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Exploring the relationships between biodiversity and benthic habitat in the Primeiras and Segundas Protected Area, Mozambique

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Exploring the relationships between biodiversity and benthic habitat in the Primeiras and Segundas Protected Area, Mozambique
Undersökning av relationen mellan biodiversitet och havsbotten miljö i det skyddade området Primeiras och Segundas, Moçambique
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Master thesis, 30 credits, in Geomatics

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Abstract

The Primeiras and Segundas Archipelago Reserve, located in the waters of northern Mozambique, is the largest marine protected area in Africa, extending over 200 km of coastline. Despite the region's importance for the local economic, information on the marine ecosystem, notably benthic habitat, is very scarce. Twelve atolls were mapped in the region using object-based image classification of very-high resolution satellite imagery (IKONOS, Quickbird, and WorldView-2). Geographically referenced data on benthic cover and depth were gathered in the course of three fieldwork expeditions covering a total of four atolls and two shallow reef structures. The resulting maps allow the estimation of three distinct types of coral cover (field, patches, spurs and grooves); the differentiation of sand, rubble and rock substrate; and the detection of seagrass and brown macroalgae, identifying up to 24 benthic habitats with overall accuracy above 50%. New information indicates the presence of deep benthic cover extending from the atolls, suggesting the need for further research, and supporting current knowledge of the existence of an almost continuous coral reef from Kenya to Mozambique. The results of the analysis of coralline and ichthyological data support the local perception that ecosystems are in decline. It was not possible to verify its connection with fishing practices and the assumption of greater fish biodiversity farther away from the main fishing harbour, i.e. in the southern islands. This work provides a detailed depiction of marine habitats adequate for standard management and planning purposes, namely in the definition of fishing zones and coral cover monitoring, while contributing to the advance of the application of remote sensing to the biodiversity and conservation fields.

Keywords: Geography, Physical Geography, Very-high resolution remote sensing, Object-based image classification, Benthic habitats, Coral reef, Fish biodiversity

Resumo

A Reserva dos Arquipélagos Primeiras e Segundas, localizada no norte de Moçambique, é a maior zona marítima protegida de África, estendendo-se por mais de 200 km de costa. Apesar da sua importância para a economia local, informações sobre os seus ecossistemas marinhos, e particularmente habitats bênticos, são escassas. Doze atóis foram mapeados na região usando *object-based image classification* de imagens de satélite de muito alta resolução (IKONOS, Quickbird, and WorldView-2). Dados georreferenciados sobre a superficie bêntica e profundidade foram recolhidos em três campanhas de campo, abrangendo um total de quarto atóis e dois baixos. Os mapas produzidos permitem a estimativa de três tipos distintos de superfície coralina (campo, retalhos e falésias), a diferenciação de areia, cascalho e rocha e a detecção de ervas marinhas e macroalgas castanhas, identificando-se até 24 habitats bênticos, com precisão média superior a 50%. Novas informações recolhidas indicam a presença de superfícies bênticas profundas a prolongarem-se dos atóis, o que sugere a necessidade de pesquisa adicional, e está de acordo com o conhecimento actual da existência de um recife de coral quase contínuo desde o Quénia até Moçambique. A análise da biodiversidade das comunidades coralinas e ictiológicas apoia a percepção local de que os ecossistemas estão em declínio. Não foi, no entanto, possível confirmar a sua ligação a práticas de pesca, nem o pressuposto de que a biodiversidade de peixes é maior nas ilhas mais a sul, i.e. longe do principal porto de pesca. Este trabalho contribui para uma descrição detalhada dos habitats marinhos, adequada a usos de gestão e planeamento típicos, nomeadamente a definição de zonas de pesca e monitorização da superfície coralina, contribuindo simultaneamente para o desenvolvimento da aplicação de detecção remota aos campos da biodiversidade e conservação.

Palavras-chave: Geografia, Geografia Física, Detecção Remota de Muito Alta Resolução, Object-based image classification, Habitats bênticos, Recife de coral, Biodiversidade de Peixes

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Finally, thank you Ludwig, for flying down to meet me.

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1. Introduction

The Primeiras and Segundas Archipelagos, northern Mozambique, together with part of the coastline, were declared an Environmental Protected Area in November 2012, forming the largest marine reserve in Africa (WWF 2012). WWF has been active in the region for the past ten years and, together with local actors, developed work on biodiversity conservation, overfishing and illegal tourism, the main problems identified in the region (WWF 2012).

In the report of the 2012 southern Indian Ocean Regional Workshop to Facilitate the Description of Ecologically or Biologically Significant Marine Areas, the Primeiras and Segundas are said to belong to *"the largest and [to be] among the most productive fisheries area in Mozambique attaining close to 50% of the entire industrial catches", "with probably the most pristine coral reefs in Mozambique", being "important for connectivity between northern and southern reefs"* (CBD 2013). Previous research in the region (Whittington and Heasman 1997, Schleyer 1999, Celliers and Schleyer 2000, Pereira and Videira 2007, Delacy, Bennett et al. 2014) gathered data on coral and fish biodiversity and although referring to impressive coral diversity, expressed concern about decreasing fish numbers.

The project to create benthic habitat maps for the region, initiated by WWF-Germany and supported by ESA's G-ECO-MON initiative, aimed to increase knowledge of the spatial distribution of reef ecosystems, and support improved management and planning. By integrating existing biodiversity data with the newly created maps, further knowledge can be acquired, and unknown spatial patterns uncovered, contributing to a more complete and comprehensive portrait of the local ecosystem.

1.1. Objectives and aims

The main objective of the present work is to explore the relationships between biodiversity and benthic habitats in the Primeiras and Segundas Protected Area, Mozambique. As such, the present work intends to build on the following questions:

- How are the benthic habitats distributed in the region?
- How are the biodiversity indicators distributed in the region?
- Is there evidence of biodiversity decline?
- Are there significant relationships between benthic habitats and biodiversity indicators?

1.2. Document organization

The current chapter, 1, introduces the thesis topic, its main objectives and goals and the current document organization. Chapter 2 provides background information on benthic habitat mapping and biodiversity analysis. The study area is presented in Chapter 3, while Chapter 4 focuses on the data and the rationale and methods behind its collection and analysis. Chapter 5 shows the obtained results, Chapter 6 expands on its discussion and Chapter 7 gathers the main conclusions. Finally, a brief reflection about the developed research, together with recommendations for further work, is presented in Chapter 8.

2. Benthic habitats mapping

2.1. Remote sensing

Mapping natural resources is a basic requirement for any conservation plan or management strategy and as such *“the science of coral reef remote sensing has emerged, in many respects, in response to management needs.”* (Goodman 2013) Managers often rely on remote sensing to gather information on baseline conditions, to inventory resources, to assess threats and monitor disturbances, to define priority conservation zones and to measure the effectiveness of management decisions.

Passive remote sensing sensors, such as multispectral ones, have been successfully used for mapping coral reefs and associated benthic habitats for the past 40 years (UNESCO 2000, Goodman 2013). Data on coral reefs ecosystems’ properties and processes has been retrieved, estimated and modeled based on satellite imagery, including extent, composition, biophysical attributes, biogeochemistry and geology (CRTR Remote Sensing Working Group 2010, Wang, Franklin et al. 2010). High spatial and temporal resolutions, continuous data availability, global coverage and relatively low costs are the reasons why multispectral instruments have been the sensors of choice worldwide for coral reef mapping.

Results will mainly depend on image characteristics such as spectral bands and spatial resolution, and cover properties. It is fundamental to ensure sea bottom visibility, usually by including the blue band. Although not strictly required, signal in the blue band will greatly improve overall results, as this is the multispectral band with the best water penetration. The selection and application of adequate techniques to compensate for the influence of the water column and water surface interactions (Figure 1), such as sun glint, are of particular relevance (UNESCO 2000, Goodman 2013).

It is generally held that it is not possible to map coral reefs effectively at depths deeper than 25 meters, although the most frequently mentioned limiting depth is around 10-15 meters (UNESCO 2000, Mellin, Andréfouët et al. 2009, Goodman 2013).

The quality of the habitat mapping results will depend on the image processing techniques used, the field data acquired, and the level of habitat discrimination desired, i.e. number of classes (UNESCO 2000).

Due to high heterogeneity of benthic covers and variability of the spatial scales, spectral signatures of reef features are often mixed. For example, coral features can cover extensions ranging from centimeters to meters in length scale, while algaes can appear as single individuals among coral, or as dense, large areas. This poses a challenge for accurate image classification, particularly when a high number of classes are desired. Hyperspectral sensors are suggested as an improved alternative for this purpose, as their narrower spectral bands allow a more effective separation of similar reflectance profiles (CRTR Remote Sensing Working Group 2010).

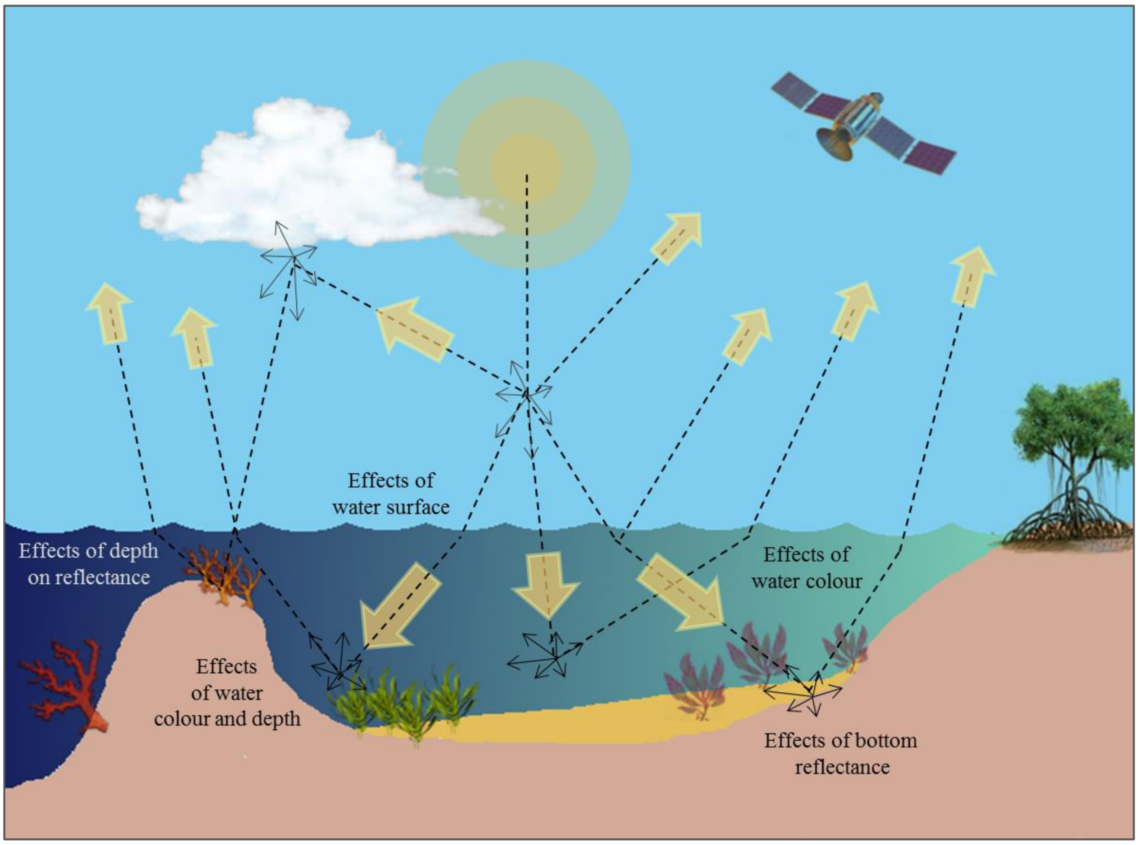

Figure 1 – Influences and effects of environmental aspects on reflectance for coral reef mapping (adapted from Goodman (2013))

The number of benthic covers that can be mapped increases with the number of spectral bands and decreases with pixel size (UNESCO 2000, Goodman 2013), which leads to an increasing preference for high and very-high resolution imagery in coral reef remote sensing projects.

High and very-high resolution imagery has been successfully used in the mapping of coral, bleaching, structural complexity, geomorphology and bathymetry, as well as for habitat classification (Andréfouët, Kramer et al. 2003, Capolsini, Payri et al. 2003, Knudby, LeDrew et al. 2010, Roelfsema, Phinn et al. 2010). Results have shown that benthic habitats can be mapped using very-high resolution multispectral satellite imagery with accuracies of about 80% for 10 to 12 classes (Table 1), while accuracies up to 70% are expected for lower resolution imagery (UNESCO 2000, Andréfouët, Kramer et al. 2003). Total number of classes vary between 5 and 26 in previously published work (Mellin, Andréfouët et al. 2009).

Table 1 – Characteristics of very-high resolution satellite sensors and typical accuracy results for coarse classification of approximately 6 classes (adapted from (Goodman 2013))

Sensor	Spatial resolution (m)	Number of bands	Revisit time (days)	Accuracy (%)
IKONOS	4	4	3	75-90
QuickBird	2.5	4	1-3.5	80
GeoEye-1	2	4	3	N/A
WorldView-2	2	7	1.1-3.7	N/A

Hierarchical classification schemes are usually based on geomorphological and ecological classes. While ecological classes have very blurry boundaries, and can be very subjective and challenging to define, geomorphological zones can usually be defined with an adequate degree of accuracy without field data (Mumby, Green et al. 1997, UNESCO 2000, Andréfouët 2012). As geomorphological classification is defined by depth and currents exposure, which also determines habitat distribution, the creation of this first level zonation can improve subsequent classification results (UNESCO 2000, Andréfouët, Kramer et al. 2003, Goodman 2013). This is most obvious when same benthic habitat displays slightly differing characteristics according to zone, such as a sandy bottom, which can have more algae cover on a protected lagoon than on a more exposed reef front.

There are, currently, some hierarchical schemes that attempt to systematize coral reef classification (Mumby and Harborne 1999, Andréfouët 2012) (Figure 2). Despite, following the same reasoning and overall structure, there are currently no standardized benthic habitat classification scheme, and the existing ones are not easily transferrable among different marine zones (Andréfouët, Kramer et al. 2003).

Visual interpretation, as well as knowledge of the local ecosystem, plays a significant role in coral reef mapping. This processing step, referred to as contextual editing and described as *"the application of common sense to habitat mapping"* by Mumby, Green et al. (1997), allows taking into account known patterns of habitat distribution that are not easily perceived through spectral signal alone. In the same study, seagrass beds and fore reef escarpments, although having similar spectra, existed in distinct geomorphological zones and could therefore be correctly reclassified. A significant number of studies refer to prior knowledge of the local system, or of coral reef mapping in general, as a significant aspect of their methodological approach (UNESCO 2000, Andréfouët, Kramer et al. 2003, Andréfouët 2008, Goodman 2013, Roelfsema, Phinn et al. 2013). Contextual editing is a usual step in benthic habitat mapping methodologies to improve map quality, as well as to quick and efficiently put into place topological rules (Andréfouët, Kramer et al. 2003, Andréfouët and Guzman 2005, Goodman 2013).

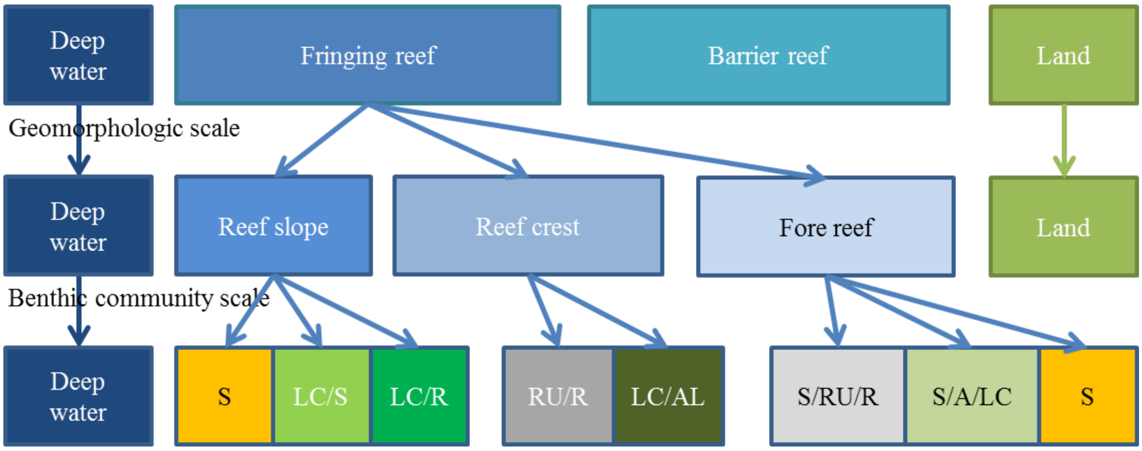

Figure 2 – Example of an hierarcical classification of coral reef systems (adapted from Roelfsema, Phinn et al. (2013))

Most recently, object-based image analysis (OBIA) has been increasingly applied to the mapping of coral reef systems. In OBIA, successive segmentation and classification of the dataset based on spectral, textural, spatial and topological properties allows for a more tailored image processing when compared to pixel based approaches (Goodman 2013). This procedure is similar to the way the human eye processes information, grouping similar features, and recognizing patterns (Blaschke 2008).

The main advantage of OBIA for coral reef mapping is the possibility to work on different spatial levels, while keeping a hierarchical connection between them (Figure 3). The integration of both geomorphological and benthic habitat characteristics into a single scheme, and the possibility of applying distinct rules at each hierarchical level, fits the functional breakdown of coral reef systems. Moreover, the use of spatial relationships can be very helpful, including parameters such as distance to other objects, asymmetry and direction.

