Using High Resolution Multispectral Imaging to Map Pacific Coral Reefs in support of UNESCO's World Heritage Central Pacific Project

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ABSTRACT

Concerns over worldwide declines in marine resources have prompted the search for innovative solutions for their conservation and management, particularly for coral reef ecosystems. Rapid advances in sensor resolution, coupled with image analysis techniques tailored to the unique optical problems of marine environments have enabled the derivation of detailed benthic habitat maps of coral reef habitats from multispectral satellite imagery. Such maps delineate coral reefs' main ecological communities, and are essential for management of these resources as baseline assessments. UNESCO's World Heritage Central Pacific Project plans to afford protection through World Heritage recognition to a number of islands and atolls in the central Pacific Ocean, including the Phoenix Archipelago in the Republic of Kiribati. Most of these islands however lack natural resource maps needed for the identification of priority areas for inclusion in a marine reserve system. Our project provides assistance to UNESCO's World Heritage Centre and the Kiribati Government by developing benthic and terrestrial habitat maps of the Phoenix Islands from high-resolution multispectral imagery. The approach involves: (i) the analysis of new Quickbird multispectral imagery; and (ii) the use of MARXAN, a simulated annealing algorithm that uses a GIS interface. Analysis of satellite imagery was performed with ENVI®, and includes removal of atmospheric effects using ATCOR (a MODTRAN4 radiative transfer model); de-glinting and water column correction algorithms; and a number of unsupervised and supervised classifiers. Previously collected ground-truth data was used to train classifications. The resulting habitat maps are then used as input to MARXAN. This algorithm ultimately identifies a proportion of each habitat to be set aside for protection, and prioritizes conservation areas. The outputs of this research are being delivered to the UNESCO World Heritage Centre office and the Kiribati Government as baseline assessments of these resources and to assist in marine reserve planning.

Keywords: Quickbird, multispectral imaging, coral reefs, benthic habitat maps, marine reserve design, coastal zone management

1. INTRODUCTION

The Phoenix Islands are the central island group of the Republic of Kiribati, with the Gilbert Islands (or Tungaru Group) to the west, and the Line Islands to the east. The Phoenix Group (174.8° W to 170.1° E Longitude and 2° to 8° S Latitude) comprises 8 low-lying islands (6 depicted in Figs. 2-7), 3 of which definable as classical atolls (Fig. 3-5). Two outlying islands north of the equator, Baker and Howland, are geologically contiguous but are United States dependencies, thus not included in Kiribati's Phoenix Group. Located approximately one thousand nautical miles north of Fiji, these are among the remotest islands in the south Pacific. All but 2 of the islands are currently uninhabited. Human settlement and use of the islands have been sporadic for over 150 years, and current populations on each of the 2 inhabited islands (Kanton Atoll and Enderbury Island) do not exceed 50 to 60 individuals. This archipelago is therefore for the large part free of the degrading influence of fishing, coastal development and other environmental degradation common in coastal areas around the world, and resembles near-pristine marine conditions[1].

The scientific literature on the Phoenix islands is very limited and is primarily derived from assessments related to military use and decommissioning of the islands following the second World War[2]; and limited marine assessments of

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Kanton Atoll in the 1970s[3,4]. The first and, to date, only comprehensive account of the marine environments of the Phoenix archipelago was compiled by the New England Aquarium in 2000[5,6]. Terrestrial and seabird studies were conducted in the 1960s by the Smithsonian Institution[7] and together with more recent surveys[8] indicate that the Phoenix Islands are one the most prolific and globally important seabird nesting grounds in the world. It is clear that while the Phoenix Islands group is one of the earth's last intact coral archipelagos, scientific information for these islands remain scarce. The coral reef habitats and bird populations of the islands are unique and virtually untouched, but their protection is incomplete, as the islands have been effectively protected throughout this century primarily by their isolation.

UNESCO's World Heritage Centre oversees conservation and management of natural resources of outstanding global value, but currently, only 9 of 788 natural World Heritage sites are marine; and the Pacific region is especially under-represented. To address these deficiencies, in 2004 UNESCO launched the World Heritage Central Pacific Project, which focuses on affording protection through World Heritage recognition for a number of islands and atolls in the central Pacific Ocean, a marine biodiversity hotspot including the Republic of Kiribati. The Kiribati government, in partnership with UNESCO, is pursuing designation of the Phoenix Islands as a World Heritage site, and is in the process of identifying priority sites deserving of special protection. Until now, these atolls and islands have lacked natural resource maps that would facilitate the identification of priority areas to include in a marine reserve system. Our project provides technical assistance to UNESCO's WH Centre and the local government jurisdiction by providing: 1) analysis of newly acquired Quickbird multispectral imagery aimed at obtaining the first benthic habitat maps for the coral reefs of the Phoenix islands; and 2) examples of the application of a mathematical algorithm that uses the remote sensing products to identify priority sites for conservation.

