14

Satellite Remote Sensing of Coral Reef Habitats Mapping in Shallow Waters at Banco Chinchorro Reefs, México: A Classification Approach

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1. Introduction

Interest in protecting nature has arisen in contemporary society as awareness has developed of the serious environmental crisis confronting us. One of the ecosystems most impacted is the coral reefs, which while offering a great wealth of habitats, diversity of species and limitless environmental services, have also been terribly damaged by anthropogenic causes. One example of this is the oil spill from petroleum platforms (in the recent case of the Gulf of Mexico). The effects of global warming—such as the increase in the incidence and intensity of hurricanes and drastic changes in ocean temperature—have caused dramatic damage, such as the bleaching and decrease of coral colonies. In light of this devastating situation, scientific studies are needed of coral reef communities and the negative effects they are undergoing.

The case study presented in this work takes place in the Chinchorro Bank coral reefs in Mexico. These are part of the great reef belt of the western Atlantic, with a biological richness that inherently provides environmental, economic and cultural services at the local scale as well as worldwide. Nevertheless, these services have been weakened for decades due to overexploitation, inducing imbalances and problems in the zone. Over recent decades, numerous biological communities that house constellations of species—whose natural evolutionary process dates back million of years (Primack et al., 1998)—have been alarmingly degraded. If this trend continues, the entire evolution that is sustained by the life of these communities will disappear in a relatively short period of time.

This study clearly demonstrates the application of state-of-art Remote Sensing (RS) in coral ecosystems. It includes an analysis based on the application of Iterative Self Organizing Data Analysis (ISODATA) as a classifier for generating classes of benthic ecosystems present in a coral reef system, using satellite images (Landsat 7-ETM+).

2. Use of remote sensing in coral reef ecosystems

The observation of the earth using remote sensors is a most complete method for monitoring the most significant natural risks (Xin et al., 2007). In general, RS has proven to be a powerful tool in the overall understanding of natural and anthropogenic phenomena. It is particularly appreciated as a non-invasive, non-destructive technique with global coverage. Thus, satellite, airborne and *in-situ* radiometry have become useful tools for tasks such as characterization, monitoring and the continuous prospecting of natural resources.

Research using RS has been strengthened in recent decades as a result of the growing concern worldwide for the preservation of coral reef systems as natural reservoirs. This has been observed to be an excellent method for analysis, which aids in the holistic study of this complex ecosystem. In order to develop an approach that helps to safeguard these ecosystems, it is necessary to understand the physical, chemical, biological and geological dynamics that occur therein (Brock et al., 2006). Andréfouët & Riegl (2004) refer to RS as a technology that is now virtually mandatory for research where spatial and temporal precision is required. RS has gone from being a tool with no application to coral reef systems to one that is *per se* indispensable. Andréfouët & Riegl (2004) discuss four reasons why this change has occurred:

- The proliferation of new sensors for acquiring direct and indirect data for monitoring coral reefs,
- The proliferation and improvement of analytical, statistical and empirical approaches,
- Recognition of global climate change due to anthropogenic human impacts that are lethal to coral reefs and
- Improved integration of technology for the conceptual design of coral reef research.

RS techniques offer an option for marine habitat mapping to determine not only the location and amount of different benthic habitats (Kirk, 1994) but also how these habitats are distributed and the degree of connectivity among them (Rivera et al., 2006). Nevertheless, the study of coral reefs using RS presents several important limitations. For example, intense cloud cover in optical images, optical similarities among spectral signatures of benthic communities, attenuation of the deep component (specific to each coral reef ecosystem) as well as the spatial and spectral resolution of remote sensors. In spite of these limitations, satellite sensors are highly useful for mapping the benthic bottom (Mumby et al., 1997), monitoring changes in its ecology (Krupa, 1999) and defining management strategies (Green et al., 1996).

2.1 Determination of ecological characteristics of coral reefs using remote sensors

Some of the characteristics of coral reefs that can be calculated using RS are temperature, wave height, sea level, turbidity, amount of chlorophyll and concentration of dissolved organic matter. In the case of atmospheric variables, it is possible to determine cloud cover, amount of seasonal rainfall, presence of contaminants and incidental solar energy (Andréfouët et al., 2003). All these factors directly and indirectly influence coral reefs and determine their health status (Andréfouët & Riegl 2004). In addition, it is possible to determine the different benthic ecosystems present in the coral reefs, such as seagrass, type of bottom, algae communities and different types of coral. If the reef is near a tourist or vacation area, anthropogenic impacts can be determined by calculating the growth of the urban stain, vegetation coverage, the structure of the hydrographic basins, etc. Intrinsic conditions of coral reefs can be described, which are largely defined by the inflows and outflow and their transport of sediments and export of dissolved organic matter. This enables us to understand the patterns involved in coral whitening, among other events (Brock et al., 2006).

The coral reefs—located in relatively clear water—allow us to use passive optic sensors (Benfield et al., 2007). The more common satellite sensors that have been used to study this are SPOT, Landsat TM and ETM+ (Andréfouët & Riegl 2004; Benfield et al., 2007; Mumby 2006; Mumby et al., 2004; Mumby and Harborne 1998). Studies previously conducted (Green, 2000; Mumby et al., 1999) have observed that Landsat and SPOT images are suitable for mapping corals, sands, and seagrass, depending on their resolution. Nevertheless, it is important to note that various types of habitats can be represented in one Landsat image pixel (or others with less spatial resolution), which may limit classification abilities (Benfield et al., 2007). Previous studies conducted (Green, 2000; Mumby et al., 1999) have observed that according to the resolution of Landsat images, they are suitable for mapping sea corals, sands and seagrass. Based on this assumption, the data obtained from Landsat and SPOT are adequate for simple complexity mapping (3-6 classes, such as seagrass, sand, dead corals and some species of corals) but for more complex targets (7-13 classes) they are limited by their spatial and spectral resolution. (Mumby, 1997; Andréfouët et al., 2003; Capolsini et al., 2003). To a lesser extent, SeaWiFS (sea-viewing wide field of view sensors) have also been used, as well as IKONOS with higher spatial resolution, LIDAR and SONAR, among others (Andréfouët & Riegl 2004; Andréfouët et al., 2003; Brock et al., 2006; Elvidge et al., 2004; Liceaga-Correa & Euan-Avila, 2002; Hsu et al., 2008; Lesser and Mobley, 2007). It is important to note that analytical methods as well as spatial modeling, statistics and empirical methods at different scales and for different applications have been used in direct relation to ecological processes of reefs (Andréfouët & Riegl 2004). The use of airborne remote sensors, such as CASI (Compact Airborne Spectrographic Imager) with a high spectral or hyperspectral resolution, has gradually been increasing in this type of studies, to the extent that the specialists mention that mapping reefs using air or satellite sensors have proven to be more effective than fieldwork (Mumby, 1999). Nevertheless, field measurements cannot be discarded, since they provide us with the basis for corroborating the information obtained from satellite images. In addition, images from satellite sensors provide the opportunity to conduct multi-temporal monitoring (Helge et al., 2005) in order to identify the status of an ecosystem and predict possible future changes.

According to the above, it can be stated that studies applying RS in coastal ecosystems and, specifically, in coral reef ecosystems provide information and knowledge that can successfully be applied to define management strategies for these important ecosystems, as well as to design viable alternatives for their conservation.

3. Spectral reflectance of coral

To make observations, we move vertically and gradually from the coral surface to the water surface, measuring the changes in the quantity of light in the water column that falls directly on the coral. The quantity of light present obviously affects the amount that is reflected by the coral, and is therefore a crucially important parameter for mapping it.

Spectral reflectance (ρ) is a key parameter for conducting studies of coral reefs using RS (Hochberg et al., 2004). Two factors clearly and concisely explain this. First, ρ represents the boundary of radiative transference in the water surface optics. Therefore, taking into account ρ can resolve the problem of inverse radiative transference presented by passive remote sensors when applied in this field. Second, ρ is the function that denotes the object, the composition of the material and its structure. Therefore, it serves as a bridge between the optics of the object and the shape of the sea bottom (Hochberg et al., 2004).