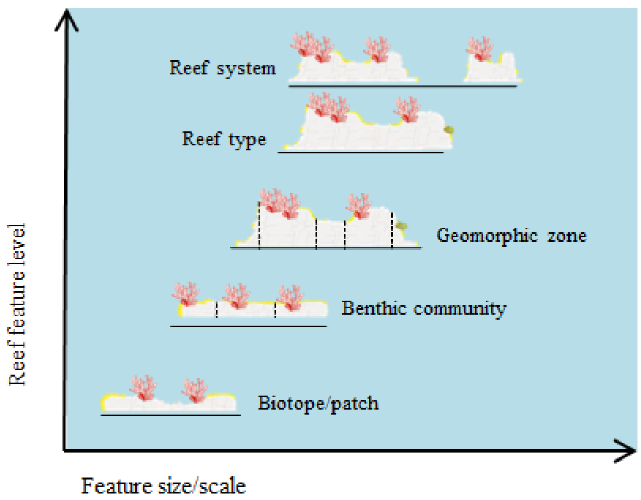

Figure 3 – The variation of coral reef mapping detail with spatial scale (adapted from Phinn, Roelfsema et al. (2011))

Finally, OBIA is well suited for very-high resolution imagery. The ability to aggregate individual pixels into objects, according to other factors than only spectra, and thus highlighting patterns, is expected to provide a better response to mixed pixels, and an overall improved differentiation within classes with similar spectral signatures (Blaschke 2008). The application of OBIA techniques to coral reef mapping makes it possible to increase the number of classes without compromising accuracy results (Roelfsema, Phinn et al. 2013).

2.2. Biodiversity analysis

Benthic habitat maps have been used, among others, in the creation and evaluation of marine protected areas (Dalleau, Andrefouet et al. 2010, Rioja-Nieto, Barrera-Falcón et al. 2013), in the estimation of habitat diversity (Mumby, Broad et al. 2008), and in the evaluation of coral reef health status (Goodman 2013). Based on field data, usually quite restricted in extent due to large collection effort, information can be extrapolated through the application of remote sensing techniques.

Following the same principles applied to terrestrial landscapes, the health of coral reefs ecosystems can be coarsely assessed by total area and proportion of live coral, and its diversity through the number of different species there observed (Andréfouët and Guzman 2005). Likewise, habitat variability is considered an adequate surrogate for estimating biodiversity in coral reefs (Mumby, Broad et al. 2008, Dalleau, Andrefouet et al. 2010). Although many studies report significant relationships between fish and habitats metrics, results are not sufficiently consistent to allow the establishment of generic rules (Knudby, Roelfsema et al. 2011).

"The most striking lesson" from a 2009 review of remote sensing and fish habitat relationships in coral reef ecosystems (Mellin, Andréfouët et al. 2009), *"is that studies do not corroborate each other"*. Relationships showed considerable variation, *"without suggesting any clear converging conclusion or generic rule of fish assemblages across different scales"*. Reviewed studies were considered very specific and unique regarding sampling and analysis methodologies, with no common framework. Nonetheless, the merits of remote sensing were emphasized, together with the need to include both fieldwork and remote sensing in a *"coherent conceptual scheme spanning all spatial and ecological scales, across a gradient of contrasted levels of perturbations on reefs and fish communities"*.

It is nonetheless accepted that the higher the map complexity, the better results can be expected when using habitats as surrogates for biodiversity parameters (Dalleau, Andrefouet et al. 2010, Knudby, Roelfsema et al. 2011).

With the availability of higher spatial resolution imagery, a much wider range of study scales has become available for fish community analysis and modelling, an aspect explored in several studies (Dalleau, Andrefouet et al. 2010, Knudby, Roelfsema et al.

2011). Relevant spatial scales vary according to habitat, species and biological processes (Mellin, Andréfouët et al. 2009). At scales from 0.1-10 km, adjacent benthic habitats are key variables on diversity, composition and abundance. Habitat connectivity influences abundance of different stages of fish life, as there can be a high mobility throughout their development. As benthic habitats are dependent on distance to coast, hydrodynamics and topography, analysis at benthic habitat scale provides an indirect linkage to the main variables determining processes at wider scales. When above 10 km scales, latitude and longitude also play a significant role, together with surface of available habitat, and species diversity is expected to increase with reef size (Mellin, Andréfouët et al. 2009). Knowledge of the most adequate modelling scale helps guide sampling and, consequently, improving the successful integration of field data in remote sensing processes.

Moreover, the application of remote sensing to fish assemblages mapping has clear financial advantages when compared to extensive field work, many times in remote locations. By integrating field data with remote sensing, it is possible to cover much larger areas, and develop predictions of fish community throughout whole reef structures (UNESCO 2000, Goodman 2013).

Depth, structural complexity, substrate type, habitat diversity and live coral cover, which can be estimated from multispectral remote sensing techniques, have been shown to relate to fish assemblages (Knudby, LeDrew et al. 2010, Knudby, Roelfsema et al. 2011). Likewise, geomorphology, reef type and benthic assemblages are considered key components in habitat definition for fish data modelling (Mellin, Andréfouët et al. 2009, Knudby, Roelfsema et al. 2011). It is known that rugose benthic habitats such as complex topologies of coral, rocks and vegetation offer refuge from predators and breeding grounds. As such, zones with seagrass bed, coral reefs and algal assemblages are expected to have increased species richness when compared to clearer, less complex habitats (McArthur, B. et al. 2009).

The most commonly used fish variables are species richness (total number of fish species), species diversity (e.g. Shannon indice), abundance (total number of individuals) and biomass. These variables can be further categorized according to functional groups (diet, mobility) and ontogenetic states (juveniles or adults) (Mellin, Andréfouët et al. 2009).

3. Study area

The Primeiras and Segundas Environmental Protected Area (PSEPA) is defined around the two Archipelagos of the same names (Figure 4). It extends for more than 1 000 000 hectares, over 200 km of coastline, spreading over the Pebane, Moma and Angoche districts in northern Mozambique (WWF 2012).

The region is comprised of a diversity of habitats – mangroves, seagrass beds, coral reefs – forming a larger coastal ecosystem that supports the locally high biodiversity (WWF 2012). Moreover, the existence of deep underwater canyons with cold nutrient-rich upwelling, that could support rare species such as the coelacanth and is likely protecting the coral reef from bleaching events, makes these some of *"the most globally productive and important reefs on the planet"* (WWF 2012).

Each archipelago includes five islands, although Segundas, further north, also includes two banks ("baixo" in Portuguese). These archipelagos are believed to be the most southern of an almost continuous series of reefs that extends for 700 km to the Rovuma river mouth, and further on to Tanzania and Kenya (Hoguane 2007, Pereira and Videira 2007).

The islands, located parallel to the coastline between 16° 12'S and 17° 17'S, build on a rock substrate of cemented dunes formed during the Pleistocene as a result of decreasing average sea levels (Pereira and Videira 2007). The complex of sandbars and rock outcrops close to the edge of the continental shelf represent the limited substrate available in the area for coral reef formation (Whittington and Heasman 1997).

The local economy relies on fisheries, and the PSEPA harbours artisanal, semi-industrial, and industrial fisheries activities. The islands are used as seasonal fishing centers. The coastal populations are highly dependent on fishing, mainly for subsistence but also for financial purposes. There is general understanding that decreasing fish stocks are due to increasing numbers of fishermen. Industrial fishing has been growing, increasing pressure on marine resources. The overfishing problem is estimated to affect about 750 000 people (de Abreu, Costa et al. 2008).

The region's climate is tropical savanna (Aw) according to the Köppen classification, with a local yearly average temperature of 26 °C. Monsoon influenced trade winds predominate, changing from Northeast during the summer or wet season (October to March) to southwest in winter or dry season (April to September) (Hoguane 2007).

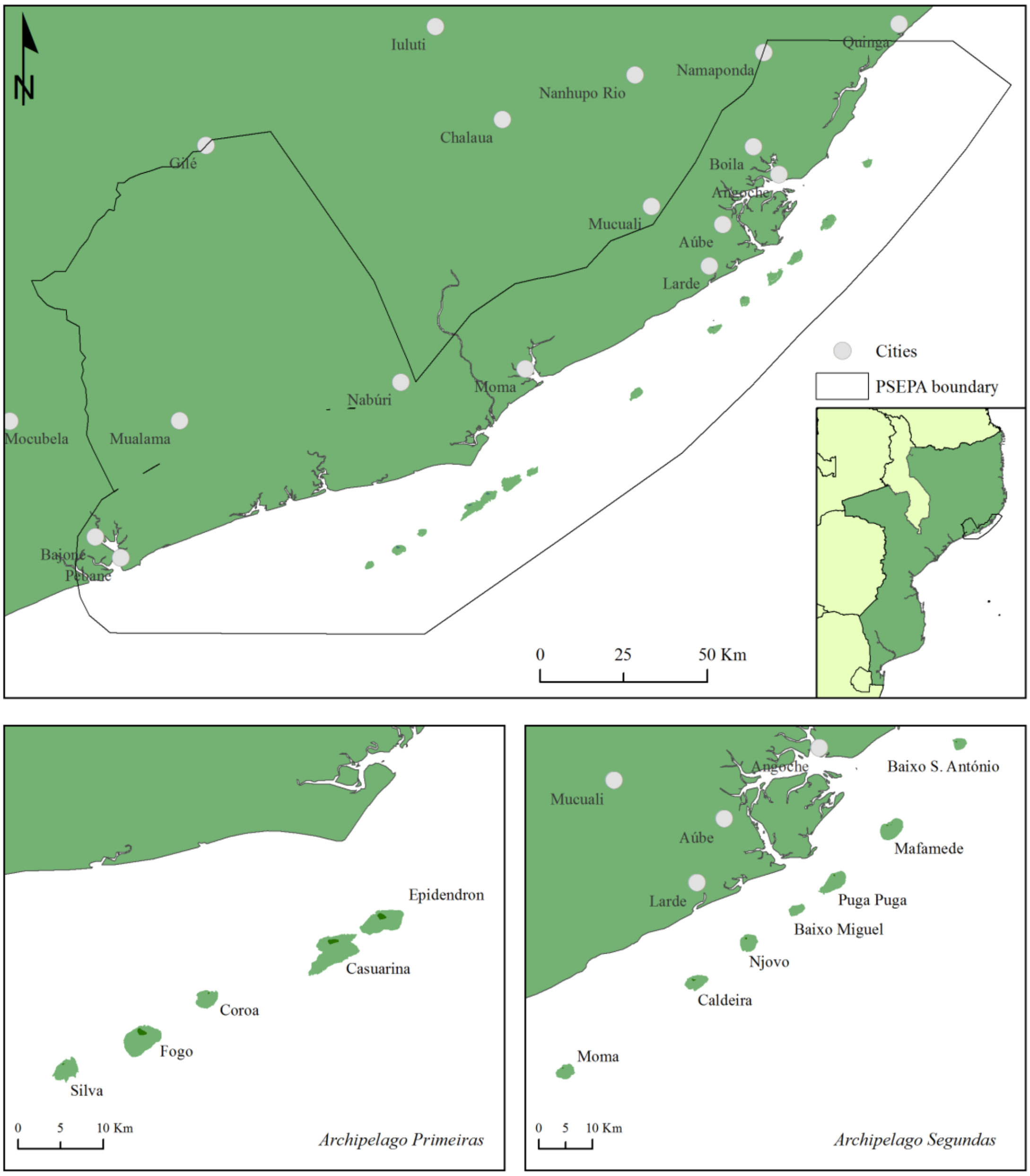

Figure 4 – Primeiras and Segundas Environmental Protected Area

Local waters are warm and have approximately 3.5% salinity, adequate for the formation of coral reefs (Pereira and Videira 2007). The general direction of the strong offshore currents is southeast, changing north at 100-150 meters deep. The large current variability is likely due to the sea floor bathymetry and predominant tidal waves, although turbulence is also resulting from upwelling (Johnsen, Krakstad et al. 2008).

Tidal variation can amount to about 4 – 5 meters, and the rocky reef tops can become exposed during low tide. Smaller islands such as Silva, Coroa, Puga Puga and Mafamede, under 2 ha, display little or no vegetation, while Fogo, Casuarina, Epidendron and Njovo, which are larger, sustain some forested area (Pereira and Videira 2007, de Abreu, Costa et al. 2008).

The islands are surrounded by fringing reef in a semi-circle shape. The lagoons, made of sand, coral rubble and seagrass beds, are shallow. In the southeast section, facing the open ocean, massive coral colonies can be seen sporadically (de Abreu, Costa et al. 2008). The islands have relatively exposed northern, eastern and southern sides, the latter usually being subject to the influence of monsoon winds (Whittington and Heasman 1997). In general, the most developed and diverse reefs occur in the most protected zones of the islands, i.e. facing mainland (de Abreu, Costa et al. 2008).

The earliest references to research in Primeiras and Segundas Archipelagos date from 1971 and focus on the state of sea turtles and dugong populations (Hughes 1971) and on environmental coastal conservation (Tinley 1971) in Mozambique. Following that, a 1983 review of the state of the western Indian Ocean coral reefs refers to the region as *"on the brink of collapse"* (Salm 1983).

More than 10 years later, a first rapid assessment was conducted in the Segundas Archipelago for the assessment of commercial fish populations status (Whittington and Heasman 1997). The study, restricted to the two most northern reefs (Baixo S. António and Mafamede) concluded that hard coral development was poor, with soft coral dominating the shallower areas and a mixture of soft coral and macroalgae at deeper depths. However, dense, low-lying hard coral cover was found in the south, in a highly developed spur and groove zone extending over 20 meters deep, very likely shaped by prevailing southern monsoon winds. Fish of commercial interest was reported to be abundant and diverse, particularly at the boulder fields to the north and at the spur and groove zone to the south, and fishing pressure was assumed to be relatively low. The same study indicated that coral reef development on the mainland side was poor due to freshwater input, shallow coastal waters and soft sediments of the inshore seabed.

Then, in 2006, a rapid assessment was performed as part of the effort to push forward the creation of a national Environmental Protected Area. The study focused on the coralline and ichthyological communities of shallow, above 15 meters, coral reefs. The report signaled overfishing, as large fish specimens and species of commercial value were mainly absent, particularly in the Primeiras Islands. The study's conclusions support the *"idea that the Primeiras and Segundas Islands reefs are among the most remarkable in Mozambique, both as regards biodiversity and state of conservation"* (Pereira and Videira 2007, de Abreu, Costa et al. 2008). Emphasis was put upon the need for ecosystem protection systems.

A follow-up rapid assessment was conducted in 2010, but its results have not yet been published. Nonetheless, collected coralline data results were made available (Pereira and Rodrigues 2014).

4. Material and Methods

The present's work overall methodology (Figure 5), which can be divided into fieldwork, benthic habitat mapping and biodiversity analysis, will be described in detail in the following sections.

4.1. Fieldwork

The fieldwork was comprised of two surveys for data gathering in the Segundas Archipelago. The first was from 15 to 17 of April 2014 on the islands of Mafamede, Puga Puga and Njovo, as well as Baixo Miguel, and the second on 10 and 11 of May 2014 on the island of Caldeira and Baixo S. António. The fieldwork was conducted by the author and the colleague Martin Nilsson, together with one representative from the CARE-WWF Alliance, one representative from the Associação de Pescadores Artesanais de Angoche (APAA, Angoche Artisanal Fisheries Association) and one to two seamen.

Data points were taken along routes at 80 – 150 meters intervals, as displayed on a GPS receiver, with a focus on benthic cover changes. The routes were adjusted to the tidal and geomorphologic characteristics of the islands, so as to allow safe navigation. The first, during the morning, was defined as the circumnavigation of the island and lagoon system outside the reef crest. The second, during early afternoon, was restricted to the lagoon, which can only be navigated during high tide. The lagoon routes were adjusted so as to cover previously defined zones of interest, based on the satellite imagery. The point count was designed to be approximately 200 points per island.

A total of 666 data points were collected. Each point comprised geographic coordinates, depth and benthic cover. Location was captured with a Garmin Montana 650t GPS, while depth was measured with a HawkEye H22PX handheld sonar system. Benthic cover was observed from the boat using a clear bottom bucket and recorded using simple descriptive categories. Additional comments, including more details of the cover, were also recorded, and underwater photographs were taken at selected locations to illustrate different benthic cover types (Appendix I.). Each point collection was made from a slowly moving boat, due to the difficulty and time consumption associated with attaining absolute "stillness".

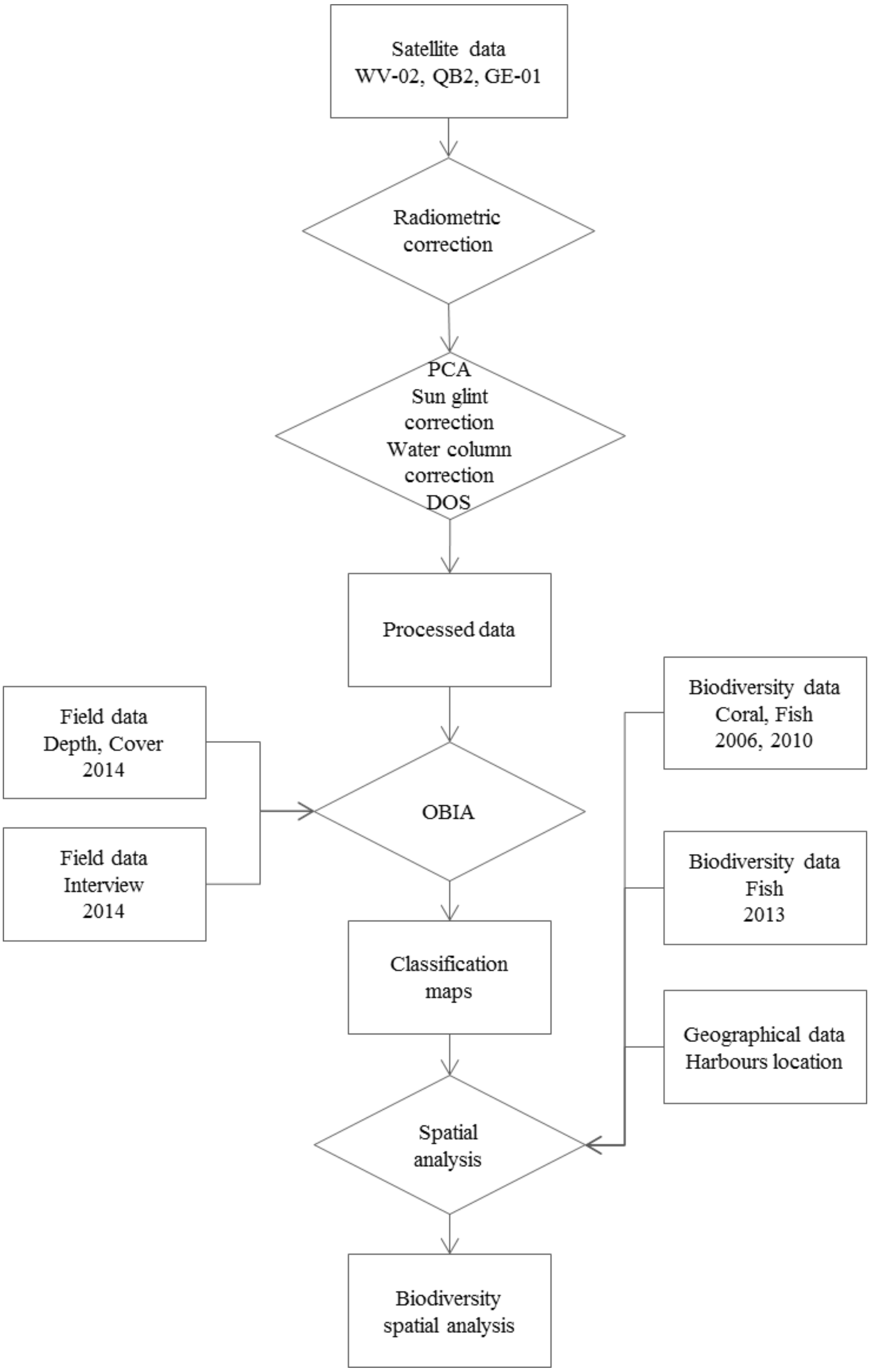

Figure 5 – Methodological overview scheme

The pixel size of the satellite imagery was considered in the sampling scheme by assessing the benthic cover over a radius of at least four meters. Additionally, point data was retrieved preferably within features and where changes of benthic cover were observed, which lead to a flexible sampling frequency.