The Government of Kiribati is also working to complement the protection of the Phoenix Islands with new legislation. As of 2006, the islands and a surrounding zone of 60 nautical miles around each of them constitute the Phoenix Islands Protected Area (Fig. 1). Small isolated, the Phoenix Islands are most vulnerable to resource extraction from inshore fisheries by unlicensed illegal foreign vessels. Illegal shark fishing practices are of great concern; other high value fisheries posing significant threats include the live reef fish trade, primarily for aquaria use. Terrestrial threats include the potential for unplanned settlements and tourism developments; and facilities related to satellite communication or space programs. These activities can potentially bring serious harm to the seabird population by introducing invasive species and reducing nesting habitat, and would also damage and deplete the surrounding reefs. Climate change is an over-arching threat for these low-lying islands, due to sea level rise and warming sea surface temperatures that may result in coral bleaching. In 2002, the Phoenix Islands experienced a bleaching event, but the reefs are now showing rapid signs of recovery. The bleaching event and ongoing recovery highlighted that one of the most critical management needs for this archipelago is the compilation of natural resource maps for the coral reefs and terrestrial habitats, to document the boundaries of benthic and vegetation habitats to be used as a baseline for future assessments (e.g. for change detection purposes).

The ever-increasing need for ecosystem approaches to coral reef conservation benefits from the use of remote sensing tools to characterize landscapes in biologically meaningful ways. Given the small patch size of coral reef benthic features, spatial resolution plays an important role in mapping coral reef benthic habitats. The recent launching at the turn of the millennium of very high resolution (< 5m) satellite sensors provided a new opportunity to map, assess and monitor natural resources at a resolution much higher than previously possible. Quickbird (DigitalGlobe) is to date the satellite with the highest resolution commercially available, and has been used widely for resource assessments in marine and terrestrial habitats[9]. Generally, land-cover or benthic habitat maps can be combined with in-situ field data to identify the biological diversity associated with each habitat, assuming that benthic or land cover classes broadly correspond to the ecological niches for those species. In recent years, new mathematical algorithms have been developed to be used in conjunction with remotely-sensed data in order to identify priority areas for biodiversity conservation, ultimately for the design of marine reserves. One such model is MARXAN, a simulated annealing algorithm that identifies potential areas representing all benthic habitat types and marine biodiversity data while at the same time minimizing the selected area, to balance economic and extractive needs with conservation goals[10]. Given spatial data on the extent and distribution of marine habitats (e.g., from the analysis of multispectral imagery), and other relevant information such as field data, the algorithm identifies a network of priority sites that represent all conservation areas of interest in a sensible spatial arrangement that minimizes both the area and the perimeter. In light of the expressed interest of the Kiribati government to designate marine protected areas within the Phoenix Islands as part of its World Heritage nomination, one of the explicit goals of this project was to identify areas on each island that deserve maximum protection based on the distribution of two biologically significant parameters: (1) presence of live coral and (2) land vegetation suitable for seabird nesting (shrubby vegetation). This was accomplished from the analysis of Quickbird data purchased by the Remote Sensing Center at the Naval Postgraduate School for 6 of the 8 islands comprising the Phoenix Archipelago; the resulting classifications were aimed at isolating the 2 classes of interest (live coral cover and shrubby vegetation cover) and used as inputs in MARXAN. Two of the 8 islands in the Phoenix archipelago lacked good quality Quickbird imagery and were therefore not included in this study.

Table 1. Imagery used

Island/Atoll name	Latitude	Longitude	Source Imagery	Acquisition Date	Spatial Resolution
Kanton	2.8198 S	171.671 W	Quickbird	03-02-2007	2.5
Orona	4.5427 S	172.208 W	Quickbird	12-25-2006	2.6
Nikumaroro	4.6734 S	174.5334 W	Quickbird	02-04-2004	2.4
Enderbury	3.1309 S	171.0888 W	Quickbird	02-25-2007	2.4
Manra	4.4536 S	171.2405 W	Quickbird	01-02-2006	2.4
McKean	3.6057 S	174.1246 W	Quickbird	06-30-2005	2.5
Rawaki	3.7216 S	170.7125 W	None available		
Birnie	3.5712 S	171.5756 W	None available		