In the process of classifying images and generating thematic maps, large differences have been noted in spectral reflectance among the coral reefs' benthic communities (Brock et al., 2006). Variability in the vertical relief, or rugosity, is a significant aspect of the complexity of a habitat, a factor that both reflects and governs the spatial distribution and density of many reef organisms (McCormick 1994). These factors, which respond to these evaluations, vary according to the differences among sediments, the presence of different algae species and the coverage of atypical algae in surface water in some reef zones. Thus, Hochberg et al. (2004) mention the importance of creating a specific approach using RS to study the surface water mass presented by atypical algae, since it has been shown that the mere presence of these organisms indicates classes that are spectrally distinct from other reef communities, even when they represent the same species.

Differences among the spectral signatures of corals provide a high likelihood of satisfactorily delineating and defining their different features in a satellite image. The problem with the above process is that the ρ of the corals is a function of pigmentation, structure, the orientation of their branches and their internal characteristics (Newman et al., 2006). In addition, though the interactions between light and the atmosphere are well-studied, the challenge is to establish controls for the effects of the water column in which the coral is found that influence these factors. Taking into account the curvatures in order to correct the acquired data provides more valuable information about the conditions and health of the living communities sheltered by the coral. Newman et al. (2006) indicate that two categories have been defined by recent studies which were conducted to measure in situ the spectral signatures of the coral environment:

i. The spectral signatures are examined according to the variation in the pigment density, which characterizes the sensorial color of the different coral species (Newman et al., 2006). Some studies have analyzed the contribution of color to the measurement of radiance (R), in particular, by comparisons with unpigmented coral structures. These observations resulted in the spectrum of coral whitening and structures saturated with zooxanthellae (Newman et al., 2006), which provide a measure of the health status of the complex reef system. Color has been used as a comparison measurement among three coral species, five algae species and three benthic communities (Hochberg and Atkinson, 2000), and as a means to differentiate between dead coral in different stages and algae colonization (Clark et al., 2000).
ii. Spectral signatures were examined according to morphological characteristics (Newman et al., 2006).
Corals exhibit distinct and complex structural morphologies, partially due to environmental conditions such as light availability, water motion and suspended sediment (Joyce & Phinn, 2002). Reflectance values measured over varying angles and azimuths were examined to determine the bidirectional reflectance distribution

function of coral species and the inter-species variation between rounded and branching types (Joyce and Phinn, 2002; Newman et al., 2006).

4. Mapping coral reefs using remote sensors

The worldwide importance of coral reefs in light of current threats has generated interest in developing methods to study this type of ecosystems at global scales (Kuhn 2006). The use of remote sensing to map underwater habitats is increasing substantially. This enables using the derived information to determine the status of these natural resources as a basis for planning, management, monitoring, conservation and evaluating their potential.

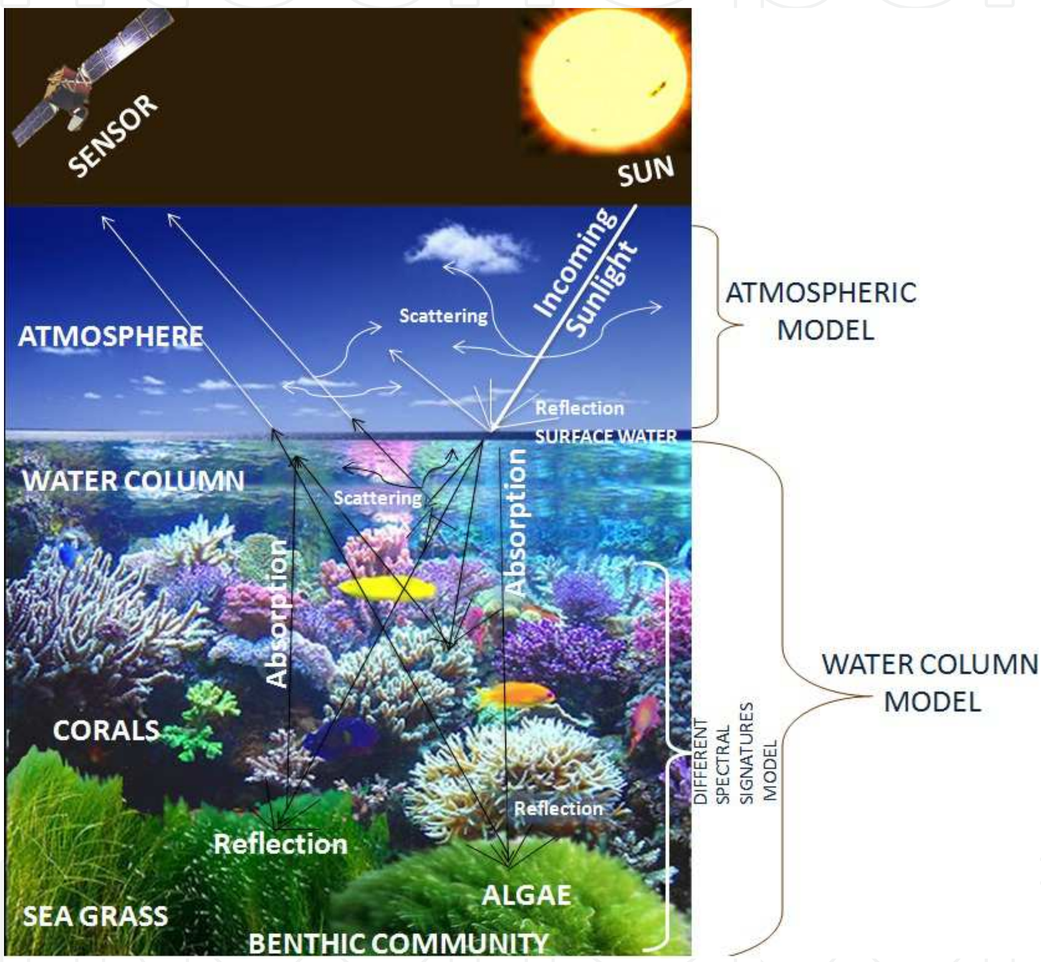

Fig. 1. Components of Remote Sensing in mapping coral reefs.

As was mentioned previously, high resolution spectral sensors exist that have elements that enable specific analysis with an excellent capacity for modelling environmental and structural variables in the coral reefs (Holden and LeDrew, 1998). The data produced by this type of sensors provide products that can be combined with models to photosynthetically calculate the radiation available through the photic zone and the surface of benthic substrates. Established models for calculating incident solar radiation are developed and evaluated based on routine satellite and meteorological observations (Brock et al., 2006). The spectral differences among corals, seagrass and algae are nearly imperceptible and not easy to detect with the three bands (blue, green and red) of the sensors that can penetrate the water column (Holden and LeDrew 1998; Hedley and Mumby 2002; Karpouzli et al., 2004). This is why RS studies applied to the mapping of submerged benthic ecosystems requires the generation of new processing methodologies. In addition, coral habitats present a heterogeneity that is inherent of their complexity, and therefore the task of discerning among the different spectral signatures is more complicated. That is, the pre-processing of images applied to this type of environments should not only incorporate the elimination of noise in the atmospheric and batimetric portions, but should also take into account the components of the water column, as shown in Figure 1.

5. Pre-processing of satellite images

All satellite images must undergo an initial processing of crude data to correct radiometric and geometric distortions of the image and eliminate noise. It must be taken into account that the energy captured by the sensor goes through a series of interactions with the atmosphere before reaching the sensor. As a result, the radiance registered by the sensor is not an exact representation of the actual radiance emitted by the covering. This means that the image acquired in a numerical form presents a series of anomalies with respect to the real scene being detected. These anomalies are located in the pixels and digital levels of the pixels that make up the data matrix. The purpose of correction operations is to minimize these alterations. The corrections are made during pre-processing operations, since they are carried out before performing the procedures to extract quantitative information. The product obtained is a corrected image that is as close as possible, geometrically and radiometrically, to the true radiant energy and spatial characteristics of the study area at the time the data are collected. Atmospheric correction is a process used to reduce or eliminate the effects of the atmosphere and allow for more precisely seeing the reflectance values of the surface being studied or analyzed.

Nevertheless, when attempting to map or derive quantitative information from subaquatic habitats, the depth of the water significantly affects the measurements taken by remote sensors, making it possible to generate confusion about spectral signatures. Therefore, atmospheric and geometric corrections are not sufficient when the objective is to extract features of the covering of the bottom of the water. That could be considered a characteristic and, in some cases, a limitation of passive sensors in remote sensor applications in marine environments. Thus, in this type of studies, a water column correction is performed to improve reliability when analyzing the results of the image and to eliminate the noise resulting from the variation in the ground's reflectance (Holden 2002; Holden and LeDrew, 1998; Mumby, 1998).