The summary of the conducted field surveys is presented in Table 2. The spatial distribution of the field data, together with an overview of the registered depths, can be seen in Appendix II.

Table 2 – Field survey details (date and time period) and sample distribution

Location	Date	Period	Sample size	
			Partial	Total
Mafamede	15.4.2014	Morning	137	176
		Afternoon	39	
Puga Puga	16.4.2014	Morning	70	103
	17.4.2014	Afternoon	33	
Njovo	17.4.2014	Morning	-	127
Baixo Miguel	17.4.2014	Morning	-	29
Caldeira	10.5.2014	Morning	70	130
		Afternoon	60	
Baixo S. António	11.5.2014	Morning	-	101
				666

4.1.1. Interviews

Representatives from Government, Industry, Non-Governmental Organization and Research previously identified by WWF and Care as knowledgeable on conservation and development aspects in the region were interviewed (Table 3).

Table 3 – Representatives from each identified group of interest

Sector	Institution	Position	Name
Government	IDPPE	Province Representative	Isidro AbuchahamaIntave
Industry	Diamante Mariscos	Manager	Sarojakshan Sugunanandadas
	SG Global	Manager	Miguel Costa
NGO	APAA	President	Sabino Omar
	WWF-Mozambique	Former Head of Rangers of P&S	Bernardo Cachimo
		Marine Officer	Cremildo Armando
	Independent consultant	Former Project Manager of PSEPA	John Guernier
Research institutions	*No responses were obtained*		

The interviews aimed at acquiring further information to provide the contextualization of the physical data within a wider sustainability scope and to support in future field surveys. Focus was put on benthic cover (type, location, perceived changes), atmospheric and maritime conditions (wind and current direction and strength, seasonality), and marine fauna (location of different catches, current fishing methods and outcomes, perceived changes). Additionally, managers and decision-makers were questioned on aspects such as map purpose and desirable characteristics (classes, level of detail, analysis), and local pressures and impacts (inter-connections, dynamics).

Open questions were used so that each interviewee could express views according to their expertise and knowledge. Unfortunately, there was no response from the representatives from Research that were contacted.

4.2. Benthic habitat mapping

The mapping of the benthic habitats was performed according to an object-based approach using the Trimble eCognition Developer software and very-high resolution imagery acquired between 2009 and 2013 (Figure 6, Table 4).

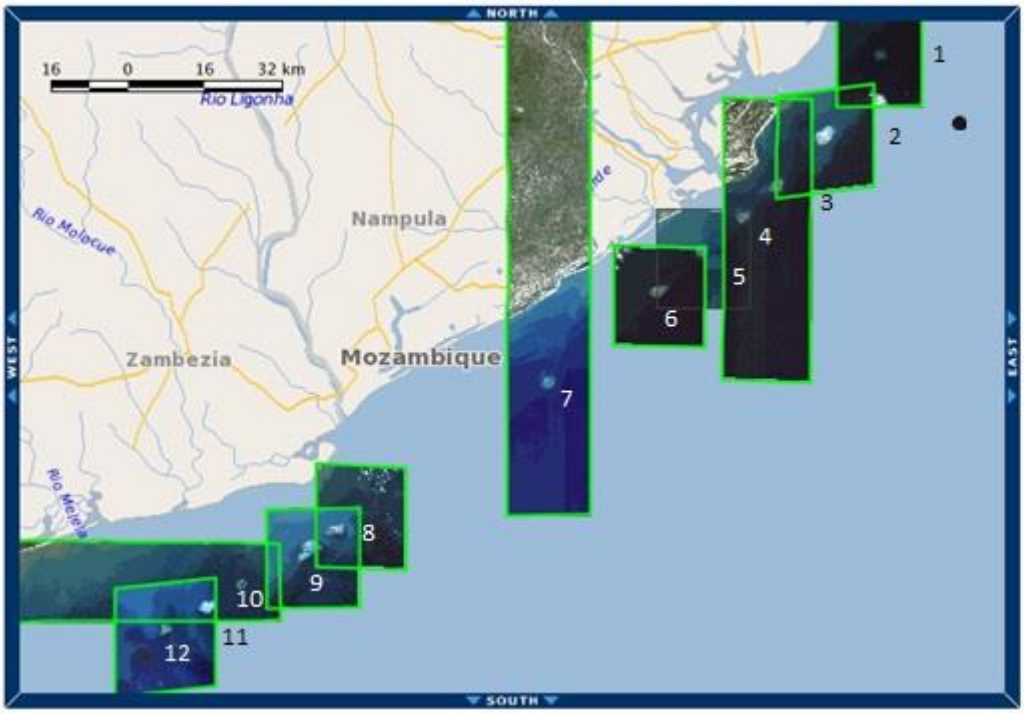

Figure 6 – Preview of the selected very-high resolution scenes; numbering as in Table 4 (courtesy of Hedley (2014))

Table 4 – Sensor, acquisition date, time and comments on visibility for the imagery covering each location

	Archipelago	Locations	Sensor	Acquisition date	Acquisition time	Comments
1	Segundas	Baixo S. António	WV-2	07.12.2009	07:36:08	No whitecaps Deep areas visible
2		Mafamede	WV-2	18.12.2009	07:34:16	Deep areas visible
3		Puga Puga	QB 2	11.05.2010	07:31:05	Clear waters
4		Baixo Miguel	QB 2	11.05.2010	07:31:05	Clear waters
5		Njovo	WV-2	09.01.2010	07:32:59	No glint Clear waters
6		Caldeira	WV-2	29.12.2009	07:34:14	No whitecaps No glint Clear waters
7		Moma	WV-2	03.06.2013	08:01:12	No whitecaps
8	Primeiras	Epidendron	WV-2	07.12.2009	07:36:41	Deep areas visible
9		Casuarina	WV-2	18.12.2009	07:35:10	Clear waters
10		Coroa	GE-1	23.03.2011	07:35:00	Deep areas visible Clear waters
11		Fogo	GE-1	23.03.2011	07:35:00	Deep areas visible Clear waters
12		Silva	WV-2	18.12.2009	07:34:47	Clear waters

Imagery had undergone standard pre-processing from the provider (DigitalGlobe 2010). The resolutions varied according to sensor as presented in Table 5.

Table 5 – Standard resolution of the selected imagery according to sensor (DigitalGlobe 2010)

	Resolution (m)
GeoEye-1	1,65
WorldView-2	1,84
QuickBird 2	2,88

4.2.1. Processing

Processing, performed with Clark Labs IDRISI Selva software, was adapted to each image's characteristics in order to maximize the visual quality of its output. As such, processing steps were not applied in exactly the same way to all scenes (Table 6). Nonetheless, the general approach was identical, and consisted of a combination of the following:

- ***Radiometric correction*** concerns the practice of removing undesirable "noise" influences from the atmosphere and sensor system (Campbell 2006). As the imagery had already undergone sensor specific corrections to account for issues with the sensor system, only conversion to top-of-atmosphere radiance was applied (DigitalGlobe 2010).
- ***Principal Components Analysis (PCA)*** allows removing noise from a dataset by separating each image band into a set of components that explain progressively less the variance of the original image. Components accountable for less than a

certain amount of the variance, believed to result from noise, can then be removed (Eastman 2012).

- ***Dark Object Subtraction (DOS)*** is based on the concept that the theoretical minimum value in a scene is null and as such the lowest reflectance found in a dataset are due to noise and consequently could be extracted. This assumes the presence of an object empirically considered to have no reflectance, such as an area known to be deep water (Campbell 2006).
- ***Sun glint correction*** attempts to correct for the specular reflection of light on water surfaces. The method here applied uses NIR as an indicator of sun glint influence, as introduced in Hedley, Harborne et al. (2005).
- ***Water column correction*** makes it possible to account for differences in depth, which have a large impact on the bottom reflectance. To mitigate this effect Lyzenga (1978, 1981) put forth an algorithm that produces depth-invariant bottom indexes from pairs of spectral bands.

Table 6 – Processing steps performed at each location

Location	Radiometric correction	PCA	DOS	Sun glint correction	Water column correction
Baixo S. António	*		*	*	*
Mafamede	*	*		*	*
Puga Puga	*		*		*
Baixo Miguel	*		*		*
Njovo	*	*		*	*
Caldeira	*	*		*	*
Moma	*		*		
Epidendron	*		*	*	*
Casuarina	*		*	*	*
Coroa	*	*		*	*
Fogo	*	*		*	*
Silva	*	*	*		

4.2.2. Classification

The classification was performed using the Nearest Neighbor classification algorithm of Trimble eCognition Developer software. Feature Optimization tools were used and empirical sampling of benthic cover was integrated on the approach. Contextual editing was applied to known situations of misclassification, and was kept to a minimum.

A benthic habitat classification scheme, including geomorphological, bottom cover and benthic habitat levels, was developed based on previous schemes (Mumby and Harborne 1999, Rohmann 2008, Andréfouët 2012). The hierarchical classification was adapted to the field data and imagery so as to maximize the variety of benthic habitats included, provided an adequate level of confidence in the recognition of features. The scheme, as it was applied, is presented in Table 7.

The general method was to use fieldwork data coupled with characteristics of major constituents – sand, rubble, rocks, seagrass, algae and coral, as described in Appendix III.

Using acquired knowledge on substrate, location and surrounding environment, both from the field surveys and from the analysis of the gathered data, training sites were selected for the Nearest Neighbor classification algorithm. In doing so, it was possible to reserve the collected data points for accuracy assessment. This approach was chosen because the dataset was too small to be divided into training and validation subsets. Furthermore, this approach supported the classification of the locations lacking *in situ* measurements, facilitating the transfer of acquired knowledge concerning benthic cover.

Table 7 – Geomorphological, bottom cover and benthic habitat classification scheme applied in the mapping of the PSEPA

Level 1 Geomorphological zone	Level 2 Bottom cover	Level 3 Benthic habitat
Land	Land	Land
Shallow waters	Sand	Sand
Lagoon Reef crest Fore reef	Sand Rubble	Sand Rubble
		with Seagrass
		with Seagrass and Rocks
		with Seagrass and Rocks with Brown Macroalgae
		with Rocks
		with Rocks with Brown Macroalgae
	Rock	Rock
		with Brown Macroalgae
		with Sand and Rubble
		with Brown Macroalgae and Sand and Rubble
	Coral	Coral
		Spurs and Grooves
		Field
		Patches
Deep (fore) reef	Sand	Sand
	Deep benthic cover	Deep benthic cover
Deep water	Deep water	Deep water
No information	No information	No information

Level 1 indicates the geomorphological zone, which was assigned based on standard reef zones, as exemplified in Figure 7. The reef crest zone was the most challenging to define, because the PSEPA reef systems are very shallow and predominantly flat, and it was not possible to collect field data in those zones. The presence of white caps was used as an indicator of the location of the reef crest, together with sea bottom appearance. The geomorphological zone classification was heavily dependent on contextual editing, following segmentation and threshold classification predominantly based on Bands 1 and 2.

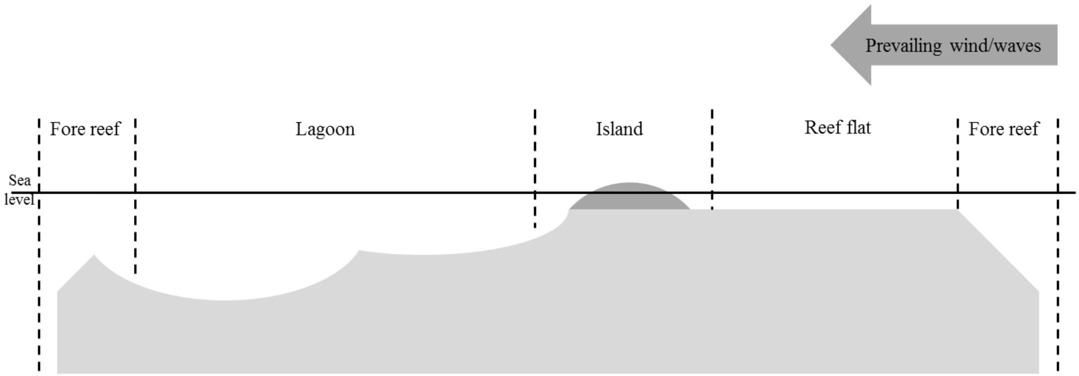

Figure 7 – Typical coral reef system geomorphological zones (adapted from Leon and Woodroffe (2011))

Level 2 indicates the main sea bottom substrate, while Level 3 refers to benthic habitats. For the scenes where fieldwork was conducted, bottom and benthic covers were mostly defined as observed in the field. Rubble was only included when it was possible to visually differentiate it from sand. It should be noted that while the term Brown Macroalgae is used in direct correspondence, Seagrass refers to all remaining algae and aquatic plants observed in the field, mostly of green coloration.

The deep reef zone was classified based on the imagery, and discriminated in sub-zones: one likely to be sand, due to its higher reflectance values, and another, not identified, here referred to as deep benthic cover.

Accuracy assessment was performed in eCognition's dedicated algorithm using all valid field data. An additional three meters buffer zone was applied to the point data to account for the field observation process, referring to areas instead of single points.

4.3. Biodiversity analysis

Biodiversity data was available from two main sources: rapid assessments of the coral reef status, commissioned by the PSEPA management, and results of the east African Marine Transect Expedition (EAMT), *"a non-institutionalised, privately funded expedition to survey the coral reef fishes and benthic communities of east Africa, from Mozambique to Kenya"* (Delacy, Bennett et al. 2014).

The Rapid Assessment (RA) reports (Pereira and Videira 2007, Pereira and Rodrigues 2014) do not provide raw data, but rather already calculated indicators of fish species diversity, individuals density and biomass, further detailed per family and trophic group, and coral genera and cover percentage.

The EAMT dataset (Delacy, Bennett et al. 2014) consists of data on fish number (family, genus, species), length and biomass, and metrics on density, diversity, among others.

An overview of the spatial and temporal distribution of the RA and EAMT data is presented in Table 8 and in the maps available in Appendix V. The data collection methods, used in each of the above referenced sources are briefly described in Appendix IV.

Table 8 – Overview of the spatial and temporal distribution of fish and coral datasets

Archipelago	Location	Data source	Year	Month	Geographic information	Number of survey locations	Metrics
Segundas	Baixo S. António	RA	2010	October	Line	1	Coral
	Mafamede	RA	2006	October/November	Point	1	Coral, Fish
		RA	2010	October	Line	1	Coral
	Puga Puga	RA	2006	October/November	Point	1	Coral, Fish
		RA	2010	October	Line	1	Coral
		EAMT	2013	January/March	Point	2	Fish
	Baixo Miguel	EAMT	2013	January/March	Point	2	Fish
	Njovo	RA	2006	October/November	Point	1	Coral, Fish
		RA	2010	October	Line	1	Coral
		EAMT	2013	January/March	Point	2	Fish
	Caldeira	RA	2010	October	Line	1	Coral
		EAMT	2013	January/March	Point	2	Fish
	Moma	-	-	-	-	-	-
Primeiras	Epidendron	RA	2006	October/November	Point	1	Coral, Fish
		RA	2010	October	Line	2	Coral
		EAMT	2013	January/March	Point	1	Fish
	Casuarina	RA	2010	October	Line	2	Coral
		EAMT	2013	January/March	Point	1	Fish
	Coroa	RA	2006	October/November	Point	1	Coral, Fish
		EAMT	2013	January/March	Point	2	Fish
	Fogo	RA	2006	October/November	Point	1	Coral, Fish
		RA	2010	October	Line	2	Coral
		EAMT	2013	January/March	Point	3	Fish
	Silva	RA	2010	October	Line	1	Coral
		EAMT	2013	January/March	Point	1	Fish

By combining both RA and EAMT datasets it is possible to obtain information on 34 locations, covering all but one island, Moma. The sampling is evenly distributed between fish and coral data, archipelagos, and survey years (Table 9).

Table 9 – Summary of the spatial and temporal distribution of fish and coral datasets

		2006 October/November	2010 October	2013 January/March	Total	
Primeiras	Coral	3	7	0	10	18
	Fish	3	0	8	11	
Segundas	Coral	3	5	0	8	16
	Fish	3	0	8	11	

As the RA reports do not provide raw data, biodiversity analysis was restricted to the available metrics. EAMT data was filtered according to the fish species targeted in the RAs, supporting the integration of the two datasets. As such, for each location of the EAMT dataset, the average fish density (number of individuals), species richness (number of different species) and total biomass (total biomass of all individuals) was calculated. As observed values refer to a specific surveyed area a simple direct proportionality was applied to standardize the metrics according to the RA's survey area (Figure 8). The RAs aforementioned data can be consulted in Pereira and Videira (2007) and Pereira and Rodrigues (2014), while the EAMT database is available at www.movingsushi.com.