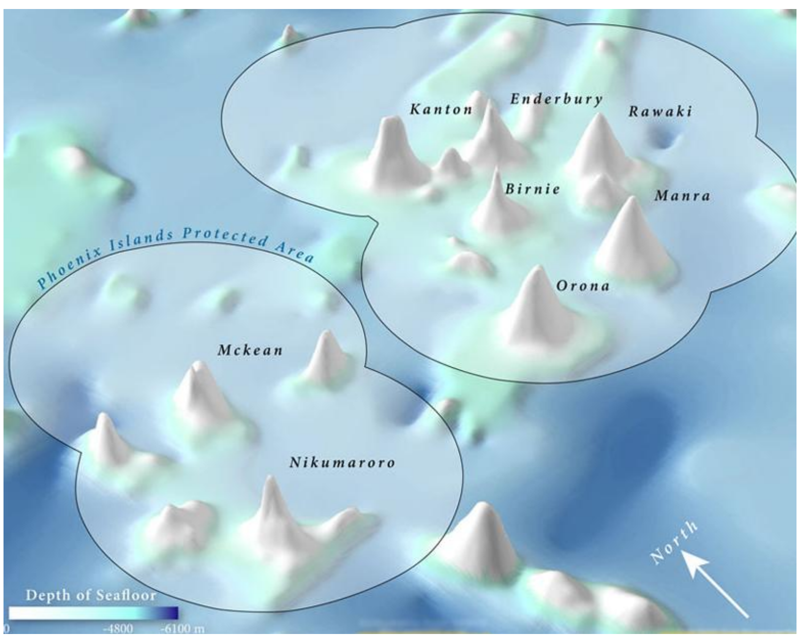

Figure 1. The Phoenix Islands group in the central equatorial Pacific Ocean, and the extent of the Phoenix Islands Protected Area.