5.1 Correction of remotely sensed imagery

5.1.1 Radiometric correction

The radiance from the sensor (L) is calculated as:

$$L=c0+c1*ND \tag{1}$$

Where c0 and c1 are the offset and gain, respectively, of the radiometric calibration and ND is the digital number recorded in a particular spectral band. The process of obtaining L is called radiometric correction.

The total signal captured by the sensor consists of three parts: atmospheric scattering of radiation, radiation reflected by the pixel and radiation reflected by the vicinity of the pixel and scattered in different (adjacent) directions.

5.1.2 Atmospheric correction

The atmospheric conditions (water vapor, aerosols and visibility) in a scene can be calculated using algorithms that are performed using a database based on atmospheric functions. The surface spectral reflectance of an interaction target in a scene can thereby be seen as a function of the atmospheric parameters. ¶(6pt)

5.1.3 Geometric correction

The geometric correction consists of distinguishing the other types of radiation and only considering that which is reflected by the pixel. The objective is to remove geometric distortion; that is, to locate each pixel in its corresponding planimetric position. This enables associating the information obtained from a satellite image with thematic information from other sources.

5.2 Water column correction

The coral reefs generally develop in transparent or clear water, which facilitates study and analysis with passive optic, multispectral or hyperspectral sensors (Mumby et al., 1999). When light penetrates the water column, its intensity exponentially decreases as the depth increases. This process is known as attenuation, and it has an important effect on data obtained by remote sensors in aquatic environments (Green, 2000). The attenuation process is shown in Figure 2.

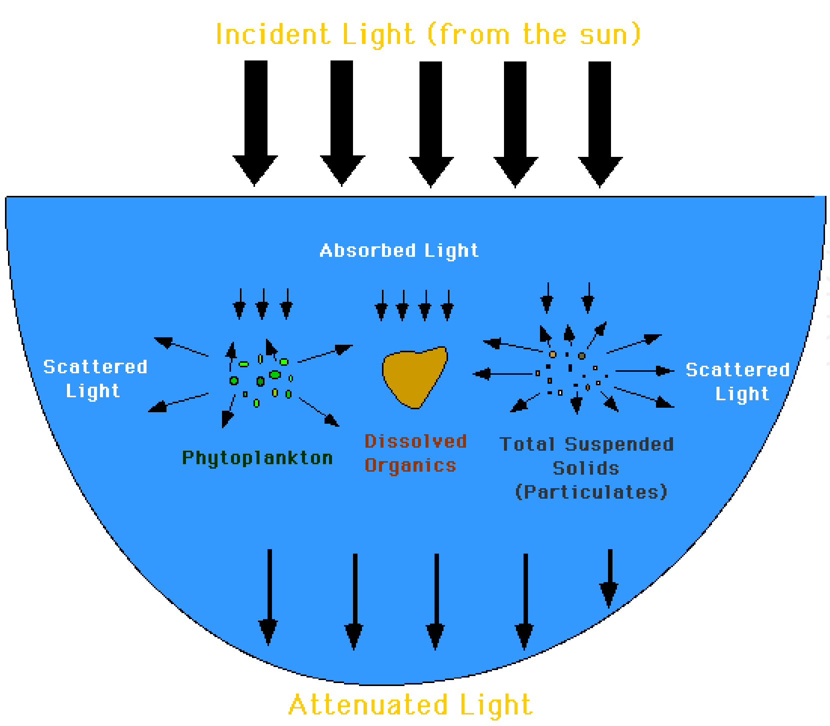

Fig. 2. Processes of light attenuation in the water column (SERC, 2011).

There are two reasons for this phenomenon:

- Absorption: light energy is converted into another type of energy, generally heat or chemical energy. This absorption is produced by the algae, which utilize the light as a source of energy, by suspended organic and inorganic particulate matter (OPM and IPM), dissolved inorganic compounds and the water itself.
- Scattering: This phenomenon results from the collision of light rays and suspended particles, causing multiple reflections. The more turbid the water (more suspended particles) the greater the scattering effect, making it difficult for light to penetrate.

The attenuation varies according to the wavelength of the electromagnetic radiation (EMR). For example, in the region of visible light, the red portion of the spectrum attenuates more quickly than the short wavelength, such as blue.

Figure 3 shows, for 4 spectral bands (blue, green, red and infrared), how the spectrum in a particular habitat (seagrass or macroalgae) can change as the depth increases. The spectral radiance registered by a sensor is dependent on the reflectance of the substrates and the depth. As the depth increases, the possibility to discriminate spectrums or spectral signatures of the habitats decreases. In practice, the spectrum of sand at a depth of 2 meters is very different than that at 20 meters. According to Mumby and Edwards (2000), the spectral signature of sand at 20 meters could be similar to that of seagrass at 3 meters. All these factors influence the signal and can create a good deal of confusion when using visual inspection or spectral classification to classify these habitats. Therefore, the influence of the variability in depth must be eliminated, which is known as water column correction or depth correction (Mumby and Edwards 2000).

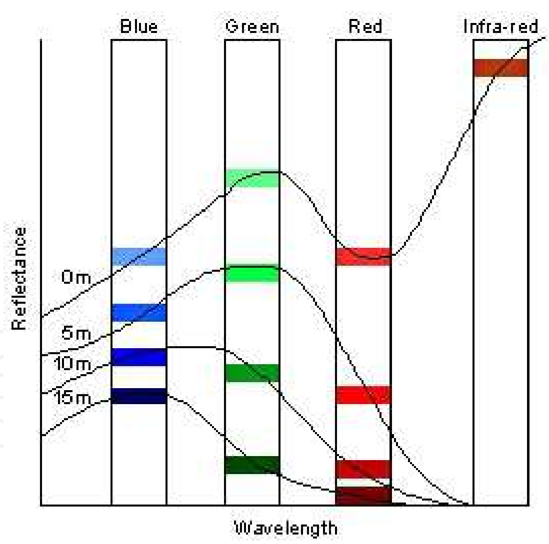

Fig. 3. Spectral differences for a habitat (seagrass or macroalgae) at different depths (Mumby and Edwards, 2000).

A variety of models exist that can be used to compensate for the effect of the water column. Nevertheless, many require optical measurements of the optical properties of the water itself, as well as information about the depth of water per pixel (Gordon, 1978; Philpot, 1989; Mobley et al., 1993; Lee et al., 1999; Maritorena et al., 1994; Maritorena 1996; Lee et al., 1999). Thus, the method proposed by Lyzenga (1981) is applied, which has been used and described by other authors, such as Mumby et al., 1997, 1998, Mumby and Edwards 2002, Andréfouët et al., 2003, etc. This approach has the advantage of taking into account the majority of the spectral information and not requiring data for the components of the water surrounding the reef. Instead of deriving the spectra of the different types of sea bottoms and water properties, this method transforms the spectral values into "depth-invariant indices." The primary limitation of this method, among others, is that it must be applied to clear water (i.e. type 1 or type 2); the study area meets this requirement.

To eliminate the influence of depth on sea bottom reflectance, the following need to be taken into account: the identification of the characteristics of attenuation of the water column and having digital models of the depth; although these are not very common, particularly for coral reef systems (Clark et al., 2000). This work used a bathymetric model provided by SEMAR (2008) that makes possible a good deal of reliability and precision to the measurements.

The procedure is divided into various steps:

1. Elimination of the atmospheric scattering and the external reflection from the water surface (atmospheric correction). This can be carried out using a variety of methods, such as dark pixel subtraction (Maritorena, 1996) and ATCOR (Richter, 1996, 1998).
2. Selection of pixel samples with the same substrate and different depths.
3. Selection of a spectral band pair, with good penetration of the water column (that is, bands found in the visible light spectrum—Landsat TM and ETM+ 1/2, 2/3 and 1/3).
4. Linearization of the relationship between depth and radiance, Xi = ln (Li), where Xi is the transformed radiance of the pixel in band i (band 1) and Li is the radiance of the pixel in band j (band 2). When the intensity of the light (radiance) is transformed using the natural logarithm (ln), this relationship becomes linear with the depth. Therefore, the transformed radiance values will decrease linearly as depth increases:

$$X_i = Ln(L_i) \tag{2}$$

5. Determination of the attenuation coefficient (quotient) using a biplot of the transformed radiance of the 2 bands (Li and Lj). The biplot contains data for one type of uniform bottom (sand) and variable depth. It is created using the following equations:

$$K_i/K_j = a + \sqrt{(a^2 + 1)} \tag{3}$$

$$a = \frac{\sigma_{jj} - \sigma_{ii}}{2\sigma_{ij}} \text{ and } \sigma_{ij} = \overline{X_i X_j} - \overline{X_i}\,\overline{X_j} \tag{4}$$

where σ_{ii} is the variance in band i and a is the covariance between bands i and j.

