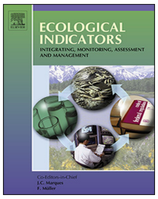
Ecological Indicators 96 (2019) 174–191

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Detection of changes in shallow coral reefs status: Towards a spatial approach using hyperspectral and multispectral data

Touria Bajjouk[a,*], Pascal Mouquet[b], Michel Ropert[c], Jean-Pascal Quod[d], Ludovic Hoarau[c,e], Lionel Bigot[f], Nicolas Le Dantec[g,h], Christophe Delacourt[h], Jacques Populus[a]

[a] IFREMER Centre de Brest, DYNECO/LEBCO, BP 70, 29280 Plouzané, France
[b] Université de La Réunion/UMR ESPACE-DEV, Antenne SEAS-OI, 40 Avenue de Soweto, 97410 Saint-Pierre, La Réunion, France
[c] IFREMER, Délégation océan Indien, Rue Jean BERTHO, BP60, 97822 Le Port, La Réunion, France
[d] Pareto, 15 Impasse des Hyménées, 97438 Sainte Marie, La Réunion, France
[e] 3R: Rehabilitation of Réunion Island Reef, 97435 Saint-Paul, La Réunion, France
[f] UMR 9220 ENTROPIE, Université de La Réunion, IRD, CNRS, Laboratoire d'Excellence CORAIL, BP 7151, 97715 Saint Denis Cedex 9, La Réunion, France
[g] CEREMA—Centre d'Etudes et d'expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement, DTecEMF, 29280 Plouzané, France
[h] Laboratoire Géosciences Océan—UMR 6538, Université de Bretagne Occidentale, IUEM, Technopôle Brest-Iroise, Rue Dumont D'Urville, 29280 Plouzané, France

ARTICLE INFO

Keywords:
Change detection
Coral to Algae Index
Hyperspectral
Reef geomorphology
Remote sensing monitoring
Reunion Island

ABSTRACT

Coral reef degradation due to environmental change, including anthropogenic disturbances, is a major concern worldwide. Detecting and assessing both temporal and spatial changes in benthic cover is a crucial requirement to inform policy makers and guide conservation measures. Here, we introduce a spatial approach based on high resolution multispectral and hyperspectral image analysis, developed in order to detect and quantify changes in benthic cover in a highly heterogeneous shallow coral reef flat in Reunion Island in the South-West Indian Ocean. We propose a new index called HCAI (Hyperspectral Coral to Algae Index), defined as the ratio of living coral cover to the sum of living coral and algal covers. Benthic cover estimates were derived from airborne hyperspectral image processing using water column correction and unmixing models implemented with the four main coral reef benthic components: corals, algae, seagrass and sand. Ground truth and LIDAR data acquired simultaneously were used to validate processing accuracy. A significant positive correlation (adjusted $R^2 = 0.72$, p-value < 0.001) was obtained between coral cover recorded *in situ* and estimated from image analysis. Moreover, 13 habitat classes based on the four main benthic component covers were mapped at a scale of an entire reef. Diachronic analyses of hyperspectral images between 2009 and 2015 revealed an overall decrease of the HCAI index and a decrease in the area of all the dominant coral classes along the reef (-28.24% for the *coral* class for example), while the area of habitat classes dominated by algae strongly increased during the same period. Moreover, we detected and documented the spatial and temporal evolutions of coral geomorphological features composed with coral rubble deposits called *rubble tongues* (RTs) using different available sensors (i.e. hyperspectral, satellite, and orthophotography). Since 2003, four detected (RTs) have spread shoreward at a mean rate of 8.4 $\mathrm{m.y}^{-1}$ including significant loss of reef structural complexity and heterogeneity, a spreading pattern which was confirmed by 2009 and 2015 hyperspectral data. Remote sensing and more specifically airborne hyperspectral approaches open new perspectives for coral reef monitoring, at high temporal and spatial resolutions.