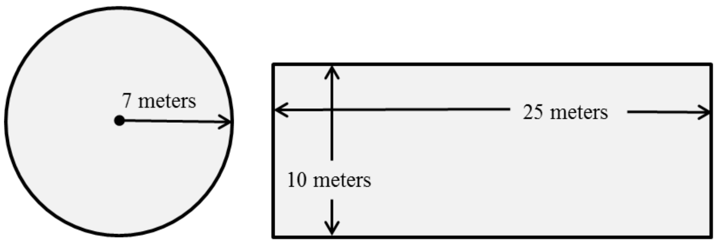

Figure 8 – Representation of the different survey areas: RA, left vs EAMT, right

The spatial and temporal behaviour of coral and fish data was studied for patterns. The relationship between coral and fish metrics was assessed by applying Spearman's rank correlation test to the 2006 RA data, the only year that features both data types.

Following the same reasoning, the relationship between map derived landscape metrics and the most recent fish dataset, i.e. EAMT, was analysed. The following landscape metrics were assessed:

- Patch density (PD), a good indicator of the extent to which the landscape is fragmented, expresses the number of areas covered by one single class (n) existing in a certain reference area (A) – $PD = n/A$.
- Edge density (ED) is a measurement of patch shape complexity and expresses spatial heterogeneity. It is the ratio between all the borders between patches (P) existing in a certain reference area (A) – $ED = P/A$.

- Number of classes (N), or richness, is a diversity measurement accounting for the totality of different classes in a certain reference area. Although easily interpreted, as biodiversity increases with class number, it can be misleading as it does not account for the classes' areas.
- The Shannon Diversity Index (SHDI) considers the number of classes (n) and their relative patch contribution (Pi), i.e., both richness and evenness. SHDI increases with the number of different classes, but also as the patch area distribution becomes more equitable, reaching its maximum value when all classes have the same area – $SHDI = -\sum_{i=1}^{n} P_i \, lnP_i$.

Landscape metrics were calculated for increasing buffer sizes (7, 12 and 25 meters) around each fish sampling point. The EAMT dataset was further used for testing the influence of relative area of fore reef, deep reef, coral field, coral patches, coral spurs and grooves, deep benthic cover, as well as distance to the main local fishing harbour, Angoche. Distance and area estimations were done using WGS 1984 UTM Zone 37 S projected coordinate system.

5. Results

5.1. Interviews

The interviews were processed and the information gathered was summarized under the four main topics: benthic cover, marine fauna, climate and social aspects.

Benthic Cover

NGO representatives and ongoing fieldwork agree that the islands show similar characteristics, which is supported by similar climate and exposure at their locations.

NGO representatives indicate the main characteristic of the reef systems to be the spurs and grooves zone in the South and East, in the deeper zone outside the rock reef crest that delimits the lagoon; this is where the vast majority of the coral can be found, often the most developed one. The spurs and grooves are shaped by the exposure to prevailing South-Eastern winds. This process also results in the transference of broken coral to the lagoon, creating areas of rubble like benthic cover. The occurrence of boulder fields in the North-Eastern also seem to be common, as verified by latest fieldwork and likewise sand fields with some seagrass extensions on the Eastern side, facing mainland. The lagoon consists mostly of broken coral, rock, seagrass and algae in sand substrate. Between the coast and the islands significant stretches of seagrass fields are believed to occur.

According to NGO representatives the coral in the Northern islands shows a larger proportion of soft coral whereas the opposite holds true in the South, possibly due to water clarity, which is said to be better there. It is thought that Casuarina and Epidendron may display some different characteristics as they create a larger, more complex system. However, this has not been possible to investigate within ongoing fieldwork, nor has there been opportunity to verify claims on differences in water clarity or of better fish stock in the South (pertaining to count, diversity and size). One NGO representative says that comparing to Segundas, the Primeiras has more coral, seagrass and algae. There is a general impression that detailed and verified data on Primeiras is lacking, and that more field efforts are needed there.

Aside from depth, geomorphology and denudation, the main influence on benthic cover is fishing pressure, leading to habitat destruction. An example is seine fishing, seen as the likely reason to perceived decrease of seagrass beds close to the island of Mafamede. The lagoons themselves are unlikely to have undergone many changes, although NGO representatives remark that if pristine they should have pelagic fish during high tide. Also it is stated that on Puga Puga the sandy beach is quite dynamic, changing the shape of the island more rapidly than most other islands. The 200 meters bathymetric line from which the PSEPA has been defined is significantly closer to Puga Puga than the rest of the islands, the results of which are unclear at the moment.

Marine Fauna

There seems to be agreement among the interviewees that marine fauna is on the decline with increasing speed and most attribute it to increased fishing pressure, as artisanal fishermen numbers have been increasing significantly (from about 37 000 in 2007 to almost 49 000 in 2012). However one industry representative comments that they have not noticed any significant changes pertaining to fish diversity and size in open water, only closer to the coast; and yet other interviewees refer climate change as a cause for marine fauna decline, although NGO representative refers that even being some indication of that (e.g. latest plunge of shrimp stock in the Sofala bank), no scientific findings have been disclosed with enough detail to be able to draw conclusions for this region.

The interviews indicate a depletive market trend where new raw products are explored when current ones show insufficient yield for exporting; this is foremost attributed to unsustainable fishing practices but aggravated by bad weather events. The trend indicates a shift from fish and shrimp (before 2010-2012) to octopus and seafood like lobster and crayfish, which still constitute the majority of the industry market. Although NGO and industry representatives are in agreement that octopus yield is declining, crayfish seems to have disappeared almost entirely and there may now be a shift towards animal farming according to NGO representative. The ongoing strategy of shifting market focus has not necessarily relieved the pressure on fish and shrimp, likely stemming from the rapid increase in artisanal fishermen numbers.

It is common opinion that Ilhas Segundas are under a larger fishing pressure than Ilhas Primeiras, as fewer fishermen venture out to more distant islands. Also within the Segundas archipelago differences in fishing pressure are mentioned, e.g. the islands North of Njovo being more heavily fished, as they are closer the main population centers. This agrees with the sighting of larger fish on Njovo, which supports the hypothesis that fishing pressure is shortening fish life cycle. The South most islands of Coroa, Fogo and Silva are mentioned as locations with greater marine fauna variety and sizes.

NGO representatives note that the fish are quite small throughout the region, even fish species that are expected to grow up to 2 meters long. Considering current fishing practices and intensity, it is expected that the decreasing fish stock trend will continue in Segundas Archipelago.

There are reports of successful NGO action, as turtles and seagulls number have increased in the region, and recent fish sanctuary pilot project have shown promising results. This is consistent with the approach of safeguarding multiple habitats instead of focusing solely on coral zones, as many of the biotic communities' life cycles are not restricted to a single habitat. The protection of the area from the mainland to the coral in Puga Puga would be an example of a more efficient approach safeguarding the whole lifecycle of many of the individuals, as it would enclose a whole ecosystem.

Climate

The region has prevailing South-Eastern winds that create strong currents, shaping the geomorphology of the region. Additionally, the hydrodynamics effect of the sudden change in depth pertaining to the 200 meters bathymetric line from which the PSEPA has been defined are a likely driver behind island shape, e.g. Epidendron, Casuarina, Fogo and Puga Puga. While the latest two are closer to the 200 meter drop off, thus consistent with this hypothesis, Epidendron and Casuarina have approximately the same distance to the protected area limit as the remaining islands. This could be an indication of the existence of other structures influencing that area's hydrodynamics.

The weather is quite unpredictable, and the industry has noticed growing wind intensities, posing an obstacle to navigation, and particularly to artisanal fishing activities. In the P&S these conditions make the South-Eastern zones particularly difficult to access and dive on, as per NGO experience.

Tidal variation also affects structure access, with intertidal zone, lagoon, and reef crest likely to be exposed during low spring tides.

The wind leads to surface ripple and underwater movement, creating zones of high turbidity which are considered disadvantageous for octopus fishing. NGO experience in the P&S determined visibility to be typically limited to 5 meters and better during high tides. Current fieldwork found consistent visibility limitations of 5 to 7 meters.

Global climate change is also brought forth by NGO and industry as adding pressure on the PSEPA, and it is feared that it may lead to coral bleaching events, as has happened in the past.

Social Aspects

Lack of administrative measurements and certain specific regulations are perceived by the Government and Industry as obstacles in addressing the conflicts related to natural resources management. An example is the regulation of mesh size but not of net length. NGO representatives point out that other conflicts arise from the interaction between different systems, namely the coastal wetlands – deforestation and wetland destruction reduce nutrient intake to the aquatic system and thus its productivity –, creating a complex management problem.

Conservation and law enforcement is considered low, driven by ineffective and inadequate inspection and control and supported by limited resources. Additionally, coordination with other sectors is lacking, leading to unexpected effects. Both Industry and Government mention that up to half of the mosquito nets distributed during the most recent malaria prevention campaign are probably being currently used for fishing, one of the main causes mentioned for fish depletion.

Industry expressed concern about the presence of a Chinese company in Angoche. Previous experience has shown a potential of uncontrolled and unsustainable fishing connected to that market, with commercial interests that disregard resources management, as a potential source of increased poverty – of natural resources, as opposed to financial – in the region.

The increasing coastal population is influencing the number of fishermen, and the Government thinks there could be a trend of Southern migration, away from depleted fishing areas and increasing competition. Potential solutions referred by Government and Industry include regulatory mechanisms based on fishing licenses and fishing techniques. By exploring the extent of application of licenses, and by experimenting with the role of Industry in the introduction and assurance of the use of specific techniques, i.e. instead of providing fishermen with equipment, it could be the companies' responsibility to ensure equipment maintenance and upkeep, thus increasing fishing practices management with less financial risk for the fishermen. Additionally, choice of open waters fishing over coastal is encouraged by the Government, so as to alleviate pressures on the coastline but also to achieve better financial results. However, since enforcement is low any restriction or prohibition of fishing is thought to have little effect, mainly because artisanal fishermen are much protected under the current law. Nonetheless, NGO approach would be a mix of fishing prohibition/restriction in pilot areas, e.g. Mafamede or Puga Puga, to later be spread throughout the archipelagos, accompanied with funding fishermen not to fish during certain key periods. There are currently two marine costal sanctuaries, started in 2010, that are showing promising results and good community acceptance. Large scale investment in alternative markets, such as tourism, seems unlikely as the local weather and natural conditions do not cater to current market trends, according to NGO.

Participative management inclusive of fishermen started about 10 years ago through the more than 30 established Fishing Community Councils throughout PSEPA. Work has been focusing on the implementation of natural resources co-management and on conflict management between artisanal and industrial fisheries. Education and awareness rising has been the main approach, aimed at establishing community self-surveying and controlling, but achieved results still fall short.

The mining activity around Ilha Caldeira is believed to have introduced new pressures, since coral reefs require very specific light and water quality conditions it is likely that it has had a negative impacts. There is an environmental management plan but it is only available to the central government so it is hard to get information.

5.2. Benthic habitat mapping

The resulting geomorphologic, bottom cover and benthic habitat maps, one for each of the 12 islands or atolls, are presented in Appendix V. One example of Casuarina island, including the original satellite imagery, can be seen in Figure 9. General information on imagery and fieldwork, as well as resulting mapping accuracy is presented in Table 11, at the end of this section.

The total mapped extent was about 130 m^2. This value is an approximation, including a partial overlap of the Epidendron and Casuarina imagery. Although both islands are included in one mosaic, additional information can be extracted from the other. This second mosaic is centered on Epidendron, and includes a shallow area further north, as well as the area in between both islands. The area values in Table 10 are likely underestimated for Casuarina and overestimated for Epidendron.

Table 10 – Total reef system mapped (excluding land) for each location

Location	Area (m^2)
Baixo S. António	5.41
Mafamede	13.37
Puga Puga	11.33
Baixo Miguel	12.87
Njovo	6.74
Caldeira	7.71
Moma	9.51
Epidendron	≈ 31.50
Casuarina	≈ 11.39
Fogo	9.18
Coroa	5.35
Silva	4.77
Total	≈ 129.13

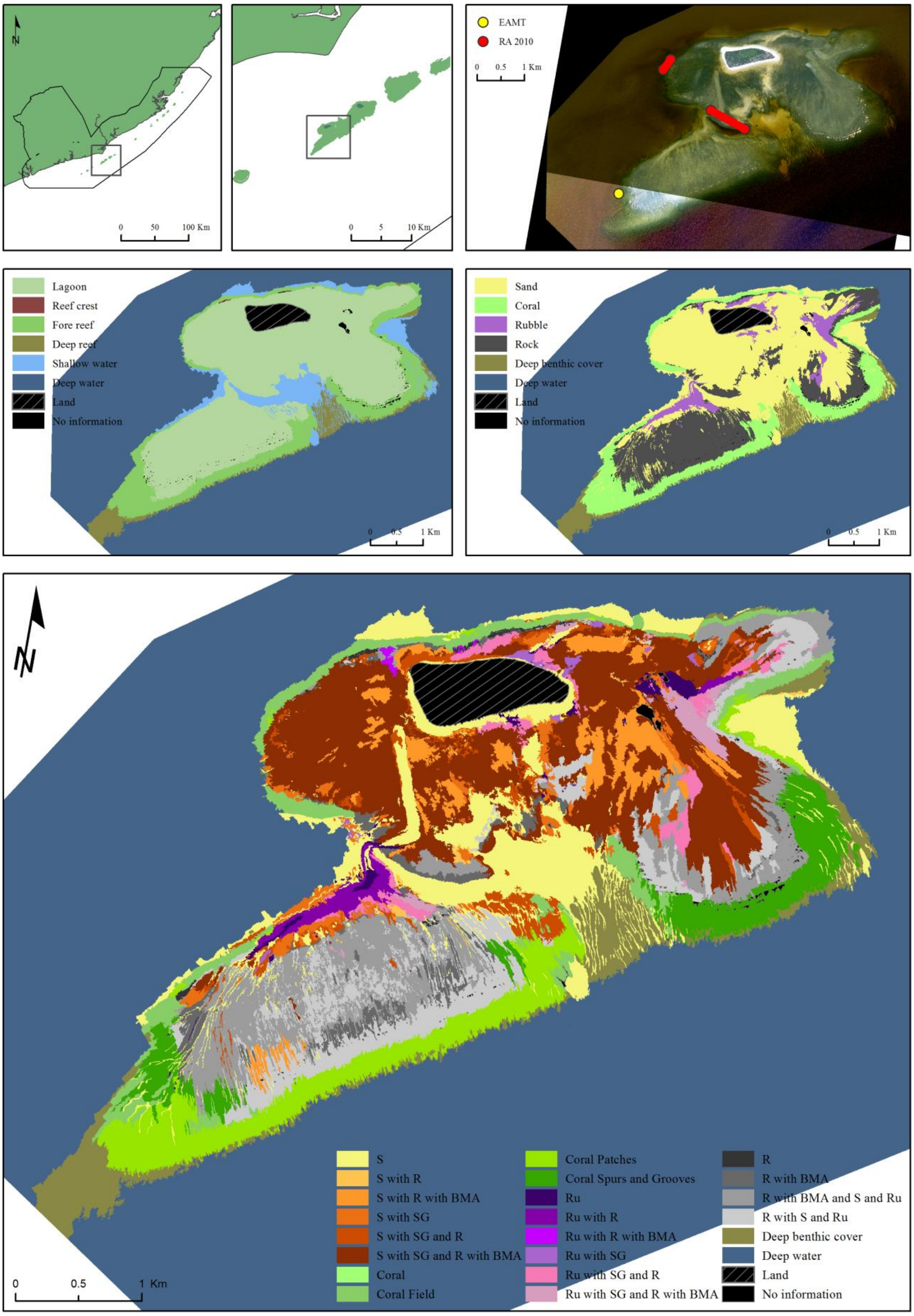

Figure 9 – Original satellite imagery, including biodiversity data survey sites, and object-based image classification results for Casuarina island (S = Sand; R = Rock(s); Ru = Rubble; BMA = Brown Macroalgae; SG = Seagrass)

At the geomorphological level (L1), each location is classified as lagoon, reef crest, fore reef, deep reef, as presented in Table 7, as well as shallow water, deep water, land and no information. All islands present a very similar geomorphological structure – a flat lagoon with shallow water on the northern side, surrounded by reef crest, fore reef and deep reef, the last usually extending towards southeast.

At the bottom cover level (L2), each island system was classified as belonging to sand, coral, rubble, rock cover and deep benthic cover classes. Sand was the predominant class, followed by coral (Figure 10). Rubble was the least common class. The number of classes varied between seven and eight, including deep benthic cover, deep water, land and no information.