6. Lastly, the depth-invariant index is generated using the equation by Lyzenga (1981):

$$IIP_{ij} = \ln(L_i) - \left[\left(\frac{k_i}{k_j}\right)\ln\right](L_j) \tag{5}$$

The result of this operation generates a new band—the image with water column correction for a band pair (depth-invariant index). Since the values of this band are whole numbers with decimals and can be negative, in order to visualize them they need to be converted into an 8-bit format, that is, gray values between 0 and 255. To this end, minimum and maximum values for the resulting image must be found and linearly distributed between the values 1 and 255 (0 is not included because it is assigned to the masked surface area). The depth-invariant index is essential when the objective of the study is to extract spectral data for submerged aquatic environments.

6. Review of classification methodologies

The classification of a satellite image consists of assigning a group of pixels to specific thematic classes based on their spectral properties. The spatial classification of underwater coastal ecosystems is one of the most complex processes in thematic cartography using satellite images. As previously mentioned, this can be attributed primarily to the influence of the atmosphere and the ocean water column, through which electromagnetic radiation passes. In addition, it is worth mentioning that these ecosystems undergo constant variation, especially after significant events such as strong hurricanes. Nevertheless, different authors (Mumby et al., 1997; Andréfouët & Payri 2000; Mumby and Edwards 2002; Andréfouët et al., 2003; Pahlevan et al., 2006; Call et al., 2003, etc.) have been using remote sensing to develop different classification methods for these ecosystems and, in particular, for coral reefs.

The maximum likelihood classifier is the most common method, and has been used by authors such as Mumby et al. (1997), Andréfouët et al. (2000), Mumby and Edwards (2002), Andréfouët et al. (2003), Pahlevan et al. (2006), and Benfield et al. (2007). Its primary advantage is that it offers a greater margin for accounting for the variations in classes through the use of statistical analysis of data, such as the mean, variance and covariance. The results of the method can be improved with the incorporation of additional spatial information during the post-classification process, since this helps to spectrally separate the classes that had been mixed.

Another method also used by Mumby et al. (1997) is agglomerative hierarchical classification with group-average sorting. An alternative proposal is object-oriented classification, which consists of two steps, segmentation and classification. Segmentation creates image-objects and is used to build blocks for further classifications based on fuzzy logic. Another method that has been used is ISODATA (iterative self-organizing data analysis), which uses a combination of Euclidian squared distance and the reclassification of the centroid (Call et al., 2003). In this study, ISODATA was used to perform the classification.

6.1 ISODATA (Iterative Self Organizing Data Analysis)

ISODATA is an unsupervised classification method as well as a way to group pixels, and uses the minimum spectral distance formula. It begins with groups that have arbitrary means and each time the pixels in each of the iterations are regrouped and the means of the groups change. The new means are then used for the next iterations.

The algorithm for obtaining the classification is based on the following parameters:

a. The user decides on the number N of clusters to be used. For the first calculation, it is recommended to use a high number, which is then reduced by interpreting the image.
b. A set of N clusters in the space between the bands is selected. The initial location is in the zones with the highest reflectance.
c. The pixels are assigned to the closest cluster.
d. The clusters are associated, dispersed or eliminated depending on the maximum distance of the class or the minimum number of pixels in a class.
e. The grouping of pixels in the image is repeated until the maximum number of iterations has been reached, or a maximum percentage of pixels are left unchanged after two iterations. Both parameters can be specified

7. Case study

The Chinchorro Biosphere Reserve (Fig. 4) is located in the open Caribbean Sea, 30.8 km east of the coastal city of Mahahual, which is the closest continental point. The coral reef of Chinchorro Bank, Mexico, is part of the great reef belt in the western Atlantic, the second largest in the world, and is the biggest oceanic reef in Mexico. With a reef lagoon area of 864 km2, it is considered a pseudo-atoll or reef platform (Camarena, 2003). Chinchorro Bank is a reef complex that contains an extensive coral formation with a vast wealth and diversity of species and high ecological, social and cultural value. It inherently provides certain services, including the protection of the coast from battering by storms and hurricanes. The area has been exploited by fishing and tourist-related scuba diving over the past decades. The Chinchorro Bank supports pristine reefs, coral patches, extensive areas of seagrass, microalgae beds and sand beds. The reserve’s ecosystems are marked by mangroves and reef zones. The composition of the taxocenosis of coral is known to contain hexacorals,

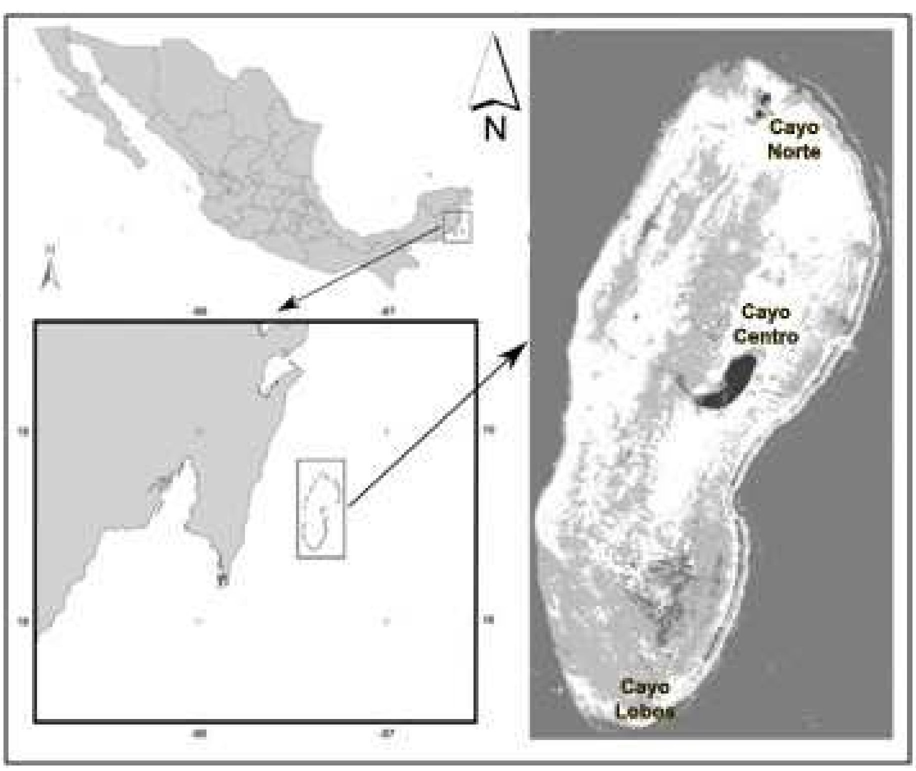

Fig. 4. Study Area: Chinchorro Bank, Mexico.

octocorals and hydrozoas and a reported 95 different species (Camarena, 2003). The diversity of the fauna in the Chinchorro Bank is very high and includes several phyla, families, genres and species, with at least 145 macro invertebrate and 211 vertebrate species, in addition to the corals (Bezaury et al., 1997).

The biogeographic region of Chinchorro Bank is delimited on the north by the Caribbean Province which extends along Central and South America. This province begins in Cabo Rojo, in southern Tampico, and extends into eastern Venezuela and the northern Orinoco delta. The land biota is greatly similar to that of the continent and is therefore considered to be part of the Yucateca Province. It is located in the Mexican Caribbean, across from the southeastern coast of the state of Quintana Roo, between the 18º47'-18º23' N and 87º14'-87º27' W parallels. It is 30.8 km from the continent and separated from it by a wide canal 1000 m deep. The shape of Chinchorro Bank is elliptic, with a reef lagoon that includes a sandy bank 46 m long (north-south) and 18 km wide (east-west) at its broadest part. The total area is 144360 ha. The periphery of the bank is bordered by active coral growth on the eastern (windward) margin, which forms a coral reef, or breaker, while along the western margin (leeward) the breaker disappears and the coral growth is semicontinuous and diffuse (Camarena, 2003). There are four emerged zones within the bank—known as "Cayo Norte" (two islands), "Cayo Centro" and "Cayo Lobos"—whose ecological value is very high because of their diverse species of land and water flora and fauna (Camarena, 2003).