1. Introduction

Coral reefs are one of the most complex, biodiverse, and productive ecosystems on the planet, playing a major social, economic and cultural role for millions of people (Spalding et al., 2017). These ecosystems also constitute a natural and physical barrier against storm-induced coastal hazards, in particular hurricanes, by significantly reducing wave energy (Ferrario et al., 2014; Guannel et al., 2016). However, coral reefs are also considered among the most vulnerable marine ecosystems (Bellwood et al., 2004; Halpern et al., 2007), facing increasing anthropogenic stressors and disturbances such as climate change, rising sea-surface temperatures, ocean acidification, soil erosion, pollution, and overfishing (Bozec and Mumby, 2014; Harborne et al., 2017). The global degradation of coral reefs has become a worldwide concern over

---

* Corresponding author.
E-mail address: touria.bajjouk@ifremer.fr (T. Bajjouk).

https://doi.org/10.1016/j.ecolind.2018.08.052
Received 24 January 2018; Received in revised form 26 June 2018; Accepted 24 August 2018

the two last decades (Hughes et al., 2017), emphasizing the urgent need for developing adequate tools to assess reef state and quality at large scales in order to propose adequate management strategies for mitigation of coral reef degradation and promoting resilience.

Management of coral reef seascapes requires an assessment of temporal variations driven by natural fluctuation, extreme disturbances such as cyclones and flood plumes (Perry et al., 2008) and by human activities. Monitoring programs can detect such change and help to understand the spatial and temporal dynamics of reef degradation and recovery, from global (Wilkinson, 2008) to local perspectives (Done et al., 2007). The most common methods used to detect temporal change in health status in the framework of reef monitoring programs are the Line or Point Intercept Transect (LIT and PIT) and Quadrats (Facon et al., 2016). Although these methods provide reliable results to quantify spatial and temporal benthic reef variations, change is often measured at small standardized scales and therefore reflects only a partial picture of the entire reef (Madin and Madin, 2015). Constrained by the accessibility of certain reef flat zones, these methods characterize a limited linear inner reef flat and therefore fail at taking into account important spatial heterogeneities of benthic communities distributed along an entire coral reef. In addition, they fail to detect geomorphological dimensions of the reef over decadal time scales. Given that coral reef organisms are affected by a wide range of processes that span scales from the cell up to thousands of kilometers (Allemand et al., 2011), proper assessment of the ecological state of the reef requires monitoring schemes that provide a comprehensive picture of coral reef structure and dynamics.

High resolution remote sensing is a suitable technique for evaluating the current trends of coral reef structure and its dynamics at larger spatial scales. Hedley et al. (2016) recently reviewed remote sensing techniques for monitoring and management of coral reefs and concluded that recent advances in sensors and processing have great potential to generate high resolution coral reef maps that incorporate various data sources in order to propose effective conservation management measures. The most common techniques applied to detect the nature and extent of land cover changes have used LANDSAT multispectral images (Andréfouët et al., 2001). However, the spatial resolution (i.e. tens of meters) of this sensor is not suitable for capturing the change in the dynamics of coral reef ecological status. Coral reef state requires monitoring at fine spatial scales in shallow waters, but currently, at this spatial resolution, most studies addressing detection of change are limited to geomorphological features. Recently, WorldView-3 satellite images were used to quantify live coral cover (LCC) using a band ratio-based index (Huang et al., 2018), however this index strongly depends on field surveyed LCCs. In addition to the spatial and spectral limitations of these two satellite sensors, Andréfouët (2012) draws attention to the issue of manual and therefore subjective boundary definitions along reef flat gradients. Furthermore, satellite-based methods often require substantial field surveys for characterization and validation of the detected benthic components (Hedley et al., 2016).