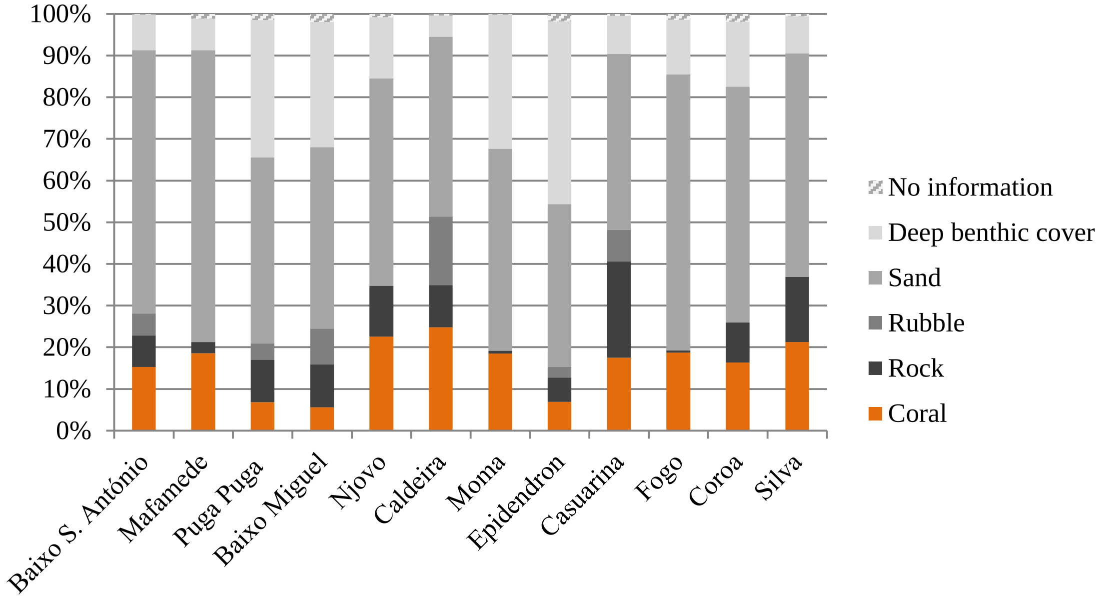

Figure 10 – Bottom cover classes distribution (L2) across the PSEPA's coral reef systems

At the benthic habitat level (L3) it was possible to determine 13 to 24 classes for each location, including the detailing of the coral class into coral field, patches and spurs and grooves. This last structure covered the largest extent, followed by coral field and then coral patches (Figure 11).

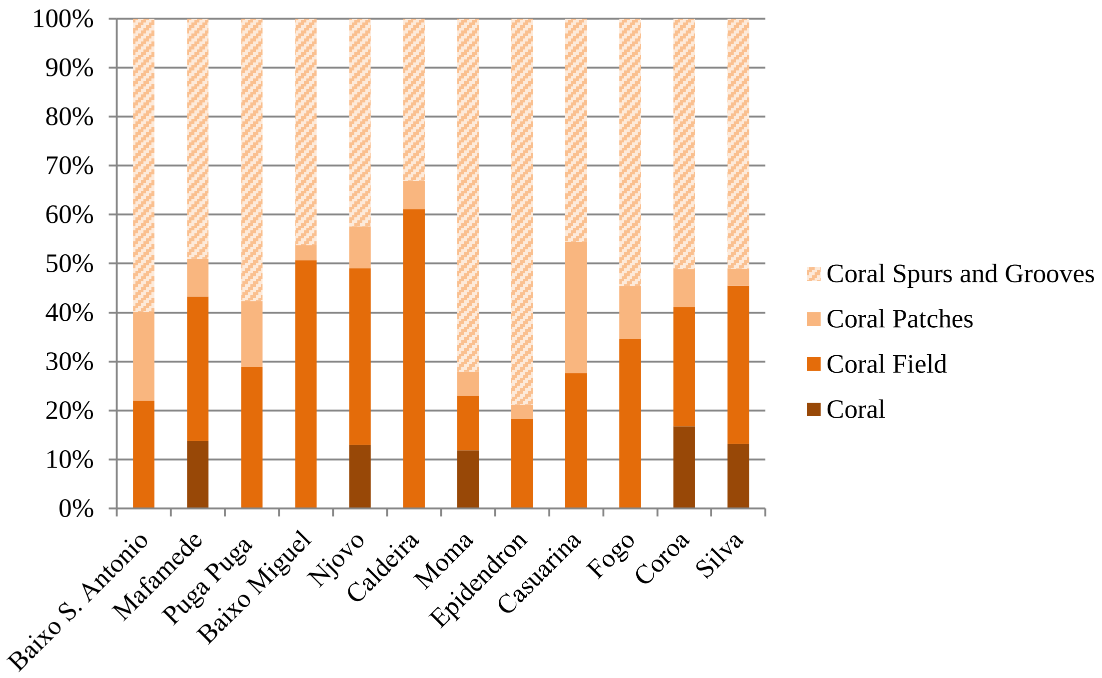

Figure 11 – Coral classes distribution, at the benthic habitat level (L3), across the PSEPA's coral reef systems

Rock, rubble and sand are distributed at the benthic habitat level with no clear class predominance (Figure 12, Figure 13 and Figure 14). However, the class Rubble with Segrass and Rocks with Brown Macroalgae has a large contribution within the rubble class at the benthic habitat level (L3).

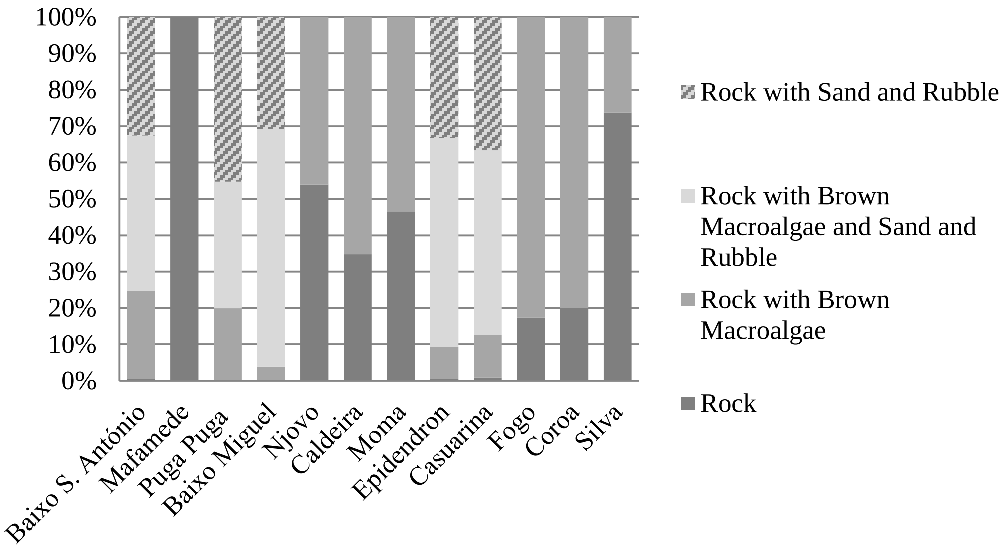

Figure 12 – Rock classes distribution, at the benthic habitat level (L3), across the PSEPA's coral reef systems

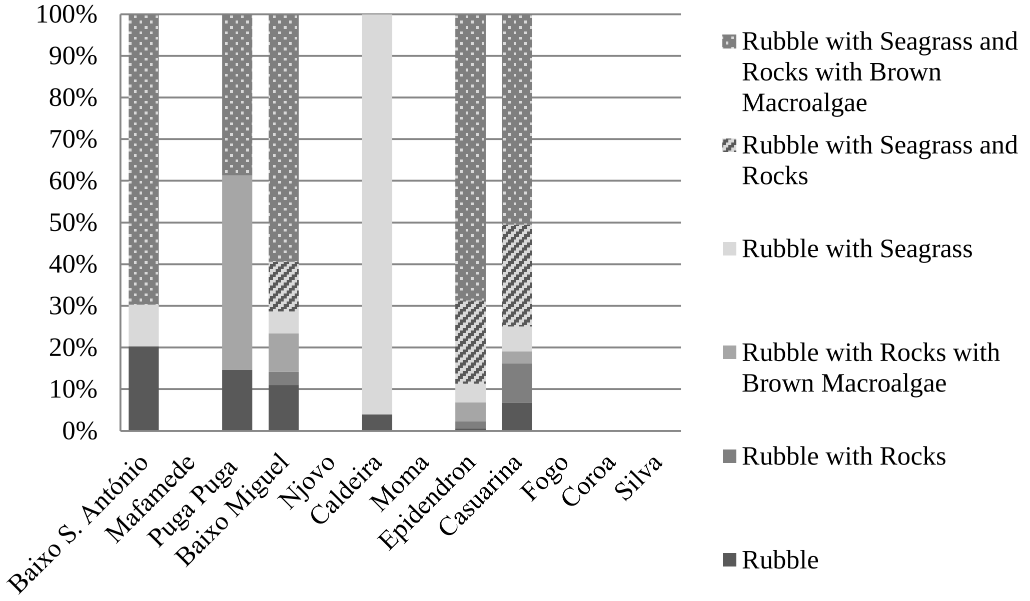

Figure 13 – Rubble classes distribution, at the benthic habitat level (L3), across the PSEPA's coral reef systems

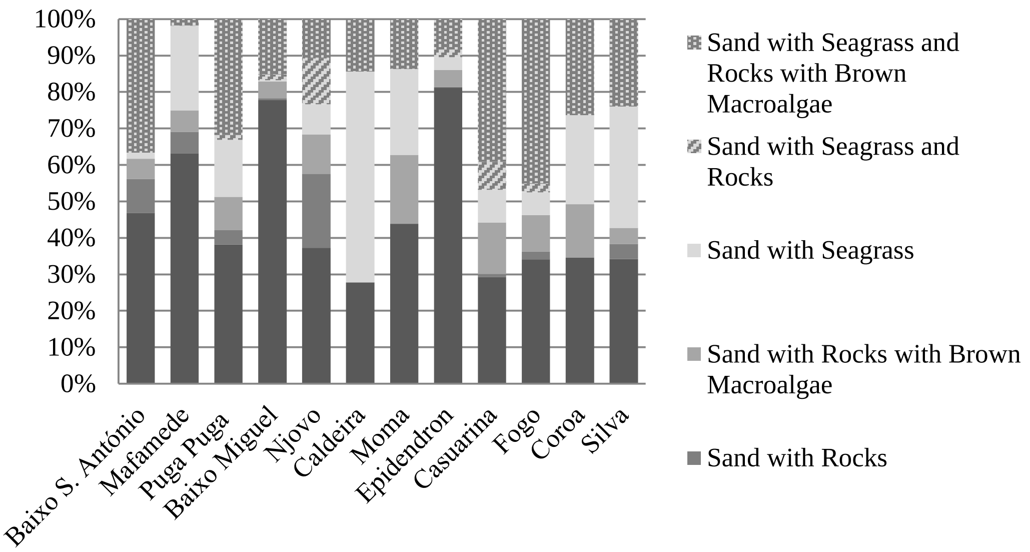

Figure 14 – Sand classes distribution, at the benthic habitat level (L3), across the PSEPA's coral reef systems

Accuracy assessment was performed using all valid fieldwork data points as ground truth points. Confusion matrixes were generated for bottom cover and benthic habitat levels. At the bottom cover level, overall accuracy was between 40% and 90%, although the lower limits of the accuracy range would improve in about 20% with the exclusion of one location (Baixo Miguel), and subsequently to 80% with the exclusion of a second island (Caldeira) (Figure 15). At the benthic cover level, accuracy is approximately 20% lower, varying between 30% and 70%.

The coefficient of agreement, KIA, varies with the overall accuracy (Figure 15). It ranges from 0.20 to 0.80 at the bottom cover level, and from 0.30 to 0.70 at the benthic habitat level. Once again, the exclusion of Baixo Miguel and Caldeira would result in a substantial improvement of the results, setting new minimums at 0.40 and 0.50.

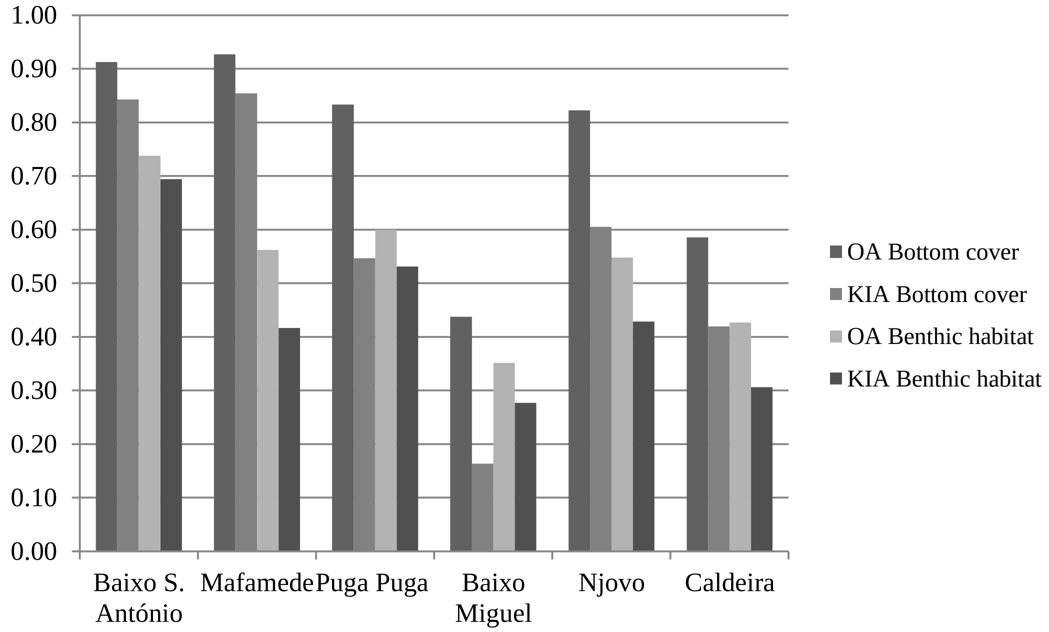

Figure 15 – Overall accuracy (OA) and coefficient of agreement (KIA) results at bottom cover (L2) and benthic habitat (L3) levels

For the remaining six islands, although mapped, it was not possible to assess the resulting accuracy due to the lack of field data. Nonetheless, considering the similarities among the coral reef systems and the applied mapping methodology, accuracy is expected to fall within the above mentioned ranges, although probably tending to lower values.

Table 11 – Overview of satellite imagery, fieldwork data and mapping results per location

Locations	Sensor	Acquisition year	Tide (meters above LAT)	Fieldwork date	Total fieldwork data points / No visibility points	Number of classes at benthic habitat level	Overall accuracy	Coefficient of agreement (K)
Baixo S. António	WV-2	2009	3.0 *	11.05.2014	101 / 0	18	L2 = 91.29% L3 = 73.77%	L2 = 0.84 L3 = 0.69
Mafamede	WV-2	2009	1.5 *	15.04.2014	175 / 36	15	L2 = 92.71% L3 = 56.25%	L2 = 0.85 L3 = 0.42
Puga Puga	QB 2	2010	1.4 *	16.04.2014 17.04.2014	103 / 39	19	L2 = 83.33% L3 = 60.00%	L2 = 0.55 L3 = 0.53
Baixo Miguel	QB 2	2010	1.4 *	17.04.2014	29 / 5	22	L2 = 43.75% L3 = 35.14%	L2 = 0.16 L3 = 0.28
Njovo	WV-2	2010	3.0 *	17.04.2014	127 / 30	16	L2 = 82.28% L3 = 54.81%	L2 = 0.61 L3 = 0.43
Caldeira	WV-2	2009	1.3 *	10.05.2014	130 / 18	14	L2 = 58.57% L3 = 42.70%	L2 = 0.42 L3 = 0.31
Moma	WV-2	2013	2.69 **	NA	NA	13	NA	NA
Epidendron	WV-2	2009	2.21 **	NA	NA	23	NA	NA
Casuarina	WV-2	2009	0.82 **	NA	NA	23	NA	NA
Coroa	GE-1	2011	0.92 **	NA	NA	16	NA	NA
Fogo	GE-1	2011	0.92 **	NA	NA	14	NA	NA
Silva	WV-2	2009	0.83 **	NA	NA	24	NA	NA

LAT = Lowest Astronomical Tide

NA = Not available

* Courtesy of John Hedley, Environmental Computer Science Ltd., as part of ESA's G-ECO-MON Project

** Estimated with WXTide32 software

5.3. Biodiversity analysis

The coral data estimates live cover percentage between 50% and 70% in 2006, and 20% to 50% in 2010 (Figure 16), as well as a negative north-south trend, indicated by the linear fit.

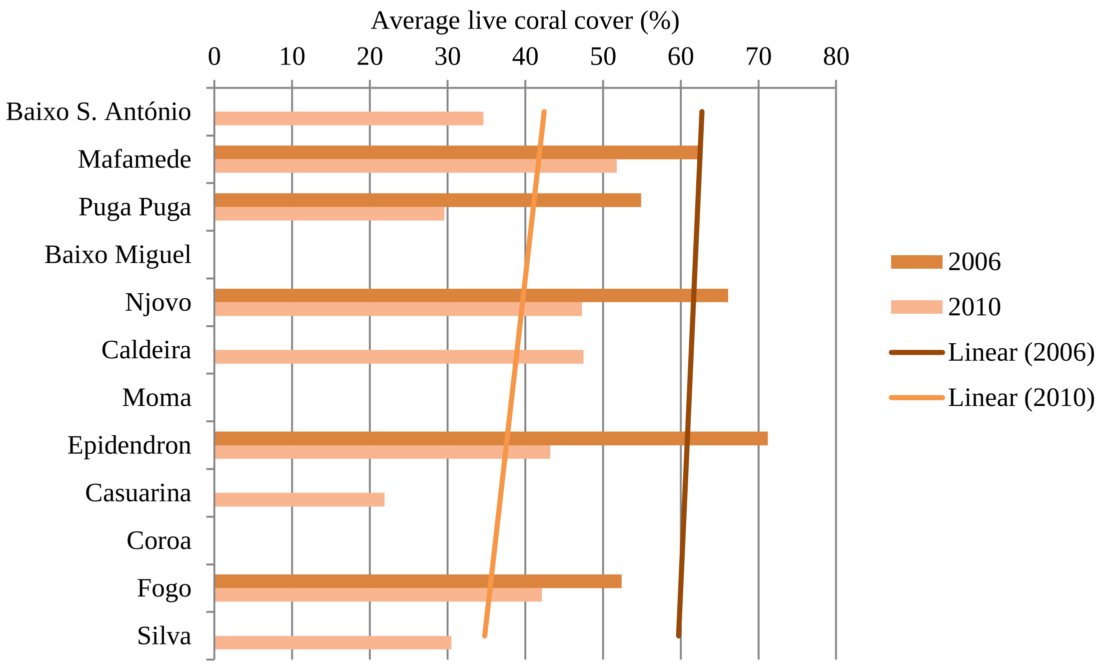

Figure 16 – Average live coral cover (%), and linear trend, in PSEPA in 2006 and 2010

The percentage of dead coral cover, overall quite low (less than 2%), also shows a decrease in the same period. Dead coral can be differentiated according to the presence of algae, as recently dead coral tends to be free of algae. It is possible to observe that both recently dead and dead for longer coral cover has decreased (Figure 17 and Figure 18). This indicates that the region's coral, despite tending to smaller extents, increased its living proportion in the 2006-2010 period.