8. Information resources

The geospatial database used in this study includes a Landsat 7-ETM+ image (Table 1), bathymetric information and in situ data for sand (Figure 5). The digital data were projected to UTM (Universal Transverse Mercator) zone 16 north with WGS-84 datum. ERDAS, GEOMATIC 10.2 and ArcMap 9.3 were used to process the data.

The importance of choosing the type of image with which to work is well-known, particularly because the users will need to make sure to use images that are suitable to the purpose of the study. The nature of a platform-sensor system determines the characteristics of the image's data (Green, 2000). The Landsat 7-ETM+ (Table 1) image obtained had no cloud cover. It is worth noting that this type of images provides adequate coverage of the area for regional and temporal monitoring studies.

Date	2000-03-29
Scan time	16:03:05
Path/Row	18/47
Spatial resolution (m)	30
Spectral bands used	3
Spectral range (µm)	0.5-0.69
Azimuth	116.29
Solar angle	59.43

Table 1. Characteristics of the Landsat 7-ETM+ image used

It is also very important to note that bathymetry is one of the most relevant factors in the dynamic ecology of coral reefs. Numerous reef studies show that coral species diversity tends to increase as a function of depth, reaching its maximum between 20–30 m and diminishing with greater depth (Huston, 1985). This depth effect results in a marked zonation of the reef community (Aguilar-Perera and Aguilar-Dávila, 1993). While the upper depth limits of corals are controlled by various physical and biological factors, their maximum depth depends largely upon light availability (García-Ureña, 2004). The bathymetric soundings for Chinchorro Bank used by this study were done in 2008 by the Mexican Navy (SEMAR, 2008). The depth of the interior of the bank varies. The northern portion is shallower, between 1 and 2 m, the depth of the central portion ranges between 3 and 7 m, and the southern portion is deepest, varying between 8 and 15 m (SEMAR, 2008). There are 4 emerged zones within the bank, known as keys, which have high ecological value because of their diverse species of flora and aquatic and land fauna (Camarena, 2003). Figure 5b shows bathymetry data for the Chinchorro Bank, where the depths of the zone can be seen.

In situ sampling data were provided by SEMAR. Data from Carricart-Ganivet et al. (2002) were also used. Based on these data, 4 of the most representative classes were determined: 1) coral mass, 2) coral patches, 3) seagrass and algae and 4) sand. The ocean and keys, or emerged areas, are not part of the classification criteria, though they are also represented. Unfortunately, the databases for the in situ sampling have disadvantages—such as mixing classes in the same point and lack of definition of the benthic bottom, among others—that prevent their being used for validation purposes. Only data for sand provided by SEMAR do not present these disadvantages and could be used for water column correction, as explained further below.

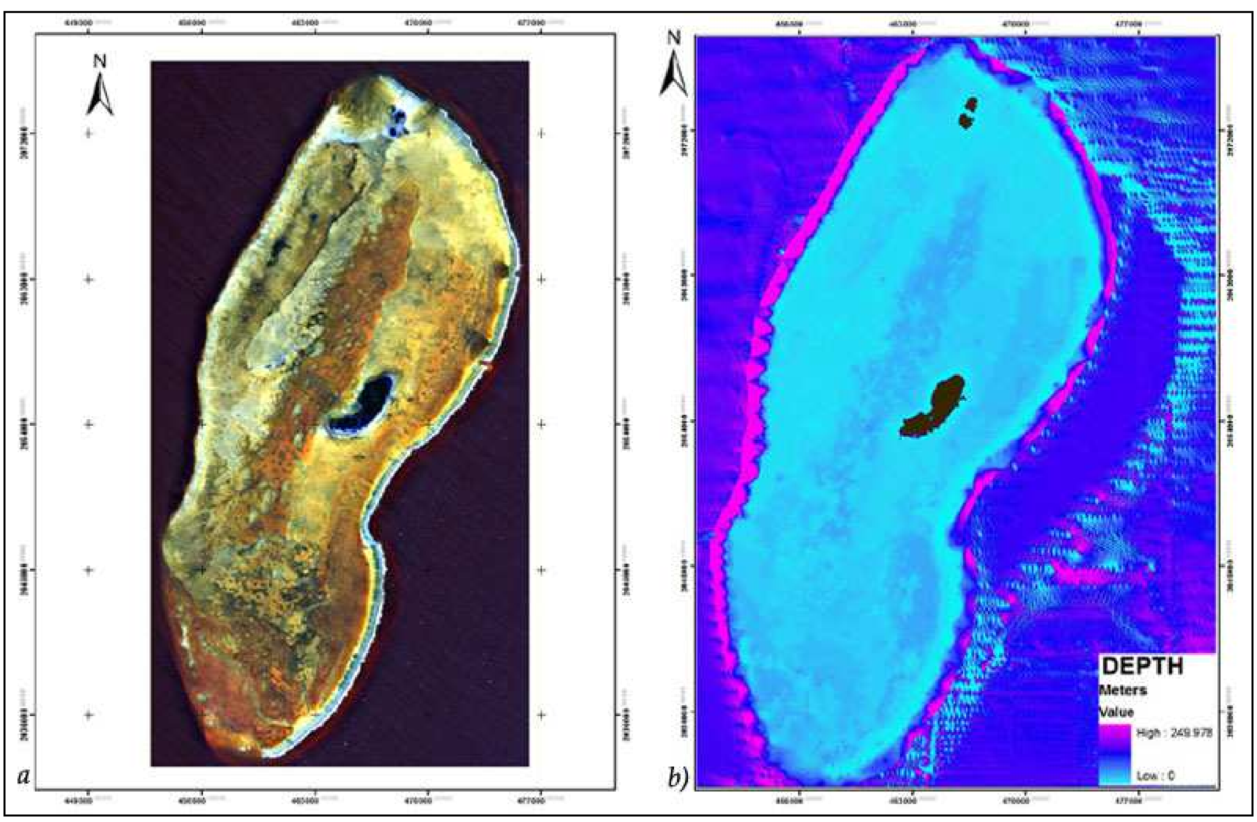

Fig. 5. Information resources. a) Landsat 7-ETM+ image and b) depth of the Chinchorro Bank

9. Results and discussion

9.1 Image processing

A Landsat 7-ETM+ image from March 29, 2000 was processed. Before conducting the quantitative analysis of the data, a post-calibration was performed of the constant gain and offset to convert the image ND to spectral radiance. The spectral radiance was also corrected for atmospheric effects to obtain the surface reflectance values. A geometric correction was not performed because the level of the processing of the Landsat images includes this correction. Only 3 of the 8 bands contained by Landsat were used (blue, green and red). The depth correction was developed with the Lyzenga (1981) method, which has been used and described by other authors (Mumby et al., 1997, 1998; Mumby and Edwards 2002; Andréfouët et al., 2003).

9.2 Water column correction

Lyzenga (1981) shows that when drawing a scatterplot of 2 of the logarithmically transformed bands in the visible spectrum (one on each axis), the pixels for the same type of bottom (i.e. sand at different depths) follow a linear trend. Repeating this process for different types of bottoms produces a series of parallel lines and the intersection of those lines generate a unique depth-invariant index which is independent of the type of bottom; all the pixels for a particular bottom have the same value as the index regardless of the depth at which they are found (Andréfouët et al., 2003). A group of pixels representative of the depth of the water column was selected for this study, therefore pixels very close to the surface (< 1m) were eliminated. Sand was the only substrate used since it is the most homogenous bottom in coral environments, and is the one most used by various authors (Mumby and Edwards 2002; Lyzenga, 1981) and the most easily recognizable for interpretation purposes. For the specific case of the Chinchorro Bank, 100 points of sand between 1 and 10m of depth were used to determine the attenuation coefficient (quotient) for the band pair ½, 99 points were used for bands 1/3 and 96 for bands 2/3. The data for point radiance to a type of bottom were extracted from the image and transferred to a spreadsheet. Figure 6a shows the graphic spectral radiance of bands 1 and 2 (atmospherically corrected) with respect to the depth for one specific type of bottom (sand) and variable depth.