Fig. 2 Quickbird image of Enderbury Island

Fig. 3. Quickbird image of Kanton Atoll

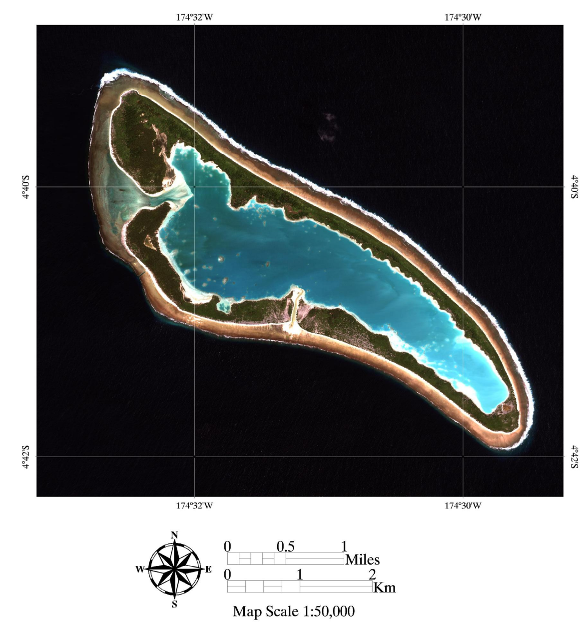

Fig. 4 Quickbird image of Nikumaroro Atoll

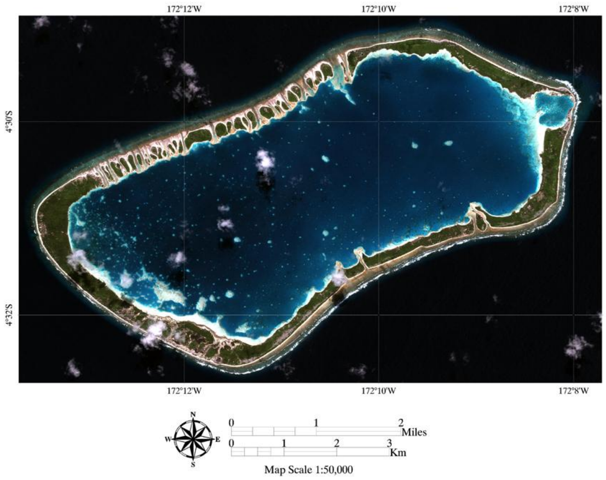

Fig. 5 Quickbird image of Orona Atoll

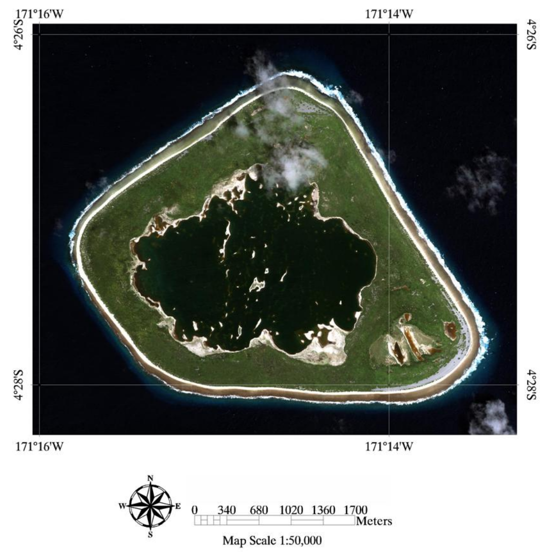

Fig. 6 Quickbird image of Manra Island

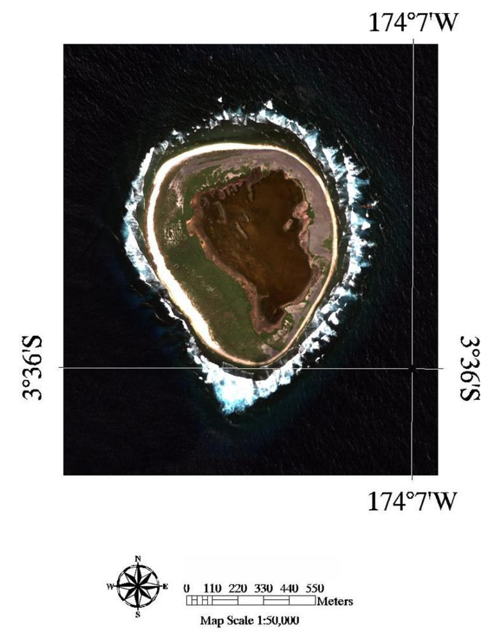

Fig. 7 Quickbird image of McKean Island

2. MATERIALS AND METHODS

2.1 Radiance conversion and Atmospheric Correction

All image analyses were performed in ENVI (® ITT VIS Corp.). The raw Quickbird images for the 6 islands (Table 1) were spatially subset to remove unnecessary portions of each image (e.g. open ocean regions, clouds and cloud shadows) and reduce processing time. QuickBird data is delivered as raw digital numbers (DN). To perform temporal analysis or comparison to other multispectral images, DN need to be converted to top-of-atmosphere spectral radiance and then to reflectance on the ground. The radiometrically corrected image pixels were multiplied by the band-specific, absolute radiometric calibration factor, and divided by the effective bandwidth to obtain spectral radiance in units of $W / m^2 / sr / \mu m$.

For atmospheric correction, the ATCOR algorithm (© Leica-Geosystems GmbH) was used. ATCOR is a spatially-adaptive fast atmospheric correction algorithm working with a database of atmospheric correction functions stored in look-up tables[11]. The database consists of a broad range of atmospheric conditions: different altitude profiles of pressure, air temperature, and humidity; several aerosol types; ground elevations from 0 to 2.5 km above sea level, solar zenith angles ranging from 0° to 70°, and visibilities (surface meteorological range) from 5 km to 120 km. ATCOR is based on the radiative transfer code of MODTRAN[12] developed by the U.S. Air Force Research Lab, and performs the atmospheric correction for image data by inverting results of MODTRAN 4 calculations previously compiled in LUT's. ATCOR 2, the module developed specifically for flat terrain (used here because of the very low relief of the islands), calculates a ground reflectance image in each spectral band in two steps: the first step assumes an isotropic reflectance law neglecting the neighborhood of each pixel, and the second step accounts for the influence of the neighboring background (adjacency effect). For each image, the following ATCOR parameters were addressed for each atmospheric correction: acquisition date and time (from each image metadata file); output scale factor (default = 4); sensor calibration file (a calibration file obtained from Quickbird's Absolute Calibration Factors found in the image metadata file, and the sensor's effective bandwidth); solar zenith angle and ground elevation (both obtained from the image metadata file); scene visibility (in km, estimated from the image and if available, an archive of meteorological data for that region); and finally, a model for the solar region that is chosen first by selecting an aerosol type (in this case "maritime"), then an atmosphere type (for our images, "tropical"), and taking into account the sensor tilt angle and the relative azimuth between the satellite and the sun. Haze in the images could potentially be estimated and removed with an ATCOR module, but this step was not performed for this project because currently the algorithm does not perform well over water, and our analyses encompass predominantly marine scenes.

2.2 Sea surface correction (glint removal)

A common problem associated with high resolution imagery over water is the specular reflection of sunlight on ocean surfaces, due to wind generated waves and swell. Four of the 6 Quickbird images of the Phoenix Islands presented sunglint that would have confounded any further analysis of the imagery. This problem was addressed with a technique first described in 2003[13] and later modified[14] to remove sunglint from remotely sensed imagery. The method exploits the maximum absorption and minimal water leaving radiance of the NIR band, which was used to characterize the spatial distribution of relative glint intensity. The image was scaled to absolute glint intensities which were subtracted from the visible bands, resulting in glint intensities that were reduced or eliminated in the output image. Two assumptions of this method are: (1) water exhibits very strong absorption of NIR wavelengths; (2) the real index of refraction in the visible bands is nearly equal to the NIR band. From these premises, a linear relationship exists between the NIR and visible bands given that the amount of light that is reflected from the water column in the NIR band is a good indicator of the amount of glint reflected in the visible bands[13].