Field studies have demonstrated the ability of using narrow spectral bands to discriminate between *in situ* hyperspectral reflectance measurements of corals and algae (Hochberg and Atkinson, 2000; Karpouzli et al., 2004) and healthy corals (Holden and LeDrew, 1998). As an alternative to multispectral satellite images, hyperspectral imagery can be used to implement detection of change in coral reef status, with greater potential for discriminating benthic components. Airborne hyperspectral sensors provide sufficiently high spectral resolution to achieve good discrimination of the seabed types, and sub-meter spatial resolution to reveal distribution patterns at the fine scale of coral communities (Hochberg and Atkinson, 2000; Mishra et al., 2007). Andréfouët et al. (2004) used Compact Airborne Spectrographic Imager (CASI) data to demonstrate spectral differences between algae and corals. Joyce et al. (2013) recently tested a spectral index for mapping live coral cover using CASI-2 airborne hyperspectral imagery. Using hyperspectral images, Garcia et al. (2018) developed a lookup table (LUT) based approach to retrieve bottom depth and reflectance, with the latter used in benthic classification. They showed that the developed classification scheme enhances benthic classification and formulated the need of its application to other regions to evaluate its portability. All of these studies demonstrate an improvement in terms of discrimination of benthic components when employing airborne hyperspectral imaging to characterize coral reefs.

One of the acknowledged difficulties when using remote sensing applied to coral reef environments is spatial resolution (Garcia et al., 2018; Holden and LeDrew, 2001; Karpouzli et al., 2004). Small patches remain within a pixel size even with fine resolution (Kobryn et al., 2013), so the structural complexity of coral reefs leads to problems with mixed pixels as a result of high spatial heterogeneity. Addressing the issue of mixed pixels using would require classifying not only biologically uniform benthic components, but also pixels with a realistic mix of component types occurring in coral reefs (Petit et al., 2017). The accuracy of image geometric registration could also be a concern in the context of change detection based on remote sensing data (Garcia et al., 2014). Change detection algorithms may result in false estimates of change, especially in the areas of rapid spatial variation such as edges. Even if this issue can be accounted for by using spatial–contextual information contained in the neighborhood of each pixel (Coppin et al., 2004), it would be important to explore the possibility of developing change detection techniques that can bypass the registration process constraint and defect.

In Reunion Island (South-West Indian Ocean), coral reef monitoring programs are being carried out as part of the Global Coral Reef Monitoring Network (GCRMN) that started in 1998 (Chabanet et al., 2002), the Reef Check initiatives and the Water Framework Directive (WFD). Given the high heterogeneity of coral reef communities in shallow waters (Scopélitis et al., 2009), and their proximity to land, large scale surveys of the whole shoreward reef area would allow evaluation of impacts in areas that are difficult to access and that are likely most exposed to damage and human impacts. To our knowledge, only one study to date has attempted to detect coral reef community change on Reunion Island at Saint-Leu reef by integrating *in situ* and manual delineation of remote sensing data (Scopélitis et al., 2009). Even if this study provided an improved basis for judging the status of the coral communities, the coral cover, regarded as the most efficient indicator of coral reef health (Huang et al., 2018), could not be evaluated over time for the entire reef.

Using a spatial approach based on high resolution multispectral and hyperspectral image analysis, the present study aims to draw, for the first time, a baseline of current coral reef status in Saint-Gilles, a highly heterogeneous shallow reef flat in Reunion Island, that complements observations recorded with conventional *in situ* methods. The first objective was to develop an automatic image processing methodology which could be repeated over time to extract accurate spatial quantitative metrics on benthic coral reefs. Coral reef health status was evaluated through coral cover estimates and a new index called Hyperspectral Coral to Algae Index (HCAI), in addition to geomorphological features of the reef. A second objective was to illustrate, through a diachronic analysis between 2009 and 2015, the value of hyperspectral and multispectral imagery in quantifying spatial-temporal changes for metrics extracted using the developed method. Previously identified issues related to mixed pixels and limitations in geometric registration accuracy were taken into account by using respectively unmixing models and post-processing techniques. A benthic classification map was also generated for the Saint-Gilles reef flat which revealed consistency with the observed variations in habitat distribution. We demonstrate that such techniques open new opportunities for evaluating coral reef flat status at large spatial scales.