Figure 6b shows the linearization of the exponential attenuation of the radiance for bands 1 and 2 using natural logarithms, since in practice it is virtually impossible for the points to adhere to a perfect line given the natural heterogeneity of the different types of bottoms, variations in the water quality, surface roughness of the water, etc. Figure 6c shows the biplot of bands 1 and 2 for a single substrate (sand) at different depths. To this end, the variance of band 1 and the covariance of bands 1 and 2 are evaluated (Table 2 and 3). Table 3 shows the different values for obtaining the attenuation coefficient, according to spectral band.

	Band 1	Band 2	Band 3
Variance (σ_{ii})	0.2628	0.6334	0.2761

Table 2. Variance of the radiance of each band

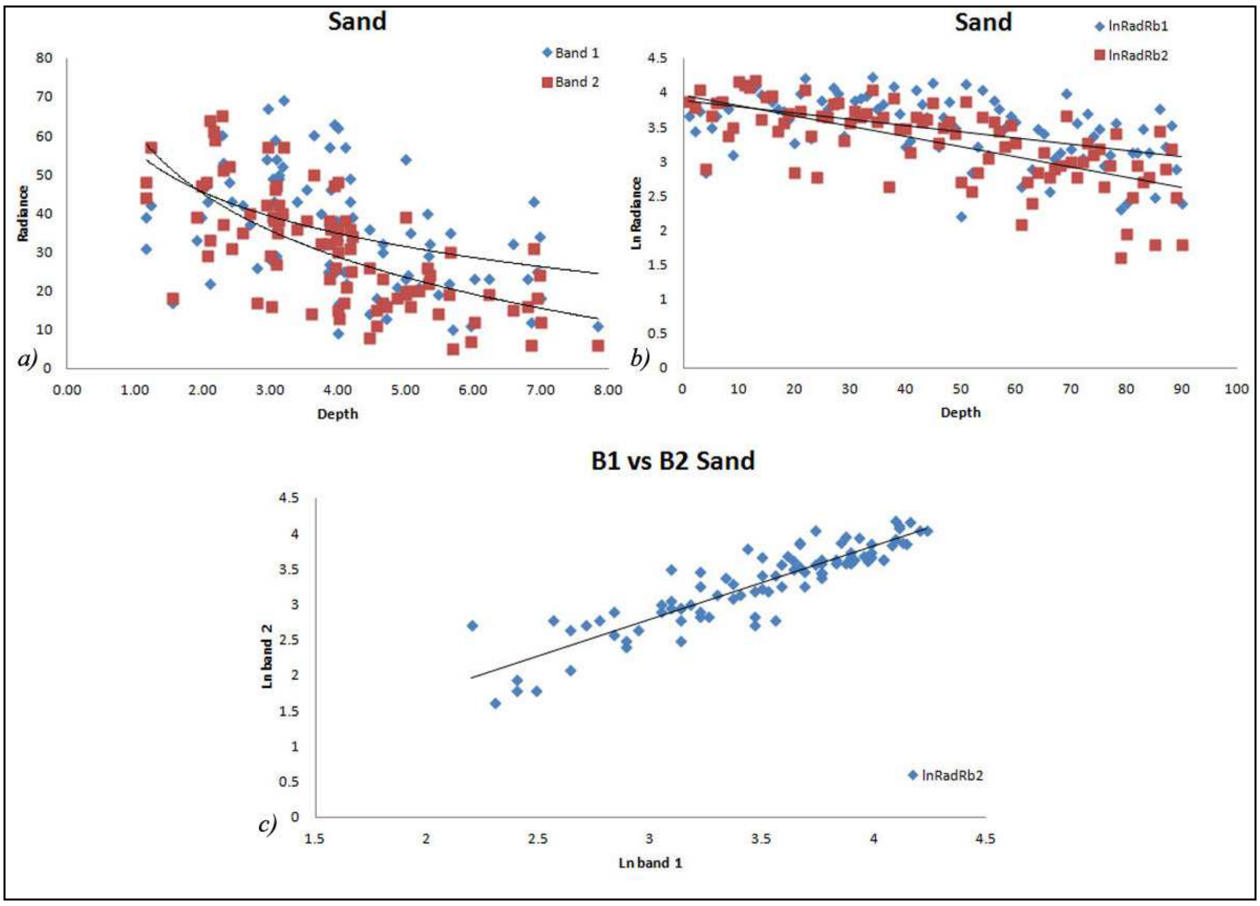

Fig. 6. Steps for water column correction: (a) spectral radiance of bands 1 and 2 (atmospherically corrected), (b) exponential decay of the radiance for bands 1 and 2 using natural logarithms and (c) biplot of bands 1 and 2 for a single bottom (sand) at different depths.

	Ratio 1/2	Ratio 1/3	Ratio 2/3
Covariance (σ_{ij})	0.3200	0.1178	0.2327
aij	-0.0593	-0.0031	0.0184
ki/kj	0.94	0.99	1.00

Table 3. Calculation of ratio of attenuation coefficients

Figure 6c shows the biplot of the logarithmically transformed bands 1 and 2, representing the attenuation coefficient (ki/kj) for bands 1 and 2. It is important to mention that if different types of bottoms are represented in a biplot, they would theoretically represent a line with a similar behavior, varying in position only due to differences in spectral reflectance. The gradient of the line would be identical since ki/kj does not depend on the type of bottom. The intersection of the line with the y-axis represents the depth-invariant index, since each type of bottom has a unique y-intersect regardless of depth. Each pixel is assigned an index depending on the type of bottom, which is obtained using the natural logarithm transformation for each band and the connection of the coordinate to the origin of the y-axis through gradient line ki/kj. The pixels are thus classified for different types of bottoms.

As mentioned before, the depth-invariant index is generated according to band pairs—1/2, 1/3 and 2/3, correponding to bands 1 (blue), 2 (green) and 3 (red) (Figure 7). The image

