnoeufs, vii. D'Arros & St Joseph, viii. Etoile, ix. Remire, x. Sand Cay, xi. Poivre. See Figure 1(ii.) for island locations.

of a small boat. The boat was driven at a constant speed along a consistent line of bearing perpendicular to the beach from a depth of *ca*. 20 m to the shallow (*ca.* 3 m), stopping at one minute intervals to record the substratum type and the GPS position.

Image pre-processing

Prior to processing of the remote sensing data, the effects of scattering and absorption in the atmosphere were corrected using the Atmospheric Correction Now (ACORN) algorithm to retrieve radiance values at the water surface (ACORN, 2001). Raw data were geo-corrected using ground control points and a first order polynomial model was applied to correct for linear offset, with nearest neighbour resampling (Erdas inc., 1997). Strips were mosaiced and a band-wise linear colour balancing model was applied to minimise across-track variance, with histogram matching to adjust for radiance offset (Rees, 1990).

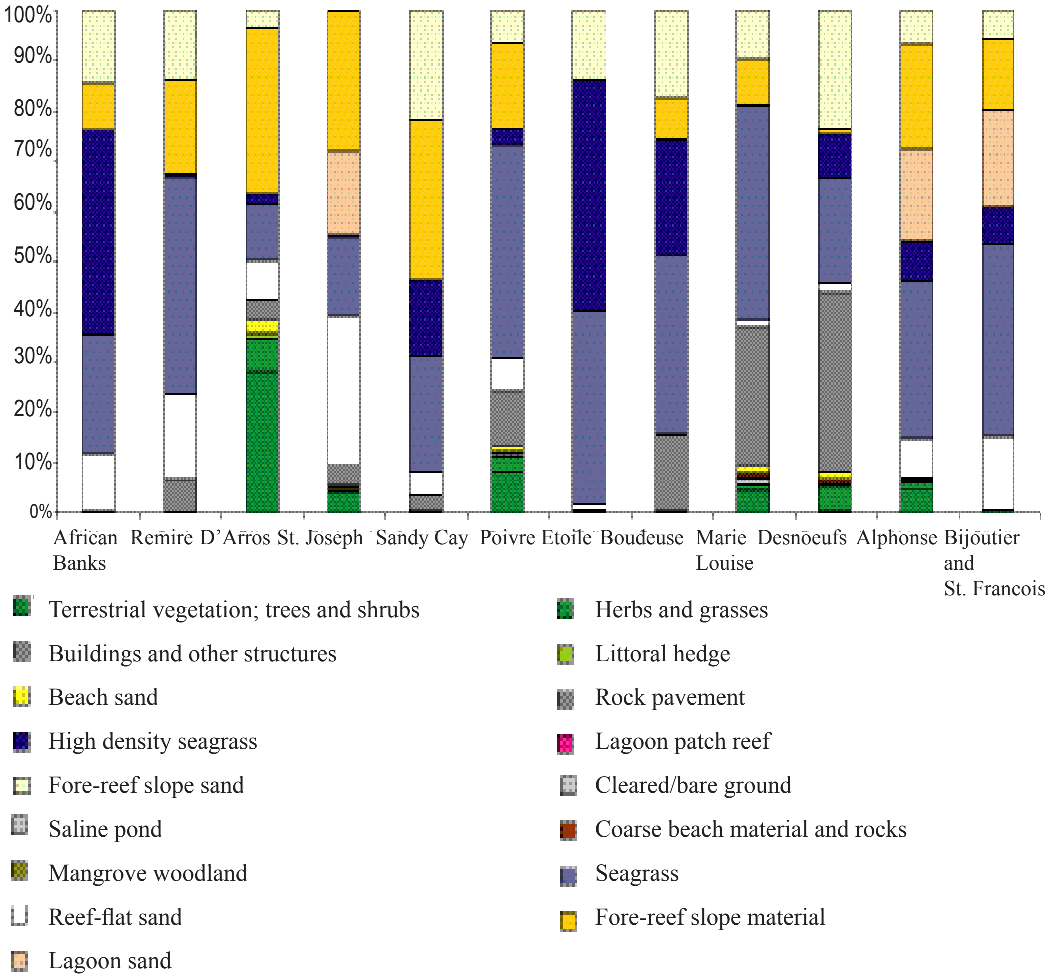

Figure 3. Tier 1 breakdown of habitat coverage in the Amirantes Islands, as mapped by the Compact Airborne Spectrographic Imager (CASI).