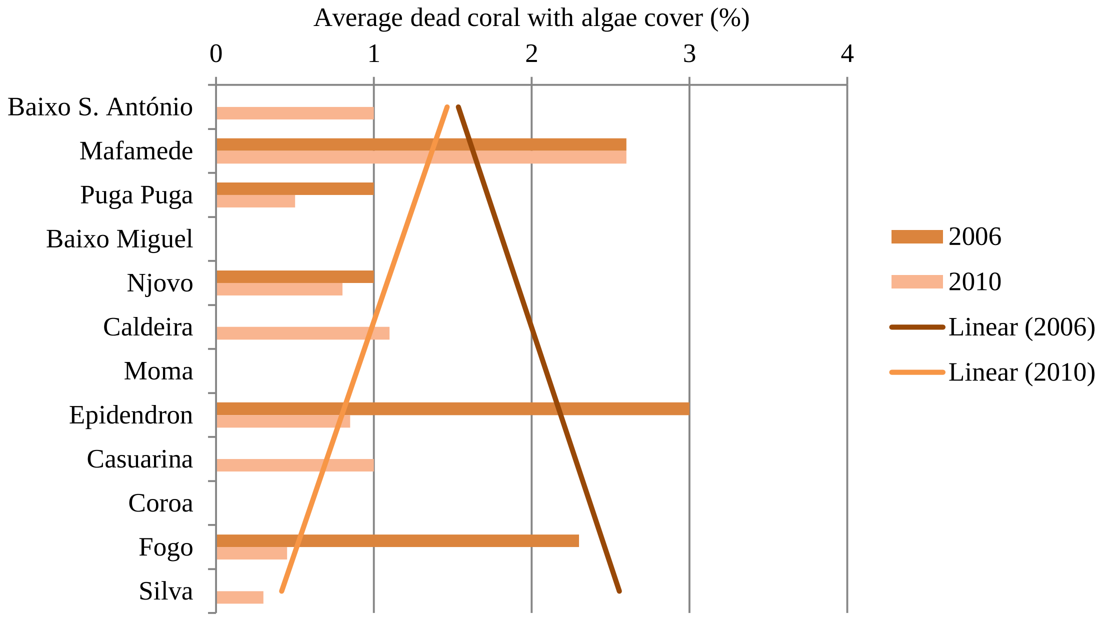

Figure 17 – Average dead coral with algae cover (%), and linear trend, in PSEPA in 2006 and 2010

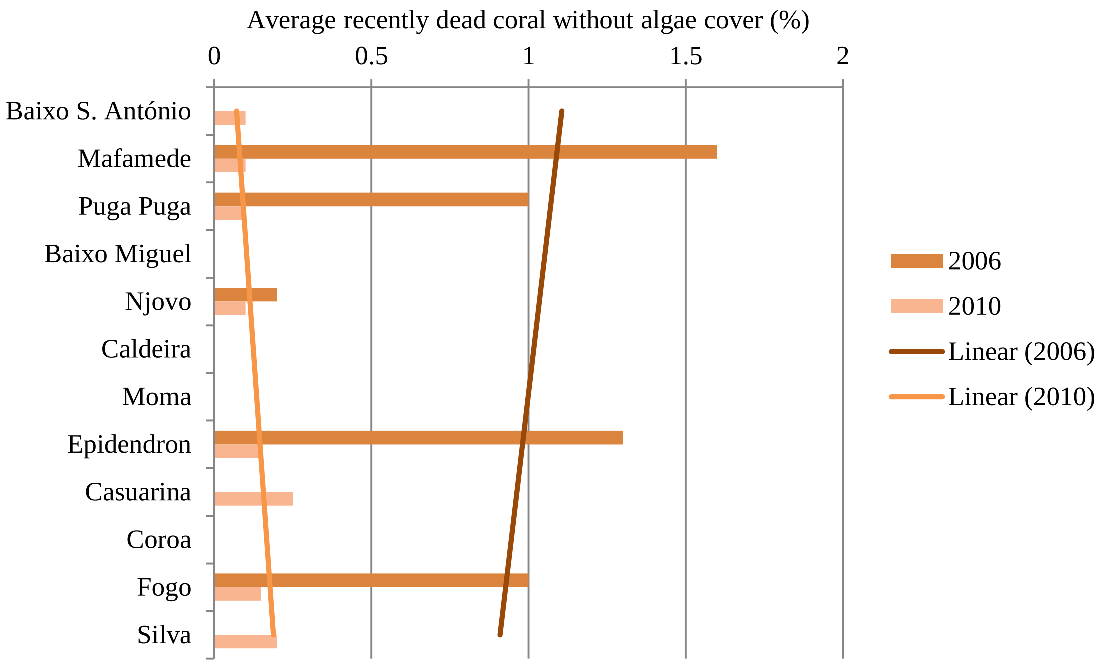

Figure 18 – Average recently dead coral without algae cover (%), and linear trend, in PSEPA in 2006 and 2010

The cover of recently and dead for longer coral varies across the archipelagos. For 2006, the proportion of dead coral with algae cover is increasing towards south, while the opposite happens for recently dead coral. For 2010. the proportion of dead coral with algal cover decreases towards south while that of recently dead coral (barely) increases.

The number of different coral genera observed during the sampling surveys also decreased between 2006 and 2013, from about 22 to 17 (Figure 19). The number of observed genera increases towards south in both years. This indicates increasing coral diversity despite lower total coverage.

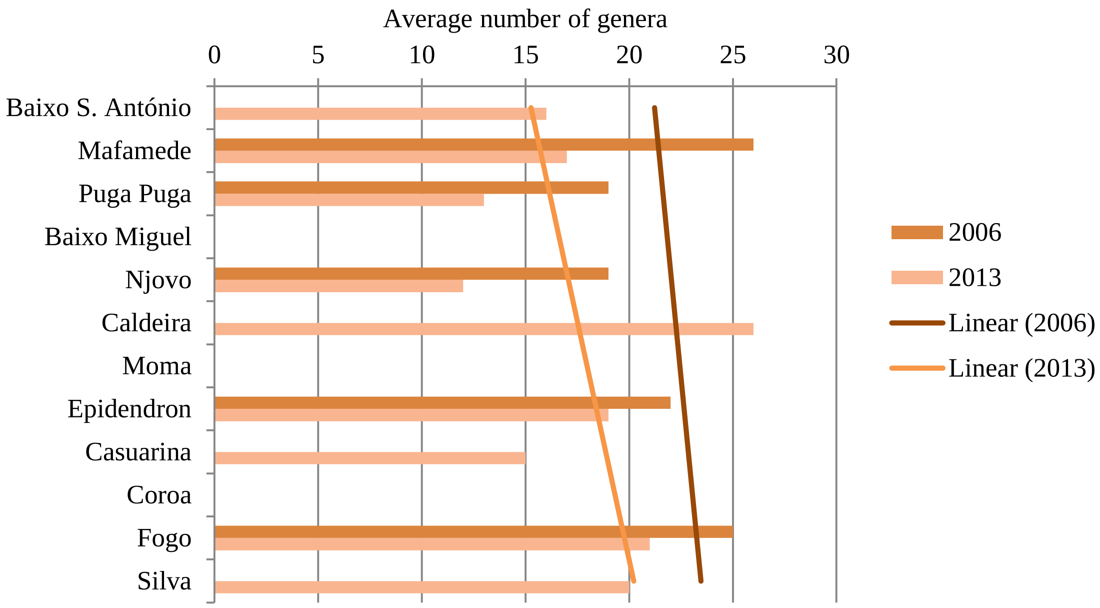

Figure 19 – Average number of genera, and linear trend, in PSEPA in 2006 and 2010

The fish metrics show an overall similar behaviour to the coral data, decreasing between 2006 and 2013, and from north to south (Figure 20 and Figure 21).

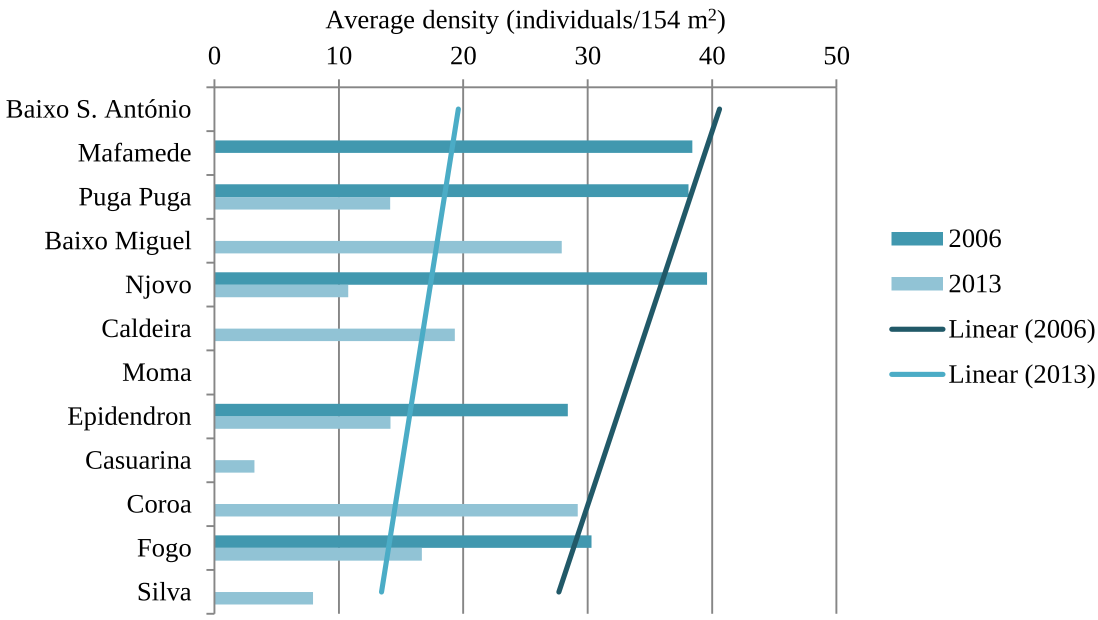

Figure 20 – Average fish density (individuals/154 m^2), and linear trend, in PSEPA from 2006 and 2013

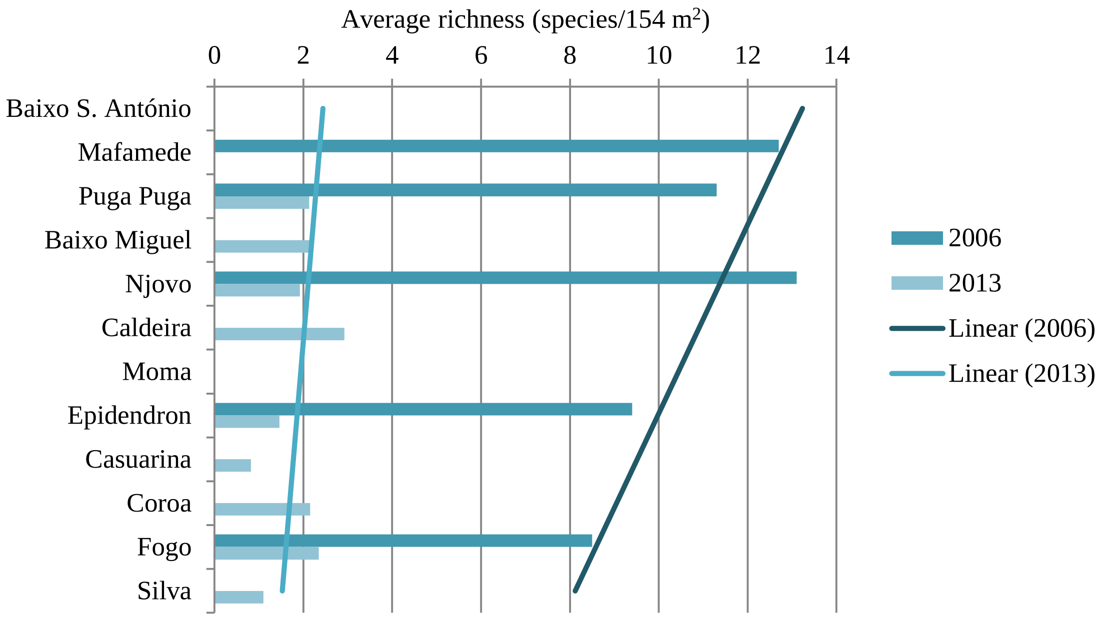

Figure 21 – Average richness (number of species/154 m^2), and linear trend, in PSEPA from 2006 and 2013

However, the fish biomass values behave otherwise. This indicator varies between 0.2 g and 0.5 kg in 2006, and 0.5 kg to 11 kg in 2013 (Figure 22). This is unexpected, and although possible, it is likely to be a reflection of the differences between the sampling methodologies. As such, fish biomass variation in time was not assessed. Nevertheless, both datasets show an approximately constant profile across the region, evermore obvious with the exclusion of Silva.

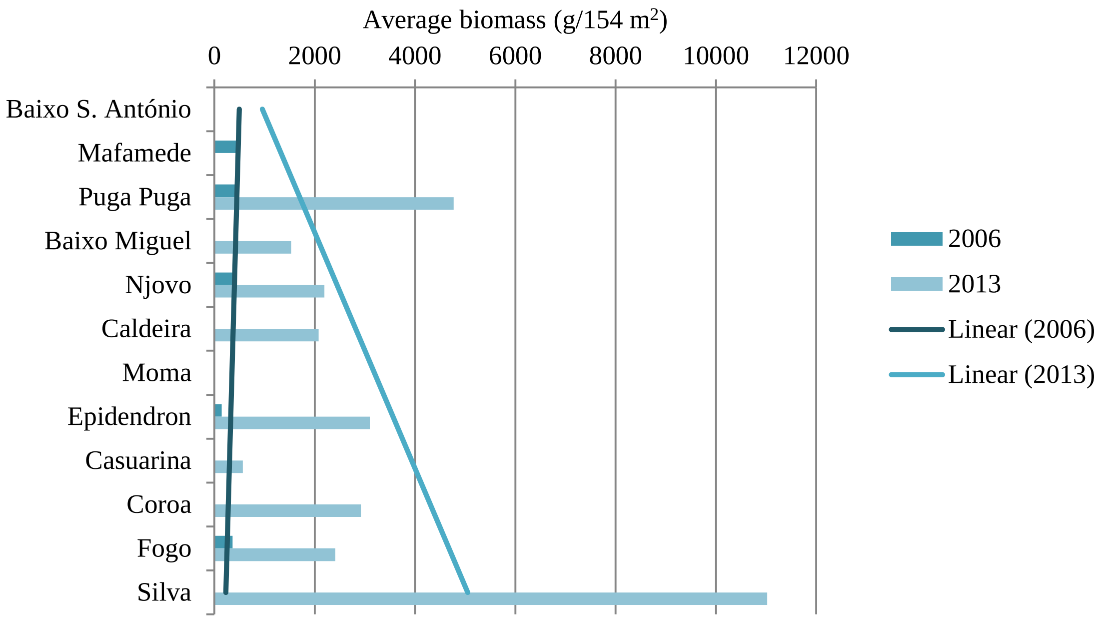

Figure 22 – Average fish biomass (g/154 m^2), and linear trend, in PSEPA from 2006 and 2013

The Spearman correlation coefficient values between coral cover and fish variables indicate mostly weak relationships (0.3 < r < 0.49), although there are moderate relationships (0.5 < r < 0.59) between both live and dead coral cover and fish density, strong (0.6 < r < 0.79) between live coral cover and fish diversity and very strong (0.8 < r < 1,0) between live coral cover and fish biomass (Table 12, Figure 23). These trends are all unexpectedly negative, indicating a decrease of fish indices with increasing coral values.

Table 12 – Spearman rank correlation test results (r) for coral cover and fish variables from the 2006 dataset

Coral cover	Fish		
	Density	Biomass	Diversity
Live	**-0.500**	**-0.800**	**-0.600**
Recently dead	-0.325	0.225	-0.175
Dead with algae cover	**-0.575**	-0.325	-0.375
Genera	-0.175	0.175	-0.275

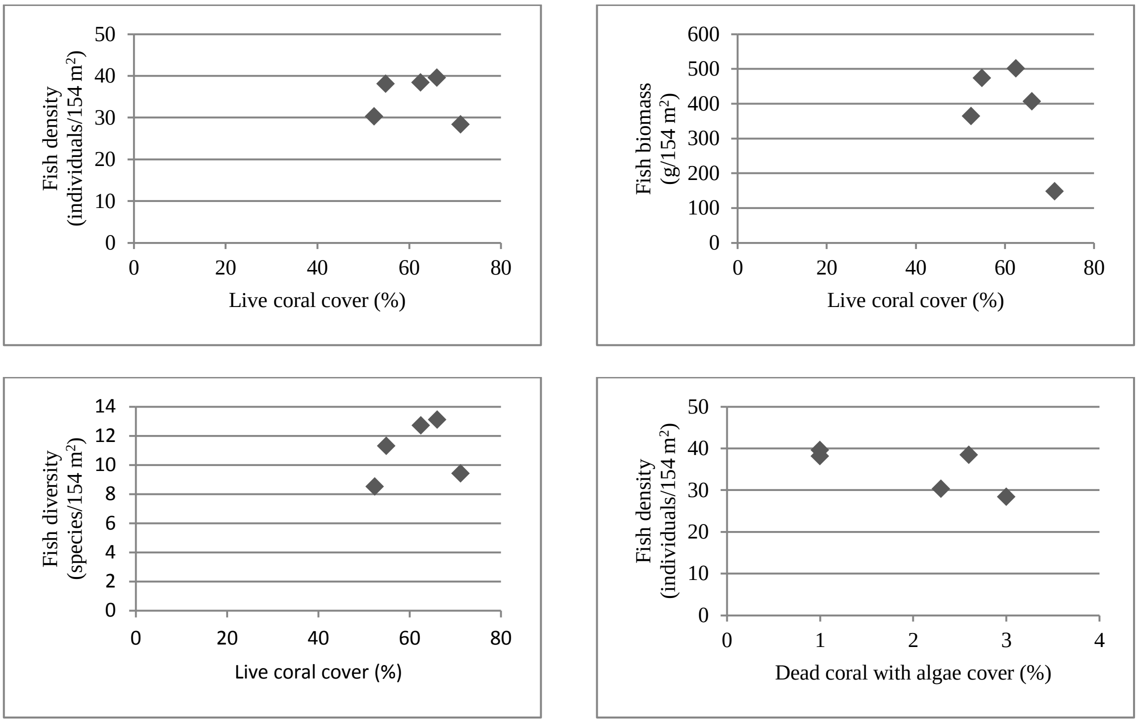

Figure 23 – Moderate to high relationship correlation according to Spearman rank test for coral cover and fish variables from the 2006 dataset

The Spearman rank correlation test was further performed with selected landscape metrics and fish variables. The selected landscape metrics were patch density, edge density, number of classes, SHDI and relative area of fore reef, deep reef, coral field, coral patches, coral spurs and grooves and deep benthic cover. These were calculated for three distinct buffer sizes (7, 12 and 25 meters), based on the survey areas of the fish sampling methodologies.