Several ROIs were selected around each atoll and island in areas exhibiting a range of sun glint, where the optically deep water appeared homogenous. Pixels from these regions were used to regress the NIR band against each visible band. If the slope of this line for band i is b_i, then all the pixels in the image can be deglinted in each visible band by applying the equation:

$$R_i' = R_i - b_i * (R_{NIR} - Min_{NIR}) \qquad (1)$$

Where R_i' is the deglinted pixel value in visible band i; R_i is the glinted pixel value, b_i is the regression slope between the NIR band and the visible band, R_{NIR} is the pixel value in the NIR band, and Min_{NIR} represents the NIR brightness of a pixel with no sunglint and is estimated as the minimum NIR value found in the ROI sample.

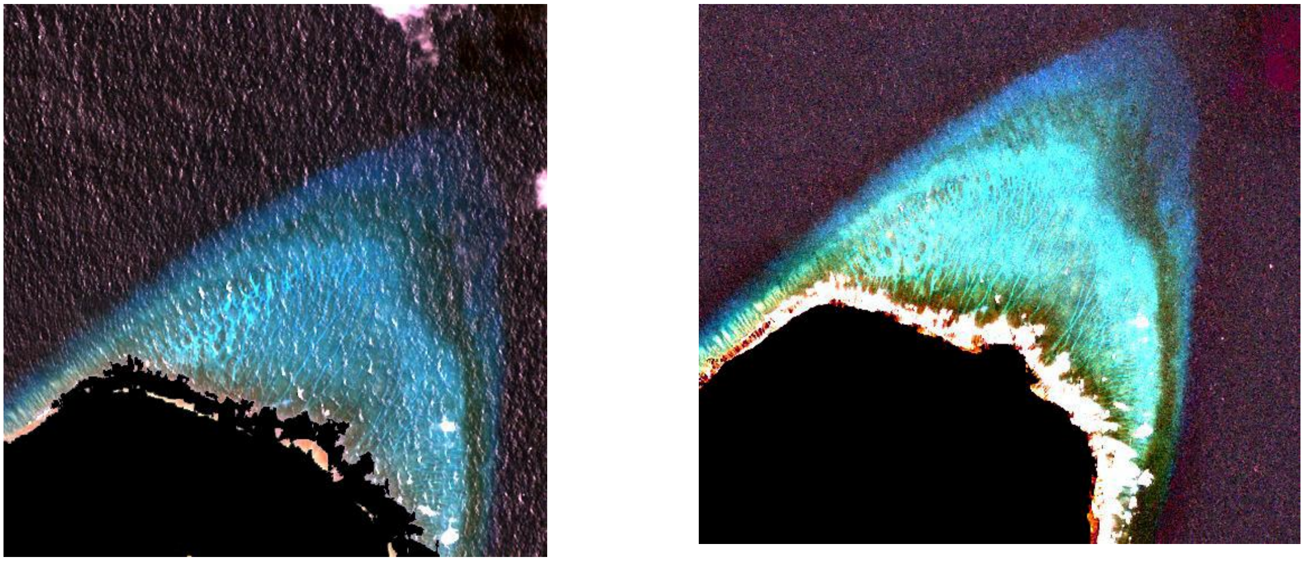

Fig. 8. Northeast subset of Enderbury Island before (left) and after (right) the sea surface correction

2.3 Water Column Correction

A commonly cited difficulty with remote sensing of marine environments is the confounding influence of variable depth on bottom reflectance[15]. Removal of this effect with empirical methods would require knowledge of depth for each pixel in the image, and of the attenuation characteristics of the water column, two requirements that are often unrealistic for most remote sensing projects, where ground information is often limited. As a compromise, an image-based approach can be applied to compensate for the effect of variable depth when mapping benthic features. Classification accuracy of coral reefs can be improved significantly by compensation for the variable and wavelength-dependent light attenuation in the water column[16]. We performed the water column correction prior to habitat classification, for each of the 6 islands. The method is based on a model first developed in 1981 by D.R. Lyzenga[17] and modified by P. Mumby[16] in 1998. This technique produces a depth-invariant band for each pair of visible spectral bands. Regions of interests were selected in each image from uniform substrate (sand) over variable depths at random locations for all 6 islands. Their pixel values were transformed to Natural logarithm values. We then calculated ratios of attenuation coefficients, k , for each visible band pair. Regression plots were created using the transformed reflectances. The slope of the plots represents the attenuation coefficient for the band pair. In particular, to calculate the ratio of attenuation coefficients $\frac{k_i}{k_j}$, the variance of band i (σ_{ii}), and covariance between bands i and j (σ_{ij}) were calculated[15] and used to obtain the ratio of attenuation coefficients $\frac{k_i}{k_j}$:

$$\frac{k_i}{k_j} = a + \sqrt{\left(a^2 + 1\right)} \qquad (2)$$

Where

$$a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}} \qquad (3)$$

The bands plotted to calculate the attenuation coefficients were 3 different combinations of the visible bands of each Quickbird image (green vs. blue, red vs. blue and red vs. green). Before the depth-invariant indexes were processed, the images were masked to exclude land and other emergent features, such as breaking waves. Once the ratio of attenuation coefficients was calculated as in (2) above, the three depth invariant bands were created according to the equation:

$$\text{depth-invariant index}_{ij} = \ln\left(L_i\right) - \left[\left(\frac{k_i}{k_j}\right)\ln\left(L_j\right)\right] \quad (4)$$

Each pair of spectral bands produced a single depth-invariant band. The three depth-invariant bands obtained from each image are now corrected for the influence of variable depth on bottom reflectance, and were used to classify the image.

2.4 Benthic classifications

Supervised classifications aimed at identifying live coral cover were performed on each image obtained from steps 2.1 through 2.3 outlined above, and used the field information on bottom/ ground cover collected by D. Obura[6] and G. Stone[5] as the training dataset. Separate classifications on land were conducted to delineate shrubby vegetation, as a proxy for seabird nesting habitat. Regions of Interest (ROIs) were selected on areas in the images corresponding to geocoded survey sites where quantitative analyses of benthic community structure had been carried out in the field[5,6]. Each ROI mean was assigned to a particular benthic cover (the class with the dominant cover) among the major algal and coral groups, and physical substrate (sand and consolidated carbonate sediments). The ROI means were imported as Endmember spectra and used in the Maximum Likelihood supervised Classification, a method that assumes that the statistics for each class in each band are normally distributed, and calculates the probability that a given pixel belongs to a specific class. The relevant classes (i.e., live coral cover for the marine environment and shrubby vegetation for the terrestrial environment) from each classification output image were isolated and used as input to the MARXAN analyses.

2.5 MARXAN analyses

The MARXAN algorithm was obtained from the Ecology Centre of the University of Queensland. MARXAN analyses require some preprocessing to assimilate the data to a specific format. ArcGIS's PATCH analyst tool was used to subdivide the area encompassed by each island in hexagonal polygons. A hexagonal polygon is a stacking shape that most closely approximates a circle, and therefore has the lowest edge/area ratio of all stacking shapes: the lower edge effect is desirable for habitat analysis, hence the choice of hexagonal polygons in MARXAN. The hexagons, covering the extent of each island and its reefs, represent the planning units on which the site selection algorithm operates. We chose the planning unit to be 5 hectares in size, a decision made taking into consideration the spatial extent and variability of the habitat features of interest for all of the islands (live coral cover habitat and shrubby vegetation distribution, also called "conservation targets") obtained from the remote sensing analyses, as well as processing time. The conservation targets were set at 30% for each habitat, meaning that no less than 30% of each conservation target was to be selected by MARXAN. Since a "cost function" needs to be specified for MARXAN to select the minimum area that meets the conservation targets, the inhabited islands (Kanton and Enderbury) were assigned a higher cost - even the small populations present on these islands have some depleting effect on the islands' resources. MARXAN aims to identify areas with low perimeter values, and does so with the required input of the "Boundary length Multiplier (BLM)", which determines the importance given to the boundary length relative to the areas of the priority sites for conservation. When the BLM is small, the MARXAN algorithm will concentrate on minimizing area, even if the priority sites for conservation are disconnected from one another; whereas when the BLM is larger, the algorithm will put highest priority on minimizing the boundary length of the areas of high biodiversity significance, and the sites selected will be more clumped. BLM values of 0.05 and 0.025 were used in different test runs of the algorithm. MARXAN was run every time specifying 1,000,000 iterations and 10 runs.