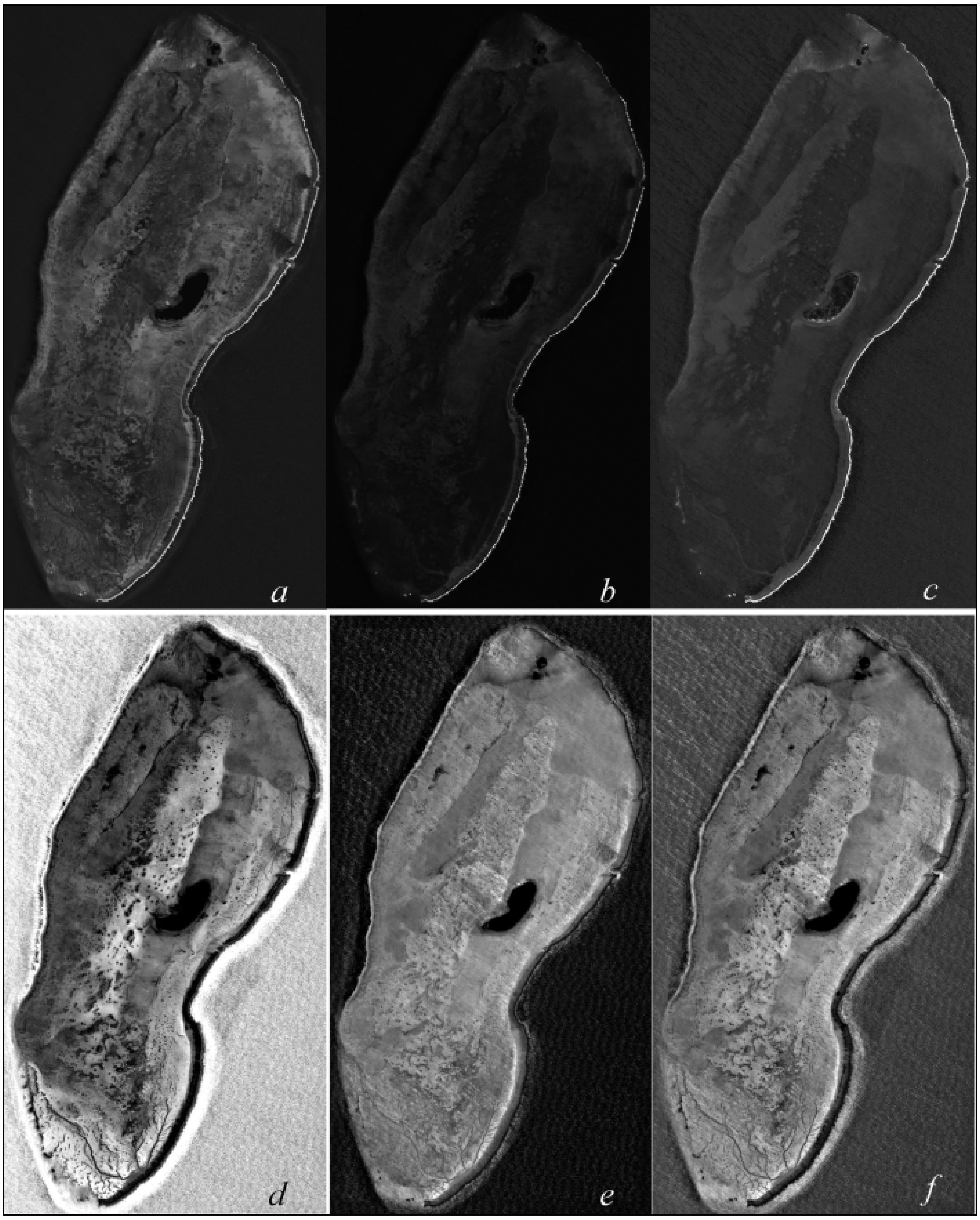

Fig. 7. Visualization of the Landsat 7-ETM+ image before and after water column correction. a) image of band 1 (blue, 450-520 nm), b) band 2 (green, 530-610 nm), c) band 3 (red, 630-655 nm), d) depth-invariant index combination of bands 1/2, e) 2/3 and f) 1/3.

resulting from the depth-invariant index was significantly different than the image without correction, since it reveals more details of the structures of the benthic bottom, especially in zones with greater depths.

9.3 ISODATA classification

As an initial approach to the classification of submerged benthic ecosystems in the Chinchorro Bank, ISODATA was used as a classification method, since not much needs to be known about that data beforehand. A little user effort is required to identify spectral clusters in data. The results of the benthic classification in the Chinchorro Bank were visually evaluated according to the quality of the segmentation using the classification by Aguilar-Perera & Aguilar-Dávila (1993), and with bathymetric data that greatly determine the ecology of the corals, as explained next.

Figure 8a shows the Landsat image with atmospheric correction for the RGB (1,2,3) combination and Figure 8b shows the image resulting from the depth-invariant index by bottom type. At the bottom of the figure, two images classified using ISODATA are included, both with the same type and number of classes. Figure 8c presents the classification performed without water column correction; that is, using the image from 8a as input. Figure 8d includes the classification performed based on the depth-invariant index (shown in 8b); that is, taking into account water column correction. To identify the categories resulting from the ISODATA process, benthic bottoms in the Chinchorro Bank as defined by Aguilar-Perera & Aguilar Dávila (1993) were used as a basis. It can be seen (8c) that the classification without water column correction produced a substantial mix of classes throughout the image, unlike the classification obtained by applying water column correction (8d). According to authors such as Aguilar-Perera & Aguilar Dávila (1993), Chávez and Hidalgo (1984) and Jordán (1979), the periphery of the Chinchorro Bank is surrounded by abundant coral growth on the eastern margin. A barrier reef is thereby formed that disappears along the western margin where the coral growth is semi-continuous and diffuse. This spatial distribution of the corals can be clearly seen in the results of the classification with water column correction (Figure 8d), unlike classification without correction (Figure 8c).

One known ecological characteristic of reef systems is that the zonation of the reef bottom and its ecological dynamics are strongly influenced by the depth (Huston, 1985; Loya, 1972; Gonzáles et al., 2003). The seagrasses constitute a type of benthic bottom normally present in shallower zones. These observations and the use of bathymetry enable corroboration of the validity of the spatial distribution of seagrasses obtained by classification with water column correction. The shallower zones are located in the northern (1-2m) and central (3 and 4 m) portions; these two zones best correspond to the zone with seagrass generated in the image shown in 8d, as opposed to the image in 8c where it can be seen that the seagrass class is distributed throughout the bank. In addition, 8c shows a mix between seagrass and corals, a result that is not justifiable since the corals normally develop at depths between 5 and 30m. Using the depth criterion again in order to define the zonation, it is possible to state that the classification with water column correction produces good results for identifying coral patches, since they are found at depths between 7 and 12 m, as can be seen in Figure 8d. As a general observation, we can state that the results of the classification with water column correction generate data that are consistent with the theory regarding the

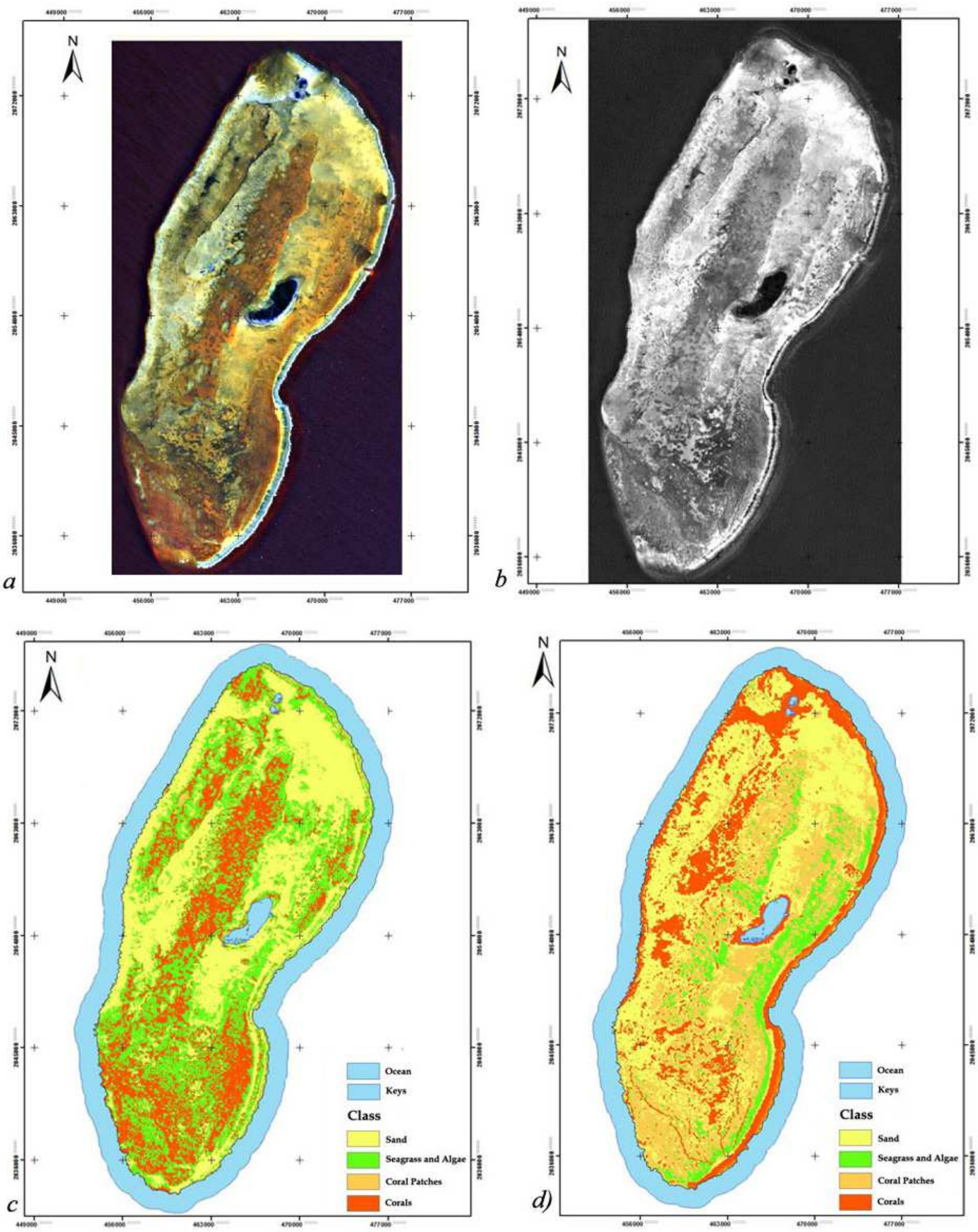

Fig. 8. a) Landsat 7-ETM+ image, RGB (1, 2, 3), b) image resulting from the depth-invariant index by bottom type using bands 1 and 2, and classification of the benthic bottom in the Chinchorro Bank using ISODATA, c)without water column correction and d) with water column correction.

influence of depth in defining the zonation of benthic bottoms, as well as observation of other authors regarding the spatial distribution of sea-bottoms.