The Spearman's correlation coefficients indicate generally weak relationships between fish variables and the selected landscape metrics. Based on its values, moderate positive relationships ($0.5 < r < 0.59$) were found at the geomorphological classification level (Table 13 and Figure 24) for

- Relative fore reef area and fish density (7 meter buffer),
- Patch density and fish species richness (7 and for a 12 meter buffer) and
- Edge density and fish species richness (12 meter buffer);

at the bottom cover level (Table 14, Figure 25) for

- Patch density and fish density (12 meter buffer);

and at the benthic habitat level (Table 15, Figure 26) for

- Coral field and fish species richness (7 and for a 25 meter buffer).

Table 13 – Spearman rank correlation test results (r) for the 2013 fish dataset indicators and landscape metrics calculated with different buffer values (7, 12 and 25 meters) applied to the geomorphological classification; density is in individuals/154 m^2, species richness in species/154m^2 and biomass in g/154m^2

	7 m			12 m			25 m		
	Density	Biomass	Species richness	Density	Biomass	Species richness	Density	Biomass	Species richness
Patch density (n/A)	0.27	0.45	**0.54**	0.23	0.37	**0.56**	-0.26	-0.10	0.06
Edge density (p/A)	0.30	0.35	0.48	0.37	0.35	**0.59**	0.05	0.07	0.39
Classes	0.22	0.42	0.28	0.22	0.42	0.28	-0.26	-0.10	0.06
Fore reef (%)	**0.57**	-0.02	0.45	0.02	-0.15	-0.02	0.49	-0.02	0.44
Deep reef (%)	-0.47	0.05	-0.39	-0.44	-0.33	-0.30	0.49	-0.02	0.44
SHDI	0.16	0.34	0.42	0.18	0.31	0.46	0.16	0.20	0.34

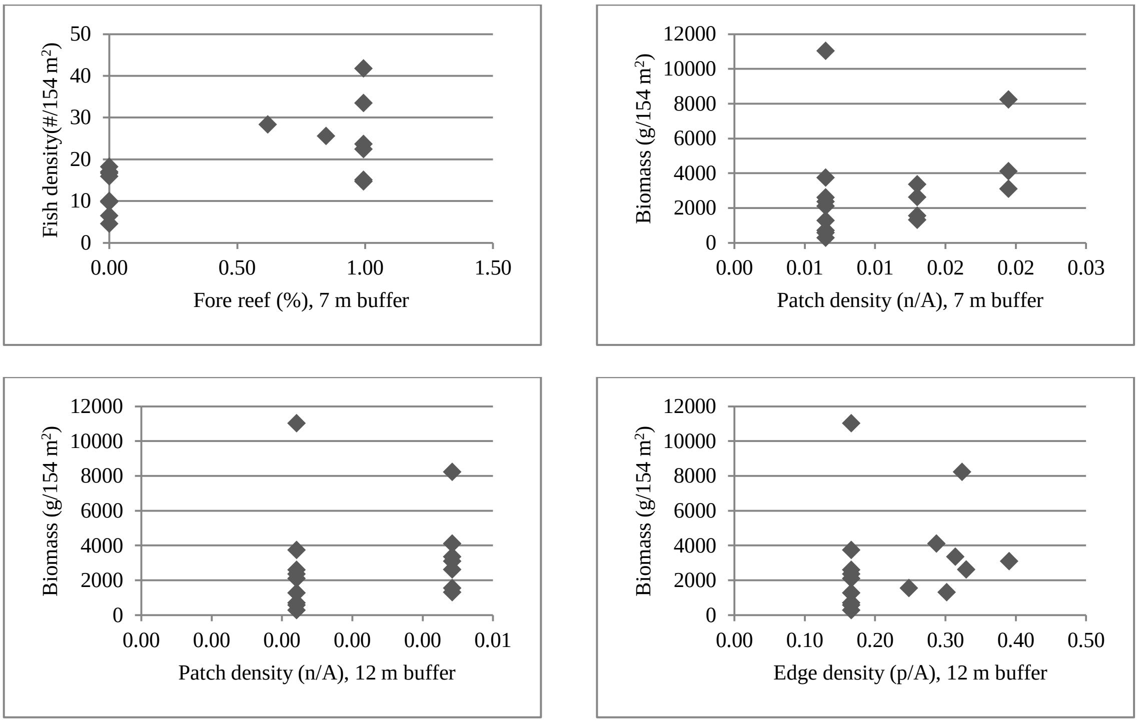

Figure 24 – Moderate relationship correlation according to Spearman rank test for landscape metrics at the geomorphological level (L1) and fish variables from the 2013 dataset

Table 14 – Spearman rank correlation test results (r) for the 2013 fish dataset indicators and landscape metrics calculated with different buffer values (7, 12 and 25 meters) applied to the bottom cover classification; density is in individuals/154 m^2, species richness in species/154m^2 and biomass in g/154m^2

	7 m			12 m			25 m		
	Density	Biomass	Species richness	Density	Biomass	Species richness	Density	Biomass	Species richness
Patch density (n/A)	0.47	0.37	0.29	**0.53**	0.23	0.31	0.09	-0.09	-0.01
Edge density (p/A)	0.23	0.22	0.15	0.38	0.29	0.48	0.06	-0.05	0.33
Classes	0.38	0.16	0.14	0.40	0.20	0.26	0.11	-0.02	0.26
Coral (%)	0.41	0.01	0.35	0.41	0.01	0.35	0.34	-0.07	0.26
Deep benthic cover (%)	-0.40	-0.01	-0.47	-0.40	-0.01	-0.47	-0.25	0.09	-0.44
SHDI	0.34	0.18	0.17	0.37	0.15	0.22	0.42	0.00	0.17

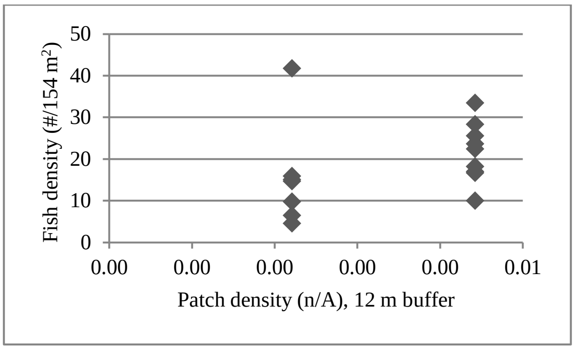

Figure 25 –Moderate relationship correlation according to Spearman rank test for landscape metrics at the bottom cover level (L2) and fish variables from the 2013 dataset

Table 15 – Spearman rank correlation test results (r) for the 2013 fish dataset indicators and landscape metrics calculated with different buffer values (7, 12 and 25 meters) applied to the benthic habitat classification; density is in individuals/154 m^2, species richness in species/154m^2 and biomass in g/154m^2

	7 m			12 m			25 m		
	Density	Biomass	Species richness	Density	Biomass	Species richness	Density	Biomass	Species richness
Patch density (n/A)	0.37	0.30	0.28	0.39	0.19	0.37	-0.02	-0.13	0.18
Edge density (p/A)	0.19	0.21	0.15	0.29	0.30	0.46	0.32	-0.07	0.36
Classes	0.37	0.30	0.28	0.39	0.22	0.48	-0.01	-0.08	0.29
Coral Field (%)	0.14	-0.04	**0.58**	0.04	-0.02	0.46	0.09	-0.15	**0.54**
Coral Patches (%)	0.31	0.14	0.36	0.31	0.14	0.36	0.31	0.14	0.36
Coral S&G (%)	0.21	-0.04	-0.09	0.21	-0.04	-0.09	0.25	-0.03	-0.07
Deep benthic cover (%)	-0.40	-0.01	-0.47	-0.40	-0.01	-0.47	-0.37	-0.01	-0.44
SHDI	0.33	0.20	0.22	0.34	0.14	0.27	0.42	-0.24	0.18

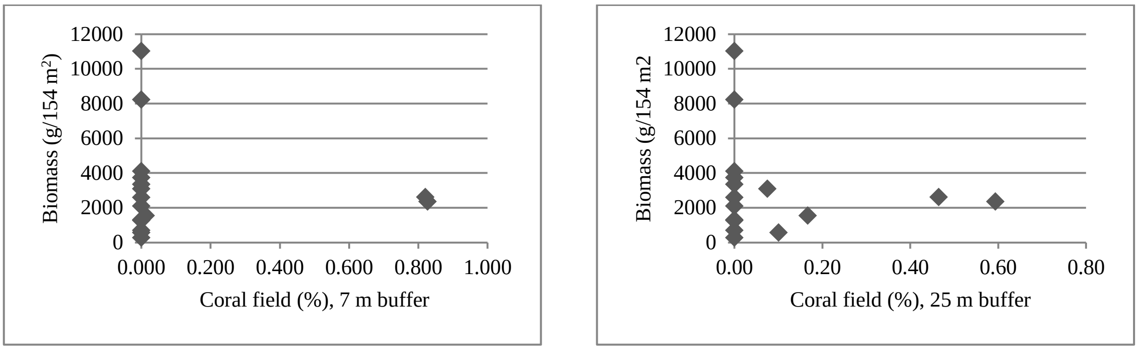

Figure 26 – Plotting of the moderate relationship correlation according to Spearman rank test for landscape metrics at the benthic habitat level (L3) and fish variables from the 2013 dataset

The relationship between distance to survey spots and the main local fishing harbour, Angoche, was also tested against the fish metrics of the 2013 dataset. Results indicate very week correlations ($0.1 < r < 0.29$) between variables (Table 16).

Table 16 – Spearman rank correlation test results (r) for distance to the main fishing harbour, Angoche, and the 2013 fish dataset

	Fish		
	Density	Biomass	Diversity
Distance to the main fishing harbour	-0.094	0.209	0.040

6. Discussion

6.1. Benthic habitat mapping

Throughout the PSEPA, there is a very consistent geomorphological pattern. The islands show similar characteristics, particularly a spurs and grooves zone in the south and east, with well-developed coral building up towards the reef crest. The spurs and grooves follow a south-southeast direction due to prevailing currents and wind. Progressing around the reef crest towards the landward side the coral becomes less developed and flatter, while the grooves become broader and filled with more sand.

The shallow lagoon (about 2 meters deep during high tide) tends to have rubble, usually made of weather broken coral, along with rock, seagrass and algae in sand substrate. In the northwest part of the islands systems there are boulders, identified during fieldwork as coral patches. On the northeastern and eastern sides, towards mainland, there are sand and seagrass and/or algae extensions. Both lagoon and reef crest are likely to be exposed during low spring tides.

The large variation of water level in the region, together with the high energy wave action, creates significant variability in the local denudation patterns, increasing the complexity of the reef and therefore the difficulty of geomorphological zones delineation. Reef crest was the most challenging class at this level due to the overall flatness of the island systems. Additionally, this area tends to coincide with the wave break, to which the no information class was applied due to its reduced visibility.

Bottom cover is, as well, generally similar throughout the archipelagos. The predominant sea bottom cover in the total mapped extent is sand, followed by coral.

Within the coral class, spurs and grooves covered the largest extension, followed by coral field and then coral patches, adding up to a total of 22 km^2 in the whole of the PSEPA. The values on Table 17 represent an estimate of the extent of each coral morphology. In fact, coral spurs and groove and coral field have quite blurry boundaries as one seems to transition into the other according to distance to reef crest and exposure to open waters. Coral patches, on the other hand, are likely to include a significant amount of sand, as the features were often too small for individual segmentation. These coral formations were mostly found on the northern parts of the island systems, generally shallower and with less dynamic waters. Here, they can even develop similar to individuals boulders, most often smaller than pixel size.

Table 17 – Estimate of the coral cover extent (km^2) according to benthic habitat level

	Coral				Total
	Indetermined	Field	Patches	Spurs and Grooves	
Baixo S. António	0.00	0.18	0.15	0.50	0.83
Mafamede	0.37	0.80	0.21	1.32	2.70
Puga Puga	0.00	0.24	0.11	0.48	0.84
Baixo Miguel	0.00	0.40	0.02	0.36	0.78
Njovo	0.21	0.60	0.14	0.70	1.65
Caldeira	0.00	1.17	0.11	0.63	1.91
Moma	0.23	0.21	0.09	1.38	1.92
Epidendron	0.00	0.59	0.10	2.56	3.25
Casuarina	0.00	1.21	1.18	1.99	4.37
Fogo	0.00	0.65	0.20	1.03	1.89
Coroa	0.16	0.23	0.07	0.49	0.96
Silva	0.15	0.36	0.04	0.57	1.11
Total	1.12	6.64	2.43	12.02	22.22

The proportion of each type of coral remains quite constant throughout the territory. The remaining class types, based on sand, rubble and rock, show no predominance or particular trend across the archipelagos, except for the overall high occurrence of mixed classes such as Rock with Brown Macroalgae and Sand and Rubble, Rubble with Seagrass and Rocks with Brown Macroalgae, Sand with Seagrass and Rocks with Brown Macroalgae. It was, nonetheless, not possible to identify one clearly predominant benthic habitat class within the lagoon.

The large variety of benthic covers and its subtle variations poses significant challenges to the clear delineation of the classes. With few exceptions, the fundamental constituents identified during the field campaigns – sand, rock, rubble, seagrass, brown macroalgae and coral – are quite intermixed. Additionally, aquatic vegetation, algae and coral come in a myriad of species with different spectral signatures, densities, growing patterns and conditions, creating a wide range of textures and colors not easily separated. Both in the field and in the mapping exercise, visual assessment and class assignment remained challenging, introducing bias and being subject to interpretation error.

The deep benthic cover class was difficult to delineate due to a weak signal, and its compositions remained unknown (Figure 27). However, it is reasonable to make two broad assumptions that support the possibility of its identification as coral. The first is that the western side of the islands shows less suitable conditions for coral, with harder to colonize sand substrate and poorer light conditions on account of sediment discharge from the mainland (Whittington and Heasman 1997). The second is that the strong currents on the exposed sides of the reef system make the presence of seagrass less likely than of coral structures. These assumptions, together with the features' proximity to identified coral structures and their alignment with the archipelagos general orientation indicate the possibility of the existence of unmapped deeper reef structures between the islands.

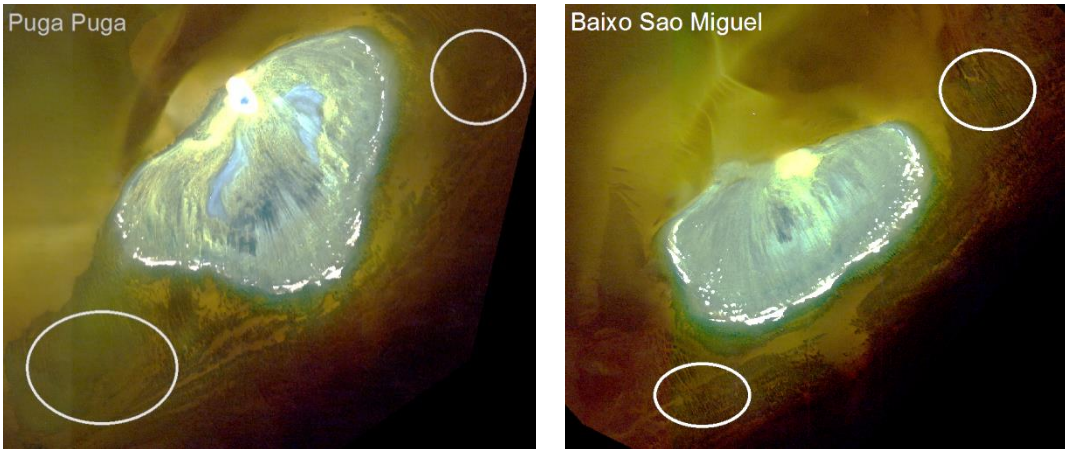

Figure 27 – Deep benthic cover examples; visualization was enhanced by increasing brightness and contrast

If the presently mapped deep benthic cover class would prove to be coral, that would result in an approximate threefold increase of the total coral extent (Figure 28), another strong incentive for further research in the region.