3. RESULTS AND DISCUSSION

Because of their remoteness and isolation, the Phoenix Islands remain largely unknown to science. They are also mostly unfamiliar to the general public, who may have heard of these islands only perhaps because they were featured in the literature (Melville's famous 1851 tale "Moby Dick"), or more recently, because they were the site of an expedition by The International Group for Historic Aircraft Recovery, in search of Amelia Earhart's plane wreckage and remains (thought to have crashed on Nikumaroro Atoll in 1937). While scientific information is scarce, it is clear that their remoteness and isolation has also fostered the development of healthy reefs and large populations of nesting seabirds on these atolls and islands. The benthic maps showing the extent and distribution of live coral shown here (e.g., Fig. 9-11) are the first to be produced for these marine habitats; and the maps of vegetation cover on the terrestrial habitats now delineate the boundaries of important seabird nesting habitat. Once the maps will be statistically assessed for accuracy with additional ground data, they can be delivered to UNESCO's World Heritage Centre and the Government of Kiribati for use as a baseline assessment of these resources and for change detection analyses with future image acquisitions.

To improve the detail and accuracy of these classifications, additional ground information is needed, but field surveys in this remote archipelago are difficult to plan and expensive to carry out. With the limited ground data available to date (collected entirely in one 5-weeks expedition in 2000), classification accuracy assessments cannot be carried out, as the limited field data was used fully for training the classifications.

The MARXAN analyses on the Phoenix Islands are still very preliminary. Difficulty was encountered in applying the algorithm to the wide spatial extent of the region of interest (6 widely spaced islands); but for illustrative purposes, we have included the results obtained for Ailinginae Atoll in a previous application of this algorithm (Fig. 12). This figure shows the island covered by the hexagonal planning units, and outlines the sites within this atoll that MARXAN recommends for selection in a marine protected area based on inputs of the extent and distribution of different benthic habitats and biodiversity data from field surveys. The recommended sites are shown in darker shades of red.