Water column correction was performed using the method outlined by Purkis and Pasterkamp (2004), in which the formulae derived by Bierwirth *et al.,* (1993) are adjusted to account for the refractive influence of the water surface at the air/water boundary and rearranged to solve for substratum reflectance, R_b:

$$R_b = \frac{1/0.54 \times R_z - (1 - e^{-2kjz})\, R_w}{e^{-2kjz}} \qquad \text{Equation 1}$$

where the radiance just above the water surface R_{rs} *(z=a)* was provided by atmospherically-corrected imagery, the water column reflectance of optically deep water (R_w) was estimated from image statistics, and the depth *(z)* of each pixel was extracted from a bathymetric map generated using the Stupmf *et al.,* band ratio model (2003). For each band, the diffuse attenuation coefficient *(k)* was estimated through regression

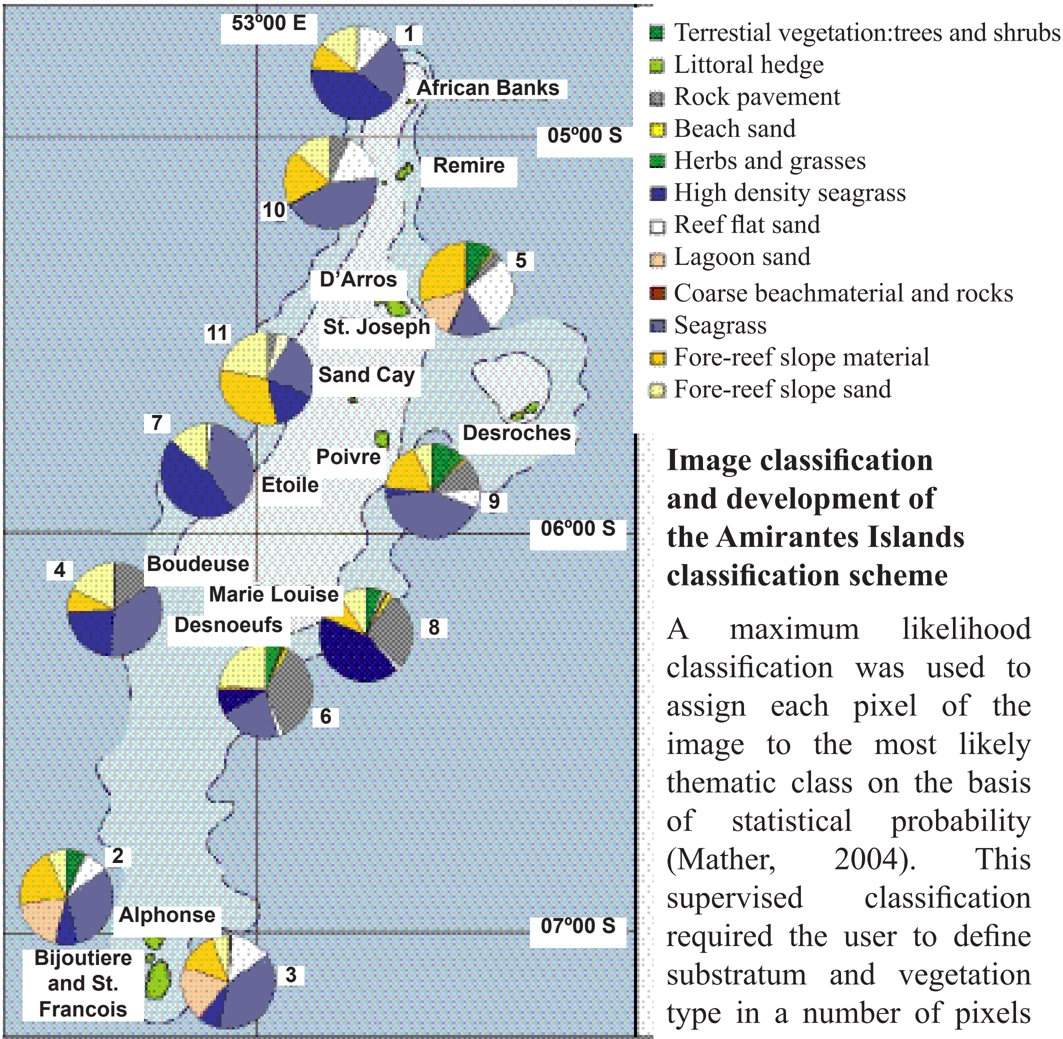

Figure 4. Tier 1 breakdown of habitat coverage in the Amirantes Islands. Pie chart key: 1. African Banks, 2. Alphonse, 3. Bijoutier & St François, 4. Boudeuse, 5. D'Arros & St Joseph, 6. Desnoeufs, 7. Etoile, 8. Marie-Louise, 9. Poivre, 10. Remire, 11. Sand Cay.

of digital data taken from a series of white targets deployed at known and varying depths. The gradient of the regression line of log-transformed data plotted against depth yielded an estimation of *k*.

Image classification and development of the Amirantes Islands classification scheme

A maximum likelihood classification was used to assign each pixel of the image to the most likely thematic class on the basis of statistical probability (Mather, 2004). This supervised classification required the user to define substratum and vegetation type in a number of pixels where the content had been verified in the field. Training signatures were thus established to analyse reflectance over each strip of imagery across a number of spectral subclasses. In this way, a statistical population of reflectance values was built up for each island habitat. For each individual flight strip, as much heterogeneity was captured in the images as possible. A total of 2,018 signatures were collected and evaluated before being merged into a subset of 720 signatures. This merging was undertaken on the basis of spectral similarity, using the Erdas Imagine signature editor (Spencer *et al.,* 2009). As a parametric classifier, the maximum likelihood function assumes that each thematic sample category can be represented by a Gaussian probability density function, derived from the varying image radiance across each spectral band (Thomas *et al.,* 1987). Given the user-specified training signatures, it is possible to compute the statistical probability of a pixel belonging to each thematic spectral class.