Figure 9 shows a close-up to facilitate the visual analysis of the differences between the classes obtained using ISODATA, implemented with and without water column correction.

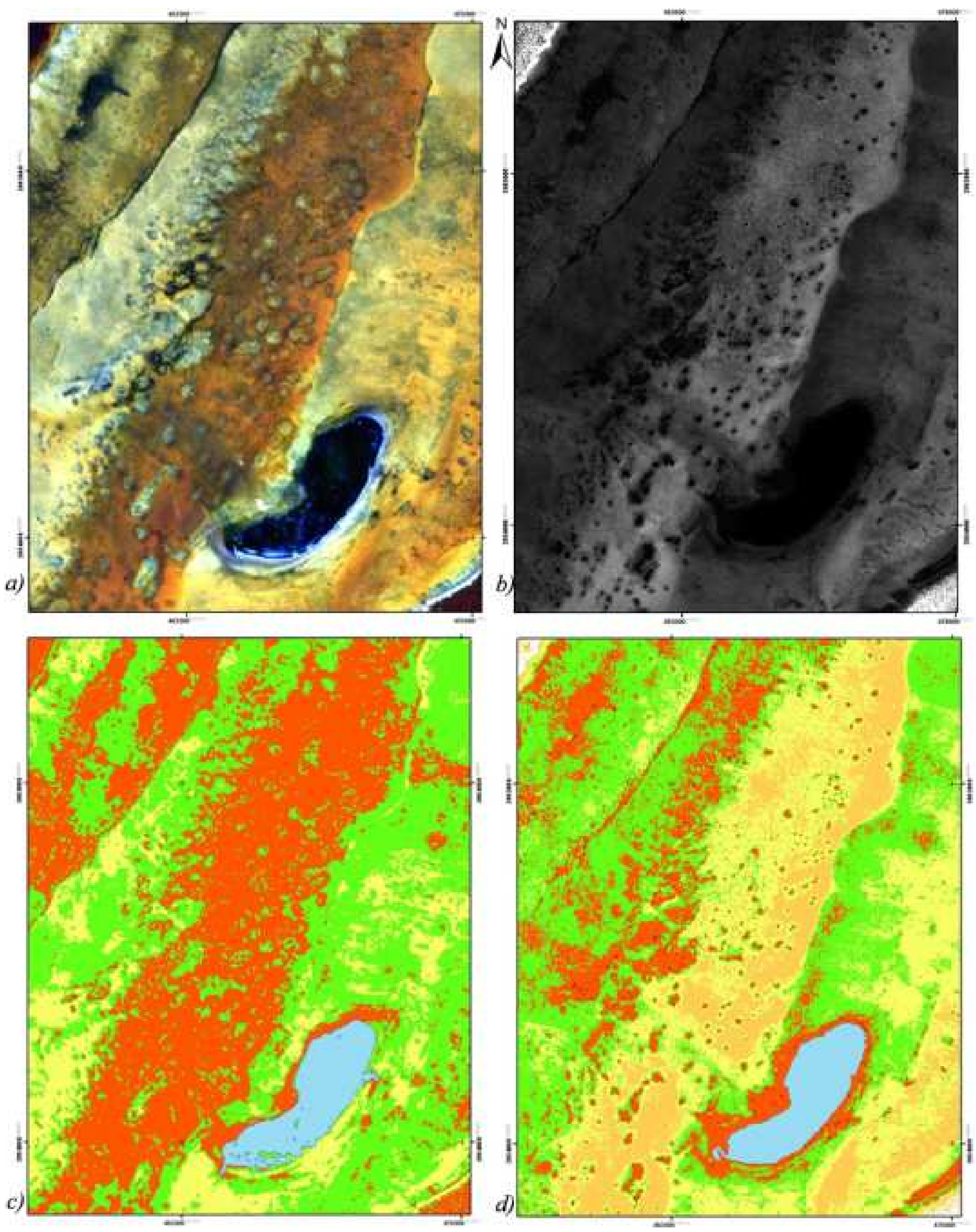

Fig. 9. Comparison among a) Landsat 7-ETM+ image, RGB (1, 2, 3), b) depth-invariant index by bottom type for bands 1/2, c) ISODATA without water column correction and c) ISODATA with water column correction.

In this figure, it can be seen that thanks to the water column correction, the classes are better defined, with mixing among them—caused by interference by the depth of the water column—avoided to whatever extent possible. The ISODATA algorithm more accurately selects and groups clusters, eliminating this problem. This visualization again confirms the advantage of performing water column corrections to obtain better results for the processes to classify benthic bottoms.

10. Conclusions

The study shows that the application of new remote sensing methods is crucial to the pre-processing of images in order to identify submerged aquatic ecosystems. This is because when quantitative information is mapped or derived from satellite images of aquatic environments, the depth of the water causes spectral confusion and therefore significantly affects the measurements of submerged habitats. Water column correction minimizes this effect, which enables distinguishing the classes of benthic ecosystems present in the Chinchorro Bank and demonstrates improvement especially in zones representing more variation in depth. Thus, water column correction is an indispensible pre-processing method in the cartography of submerged aquatic ecosystems.

The water column correction method used in this study uses the majority of the spectral information while disregarding the characteristics of the water surrounding the reef, such that the spectral values are transformed from a band pair into a depth-invariant index. This should be applied in relatively clear water (type 1 or type 2), as is the case of the Chinchorro Bank. Using this process, the attenuation effect of the water column was minimized, which is one of the primary problems with the segmentation of images of submerged ecosystems.

Traditional, unsupervised classification methods, such as ISODATA, have difficulty detecting subclasses, that is, this type of classifier makes it complicated to detect pixels between very close classes with distributions that share an overlapping zone. When classifying benthonic habitats in the Chinchorro Bank, it was possible to observe that the classes with less concentration of pixels were masked by those with greater amounts. This may be because standard methods, such as ISODATA, use moving mass center techniques to locate the classes and, thus, what are called subclasses become undetectable.

In general, the data from remote sensors are used for mapping reef habitats. Although the classification presented here was quite general—only 4 classes were determined—the results show that the Landsat 7-ETM+ images are able to identify different classes in submerged benthonic environments. Although the classification resulted in visually optimal results, the need to incorporate statistical validation of the data is important, so as to determine the accuracy of the classification performed in comparison to the reality; this was not possible for this study because an adequate database of in situ sampling was not available. Nevertheless, because of the visual comparison with classes identified by studies such as those by Aguilar-Perera & Aguilar Dávila (1993), Chávez and Hidalgo (1984) and Jordán (1979) and the consistency with the theory of the zonation of benthic bottoms based on depth, it can be concluded that the classifications obtained by ISODATA successfully determined the majority of the benthonic cases defined in this study of the Chinchorro Bank.

Coral reefs are being threatened worldwide by a combination of natural and anthropogenic impacts. Although the natural impacts are intense, there are intermediate time lapses that can contribute to maintaining biodiversity. On the other hand, the human impacts—which may seem to be less intense because they are not as perceivable to the eye—are chronic and can unleash a chain of negative effects. This sequence of negative effects normally does not give ecosystems the opportunity to recover and maintain their characteristic function and structure.

The search for new methodologies to process satellite images is indispensable to identifying the current trend in the degradation of marine habitats; methodologies that generate new and improved classifications that are highly reliable and with a level of detail that is adequate for mapping these ecosystems. Through this type of study, it is possible to organize, relate and manage information from satellite images in order to propose agreed-upon strategies to conserve natural resources, as part of comprehensive environmental policies to properly solve the problems. Thus, these data can be used as a basis to plan the monitoring of reefs in order to create scientific methods to generate knowledge and environmental awareness in the society and to contribute to the mitigation of the loss of reefs due to impacts from current global warming and other anthropogenic and global changes.

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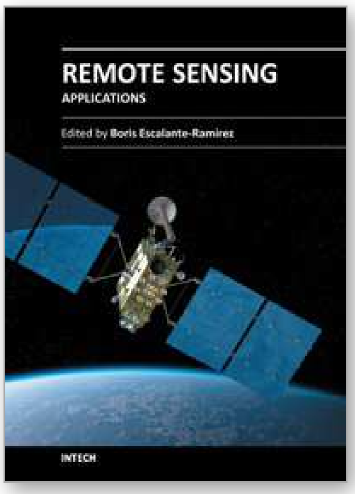

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