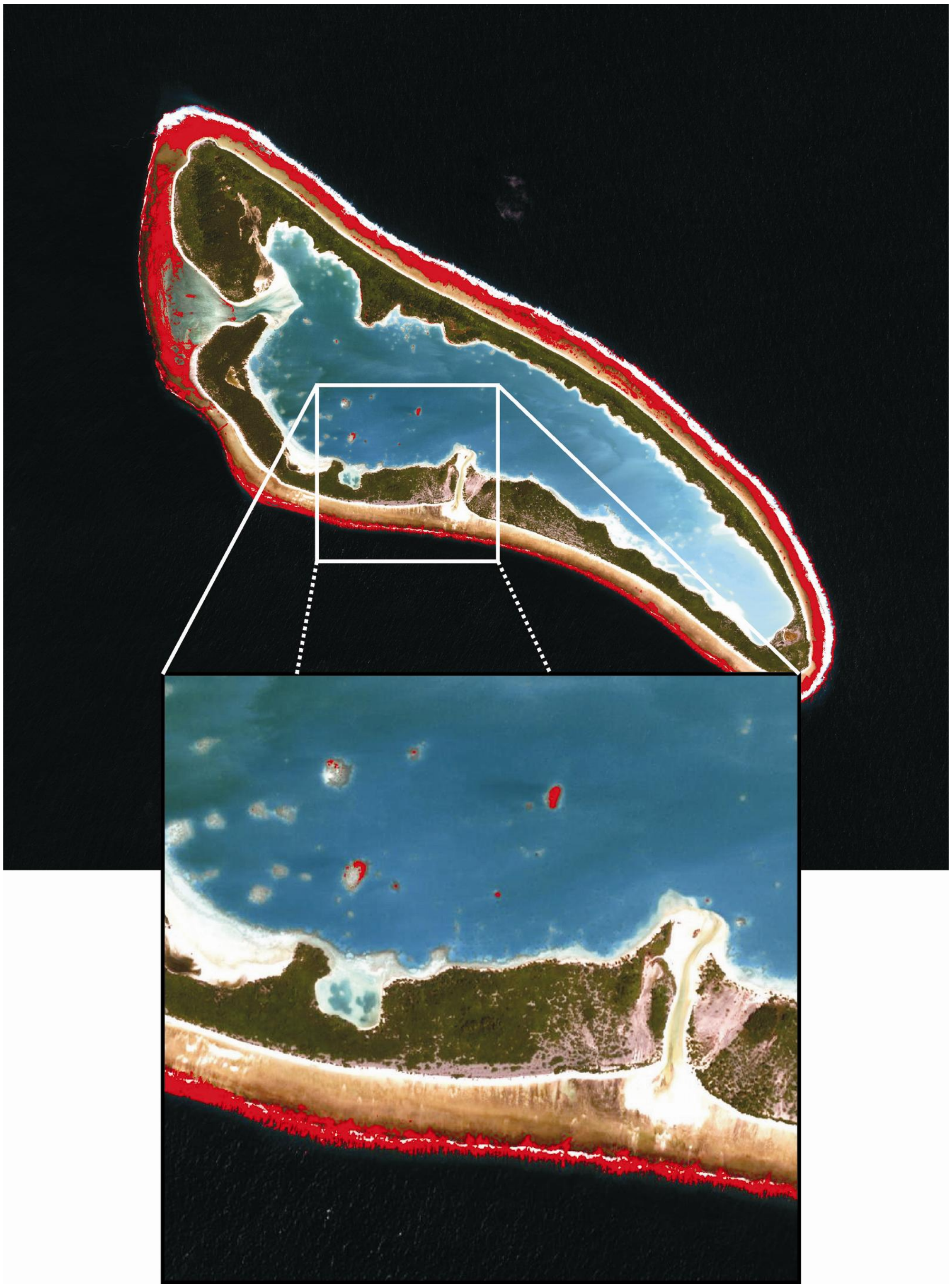

Fig. 9. Nikumaroro Atoll with the live coral class superimposed on the Quickbird RGB image

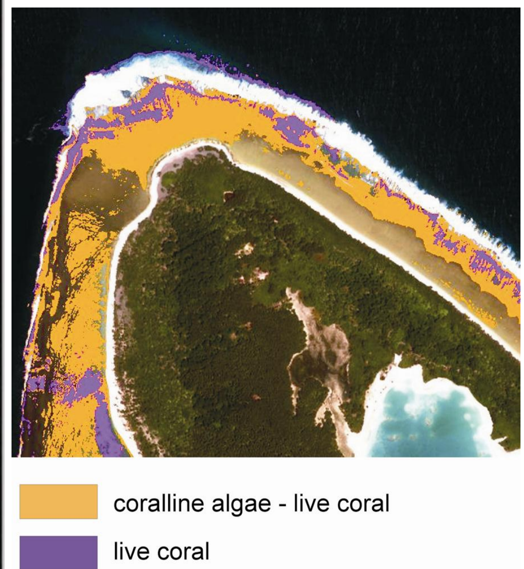

Fig. 10. Nikumaroro Atoll with overlaid benthic classification

Fig. 11. Enderbury Island with the live coral class overlaid on the RGB Quickbird image.

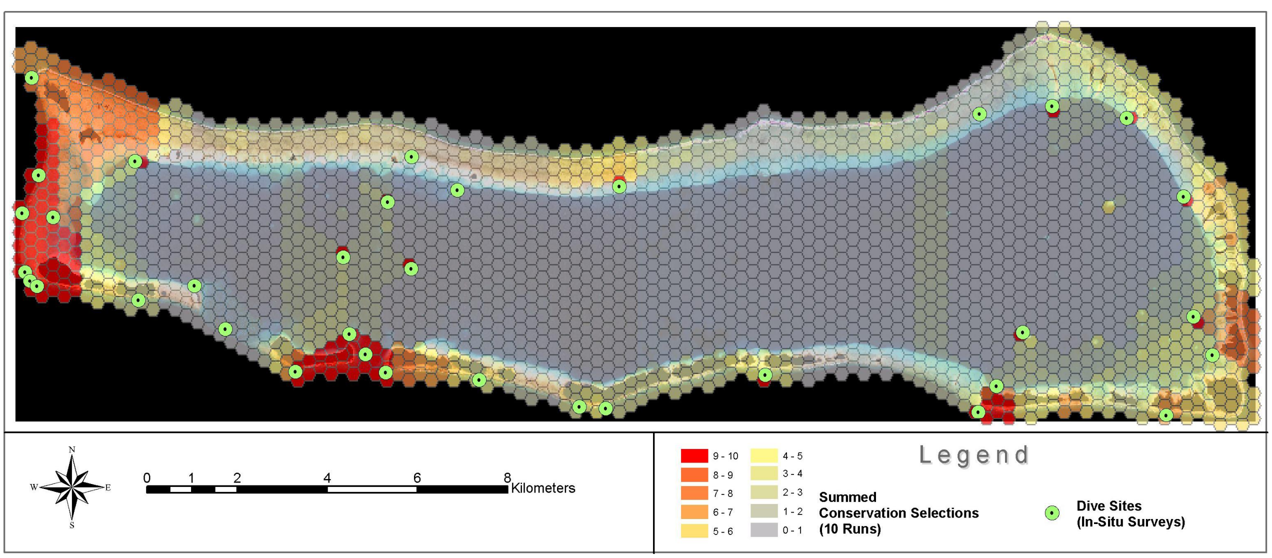

Fig. 12. Example of a Marxan scenario: hexagons covering the atoll represent the planning units; hexagons in red represent the selected areas for priority consideration in a marine reserve design.

Future work is aimed at perfecting the MARXAN analyses for all 6 islands considered in this study and delivering the products to the UNESCO's World Heritage Centre and the Government of Kiribati.

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