At the regional scale, individual island habitat map keys were combined to produce an overall scheme for the Amirantes Islands. A habitat classification scheme with a hierarchical structure was developed to accommodate user requirements, field data availability and the spatial and spectral resolution of the CASI sensor. The classification process yielded 15 classes at Tier 1; four of these Tier 1 classes were subsequently sub-divided into a series of Tier 2 classes, totalling 24 habitat classes (Table 2).

Map Validation

Classification accuracy was assessed with field data collected *in situ* on the eight islands that were visited. Large, heterogeneous patches of the island habitat maps were randomly selected and their central coordinates were loaded into a hand-held GPS. These locations were visited in the field and the habitat type at each location was recorded in terms of the overall classification scheme. Validation data were compared against the habitat class assigned by the mapping process and scored as being correct or incorrect. The overall accuracy was expressed as the proportion of patches that were correct (Congleton, 1991). This approach encompassed both the locational and thematic aspects of accuracy. Where islands could not be visited, a similar approach was undertaken by comparing the maps with oblique aerial photographs of the islands. Habitats were identified in these photographs by three independent validators with expert knowledge of western Indian Ocean shallow water geomorphology and ecology.

Using the conversion tools in ArcMap (ArcGIS 9), a raster to vector conversion was carried out on the resultant habitat maps and the cover of the different habitat types was computed with respect to both the first and second tiers of the classification scheme.

RESULTS

Habitat classification scheme

Image classification provided a clear and accurate representation of the heterogeneity apparent in the raw images (Fig. 2). The overall accuracy of the maps when ground-truthed ranged from 67-77%.

Seagrasses constituted the most widely represented shallow marine habitat class (13-84% cover), encompassing low, medium and high density communities. The most abundant seagrass species were *Thalassodendron ciliatum* and *Thalassia hemprichii*. Fore-reef slope material, reef-flat sand and lagoon sand were also abundant (Fig. 3).

Habitat types particularly in subaerial conditions (Fig. 4) on the islands on the western margin of the Amirantes Bank were characterised by a restricted range of terrestrial and littoral habitats, whereas those on the eastern side of the Bank were more diverse in habitat, particularly in subaerial conditions.

DISCUSSION AND CONCLUSIONS

The map classification scheme incorporated the variable geomorphological nature of the islands within a consistent, standardised approach. This was largely made possible by the use of the CASI sensor. The image-based classification employed data from an extensive set of training signatures, which represented a combination of user and computer input into the classification process.

The hierarchical structure of the classification scheme reflected the capability of the CASI sensor to resolve the various tiers at a comparably high spectral resolution. The scheme employed both geomorphological structure and benthic characteristics as class descriptors. In doing so, it drew on both of these aspects of the remotely-sensed image. Langrebe (1998) describes three domains in which spectral datasets can be viewed: image space, spectral space and feature space. Geomorphological zones have more distinct contextual boundaries than benthic assemblages and, as such, the position of a pixel in typical reef zones (Done, 1983), determined by viewing the image space, can facilitated contextual editing. The classification algorithm on the other hand, operated in feature space to fully exploit the spectral information of the image.

The inclusion of a substantial set of training signatures facilitated the application of image statistics in the development of the habitat classification scheme. A top-down approach in resolving the different habitats from the CASI data was found to be an appropriate technique in devising the habitat classification scheme for the Amirantes Islands.

Seagrasses were the most widely represented class in the maps as the extensive reef-flats provided the habitat needs of the genera *Thalassodendron and Thalassia*. Their requirements include an adequate rooting substratum, sufficient immersion in seawater and adequate illumination to maintain growth (Hemminga and Duarte, 2000). Seagrasses have broad, splayed leaves, a growth form that maximises light capture. These appeared extensive when viewed from above and remote sensing thus lends itself well to mapping their spatial coverage. They were, therefore, well represented in habitat coverage statistics, alongside the equally extensive cover of reef-flat and lagoonal sands (Fig. 3). Conversely, some habitats, such as beach sand and the fore-reef categories, appeared to be limited in their spatial extent being characterised by relatively steeply sloping surfaces.

There was a clear distinction in the habitat maps between stable, vegetated islands located on a rock or reef platform (e.g. Alphonse) and islands characterised by ephemeral sand cays surrounded by extensive seagrass beds (e.g. Etoile). These differences relate to the presence or absence of suitable antecendent topography for postglacial coral growth and the variation in environmental parameters such as wave and current fields across the Amirantes Bank.

Comparisons of habitat coverage between the 13 islands of the Amirantes revealed biological and geomorphological trends that would not have been apparent without a standardised classification scheme applied at the regional scale. This study demonstrates how remotely-sensed imagery can be used for resource assessment and regional comparison of habitat coverage. Such an approach would not have been possible in a cost-efficient manner through field surveys alone. With repeat surveys, such comparisons can be extended to the temporal domain, adding to its usefulness in coastal management.

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