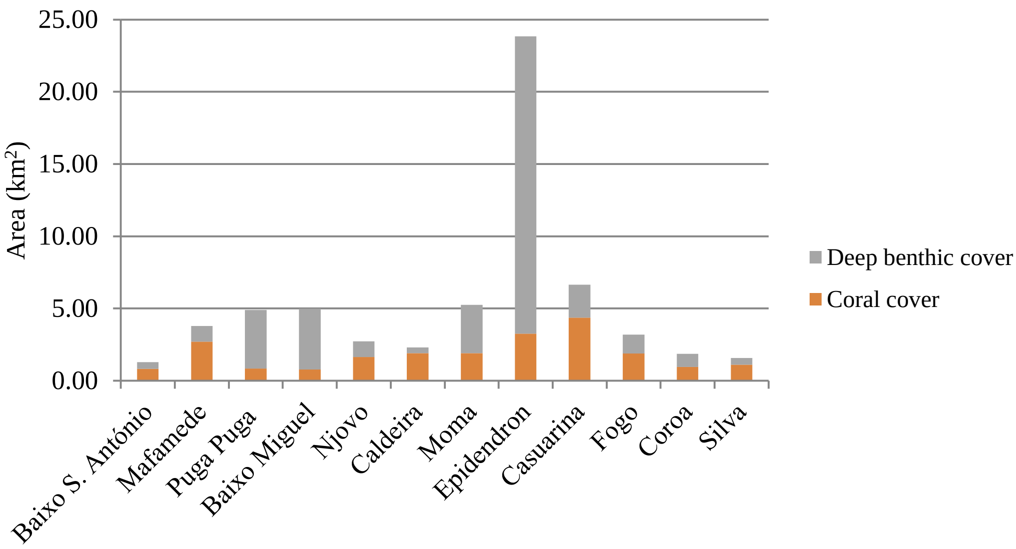

Figure 28 – Total coral and deep benthic cover across the PSEPA

Furthermore, records from the British Admiralty Nautical Charts (UKHO) point out the existence of other shallow areas in the region. These six additional locations within the PSEPA territory are of about the same depth as the mapped atolls (10-15 meters deep), and in-line with the archipelagos (Figure 29). They concentrate in the section between Moma and Epidendron, which corresponds to the most isolated and less visited part of the protected area, according to information gathered during the interviews.

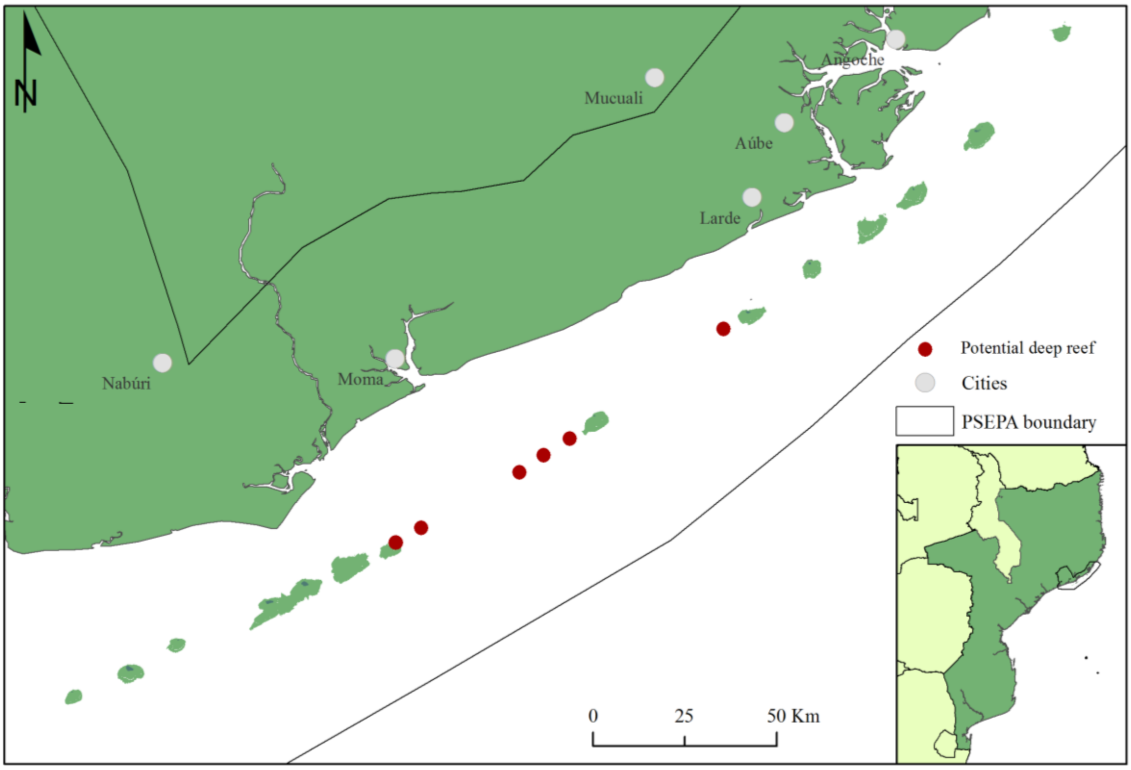

Figure 29 – Potential additional deep reef structures, considered as such because they a) are mapped shallower areas, like for example Baixo Miguel, b) are in allignment with the archipelagos and its deep benthic cover

Considering the archipelagos alignment and the mapped atolls configuration, with deep benthic cover extending in that same direction, further research is recommended to explore the hypothesis of the existence of more coral reef systems in the region. The detection of new coral reef would have a significant impact on the relative importance of this protected area regarding regional connectivity and resilience, as well as new requirements for the PSEPA's management plan.

Bottom cover level (L2) mapping results show very high quality for standard management and planning purposes, for which 60% overall accuracy is generally considered adequate (UNESCO 2000, Dalleau, Andrefouet et al. 2010). At this level it is possible to discern coral from sand, vegetated areas and rocky areas with a quite high level of confidence. This would be sufficient for the delineation of non-fishing and prohibited/restricted fishing activity zones, an application mentioned by PSEPA conservation officers. The quality of these results support the idea that the remaining maps, although not having an estimate of accuracy, would be adequate for the same uses.

At the benthic cover level (L3), overall accuracy is lower, between 30% and 70%, and this is very likely the result of the large increase of class number. Observation and class description in the field was difficult due to characteristics of the coral reef system (similarities between sand and rubble, algae and seagrass, etc.), the sampling methodology (heavily dependent on visibility and sea conditions), and lack of detailed knowledge of local habitats, particularly the vegetated ones. Benthic cover was visually assessed in a qualitative way and, despite the mentioned issues, is expected to have improved throughout fieldwork.

Variation of overall accuracy with class number was observed by Andréfouët (2008), who assessed results of mapping efforts using IKONOS, suggesting that *"high accuracy (>70%) is limited to a low number of ~10 classes"*, which was later confirmed by Roelfsema, Phinn et al. (2013). In this last study, it was observed that the variation of mapping categories *"did not influence the overall accuracy of the [VHR, OBIA] maps, with overall accuracy for each map type falling within the same range: 'geomorphic zone' map with 70–90% overall accuracy and 'benthic community' map with 52–80% overall accuracy"*.

Our results are consistent with the described behaviour, with accuracy decreasing 20% to 30% when the number of classes increases by 10 to 15 (Figure 30). Moreover, overall accuracy ranges are concordant with current research results (Capolsini, Payri et al. 2003, Andréfouët 2008, Knudby, LeDrew et al. 2010, Roelfsema, Phinn et al. 2013).

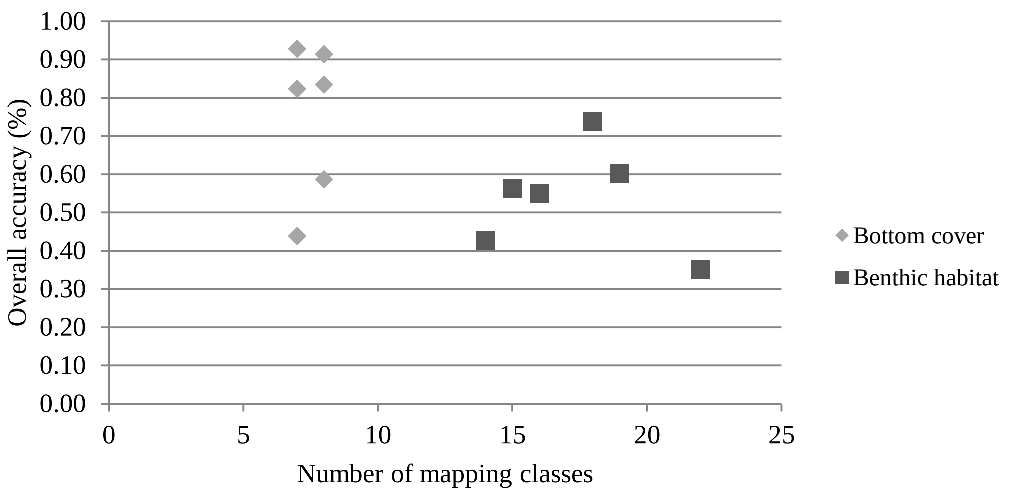

Figure 30 – Overall accuracy variation with number of bottom cover (L2) and benthic habitat (L3) mapping classes

It was not possible to find a pattern between accuracy values and imagery acquisition time (month, i.e. season, or year) or applied processing techniques that could explain the variation of mapping quality. One possibility, not explored in this work, is the influence of the water surface

According to the calculated Kappa index of agreement (KIA), a measure of how much error is avoided by map classification when compared to a random classification (UNESCO 2000), the reliability of the produced benthic habitat maps is low, with most registering below 0.5. The lowest values obtained are for Baixo Miguel, where KIA is below 0.20 at the L2 level, and 0.30 at the L3 level. The use of this particular map would then, according to this accuracy measurement, avoid up to 30% of the error associated with using a completely random classification.

The low KIA results are probably due to the challenges faced during fieldwork, such as the influence of tidal variations and difficulties in benthic cover identification, and particularly temporal precision and geolocation accuracy, which have implications both in the classification process – as the field data was used to guide feature identification – and the accuracy assessment.

Precise geo-location was challenging due to the fieldwork methodology and the fine scale heterogeneity of the sea bottom. The measurement of three variables (GPS coordinates, depth and bottom/benthic cover), by two to three operators using different devices, was bound to lead to some lag between measurements. Moreover, the continuous movement of the boat, even if slow, adds to positional and synchronization errors. This undoubtedly resulted in spatial discrepancies between field and imagery data.

The imagery was not further geo-corrected post-delivery. However, imagery of this type has a typical geo-locational accuracy of 10 to 15 meters, while for the GPS equipment used this is approximately 5 to 10 meters. As such, the benthos observed in the field may diverge as much as 25 meters from the position indicated in the imagery, which may increase classification confusion (Figure 31).

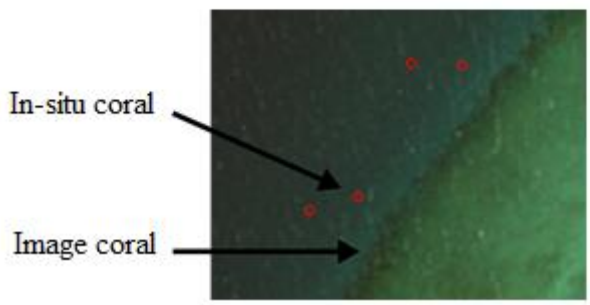

Figure 31 – Example of discrepancy between in-situ benthic class and visual interpretation (courtesy of (Hedley 2014)

Additionally, as imagery and field data differ in their moment of collection (to a maximum of 5 years), it is likely that the benthos has suffered changes. Although this is primarily an issue concerning aquatic vegetation, more susceptible to change, deposition and erosion processes may also result in relatively rapid change, particularly on sand and rubble substrate.

Visibility was an additional issue, being responsible for the exclusion of 128 out of 666 points from the fieldwork. Although there are no strict guidelines, it is generally recommended to have around 80 training and 30 to 50 accuracy assessment sites per class for coarse four habitat class maps, covering areas of several square kilometers (UNESCO 2000). As the amount of data points was small, and the number of mapping classes quite high, the direct application of the field data as training sites was avoided. Field data was then used for accuracy assessment, in an attempt to assure the statistical quality of its output.

The recommended collection of data in heterogeneous areas and along transects across different geomorphological zones (Andréfouët 2008) was to a great extent impossible for safety reasons. The reef crest, inaccessible due to its strong current and low depth, acted as a divide between the lagoon and the fore reef, preventing data collection in many zones of interest. Collected field data was clearly insufficient for the assessment of all 22 benthos classes, and in some cases, was too poorly distributed for adequate evaluation at the bottom cover level. As expected, bad accuracy scores were associated with mixed, thematically close classes such as Sand/Rubble/Rock with Macroalgae and Seagrass.

Thus, even with low Kappa values, the maps could nonetheless serve their purpose with an adequate level of confidence, as a significant portion of misclassification was between thematically close classes.

Interviewees had mentioned the lack of better and more detailed information of the area as an obstacle for future studies design, for which the current maps are expected to contribute. The type and details of data collected during the surveys was perceived as quite helpful for the PSEPA management and a good starting point for further research work. With the gathered data on depth and benthic cover it will be possible to define zones where each fishing technique can be used, and to better communicate and justify those choices. The definition of recreational fishing areas, as well as line vs. seine fishing zones, are likely uses for this information.

Current and former PSEPA management expressed, during the interviews, that simpler benthic habitat maps would be more useful – too much information and a clutter of detailed, although similar benthic habitats could hinder the effective use of the maps. By applying an hierarchical approach, it is possible to simultaneously provide detailed information and the ability to reduce map complexity by merging selected classes. In that, GIS can simplify data use, provided some basic knowledge of appropriate software, or online visualization tools.

In general, the primary value of the benthic habitat maps produced within this project is the overview they offer, which contrasts with the small scale and spatial fragmentation results offered by previous surveys.

6.2. Biodiversity analysis

Coral cover decreased by approximately 20% between 2006 and 2013, although the proportion of live coral remained the same. So, despite a decreasing trend of coral extend, its health appears to be stable. Local variation, i.e. within the same island, was up to 20%, but regardless of that, both surveys denote a decreasing trend of live coral cover towards south. Coral diversity also decreased in the same period, from an average of 22 to 17 genera. However, its north-south variation is positive, indicating more diverse ecosystems in the south despite the lower live coral coverage.

The general spatial negative trend is further noticeable in the fish dataset. Fish density, diversity and biomass all have lower values towards the south of the PSEPA archipelagos. While fish density decreases between 2006 and 2013, diversity and biomass were not assessed due to large value discrepancies. This reflects an inherent difficulty of using datasets originating from distinct field survey methodologies.

No new spatial pattern emerged from the standardization of the fish communities indicators according to coral cover or coral reef system area.

While in 2006 the selected method was the Point Count (PC) technique according to Bohnsack and Bannerot (1986), in 2013 a diver-operated stereo video census (DOSVC) was used. Although based on the same observational principals, studies have shown that PC and DOSVC results differ significantly (Harvey, Fletcher et al. 2002, Tessier, Chabaneta et al. 2005, Bower, Gaines et al. 2011). While PC is man based, DOSVC makes use of recordings and image analysis software, allowing a more accurate fish count, species assessment and size estimate. Photogrammetric measurements from DOSVC were found to be more accurate and precise in estimating fish length than PC, where there is a tendency for underestimating (Tessier, Chabaneta et al. 2005, Bower, Gaines et al. 2011). Additionally, *"the magnitude of underestimation error increased with fish length"* (Bower, Gaines et al. 2011). Even when divers are particularly experienced and able to accurately estimate length, they have been found to be unable to detect subtle size variation and to lack precision, which can deeply affect results for small samples (Harvey, Fletcher et al. 2002).

These findings are consistent with the lower values recorded for biomass in the 2006 survey, a PC survey whose total sample size was about 10 times smaller than the DOSVC one. Based on this, the 2013 values are considered to better represent fish biomass in the region.

The use of different methods could also explain the discrepancy between 2006 and 2013 species richness values. Video detected species richness values tend to be lower than those collected through direct observation, on account of limited field of vision, *"even though one's vision is partially reduced when using a diving mask"* (Tessier, Chabaneta et al. 2005). Regarding this metric, the dataset of 2006 should then be the most indicative of local species richness.

The different survey areas doesn't necessarily pose a problem, as both methods are based on the undisturbed observation of marine wild life and were conducted in what are expected to be fairly similar locations and thus, conditions. Furthermore, datasets originating from different methods have been used before as part of the same data pool in coral reef ecosystem studies (Mumby, Broad et al. 2008).

As it was not possible to evaluate the variation of both fish biomass and diversity over time, the claim of decreasing size and diversity couldn't be supported nor refuted. It is nonetheless possible to refer to their spatial north-south decrease. This is an important point, as it contradicts general impressions from the PSEPA management that southern islands, further away from the reach of fishermen, should present more rich and diverse fish communities.

The application of the Spearman rank correlation test did not assist in uncovering relationships between coral cover and fish variables from the 2006 dataset. The results show moderate to very strong negative relationships between live coral cover and fish density, live coral cover and fish diversity, dead coral with algae cover and fish density, and live coral cover and fish biomass. The remaining pairs of variables have weak, negative relationships; with the exception of recently dead coral cover and fish biomass and coral genera and fish biomass, which have low positive relationships. These results are unexpected, as fish variables wouldn't normally display the same trend for both live and dead coral. Additionally, it is generally accepted that the richer the coral reefs, the healthier their fish communities (McArthur, B. et al. 2009, Mellin, Andréfouët et al. 2009, Knudby, LeDrew et al. 2010, Knudby, Roelfsema et al. 2011). This would imply that more fish, of bigger sizes and with higher species diversity, should be found in environments with higher live coral cover and variety of genera, which is not supported by the present analysis. One possible reason could be that the species included in the survey are not the best to represent fish habitat preferences, and other species could be more adequate as coral (health) indicators in this protected area (Sawayama, Komatsu et al. 2012).

The p-values indicate that all pairs of variables show a non-significant rank order relationship ($N = 10$, $\alpha = 0.05$). This means that the datasets do not provide reasons to conclude that changes in one variable cause changes in another. Due to the particularly small sample size, further data would be necessary to better assess the existence/absence of statistically significant relationships.

The Spearman rank correlation was also used to test the statistical relationship between benthic landscape metrics and fish variables. The test was conducted using the 2013 dataset, thus basing the analysis on the most recent data from both biological and physical aspects of the reef system, and consequently increasing confidence in the results. Landscape metrics at geomorphological, bottom cover and benthic habitat levels were calculated for the areas surrounding each fish data sampling site, for various radii, a commonly used methodology (Andréfouët and Guzman 2005, Dalleau, Andrefouet et al. 2010, Knudby, Roelfsema et al. 2011, Sawayama, Komatsu et al. 2012). The selected buffer radii were 7, 12 and 25 meters (Figure 32). The first was chosen to match the indicator standardization area, according to the RA sampling methodology; the second was chosen to consider the total area used in the 2013 fish surveys; and the last to include larger scale landscape dynamics.

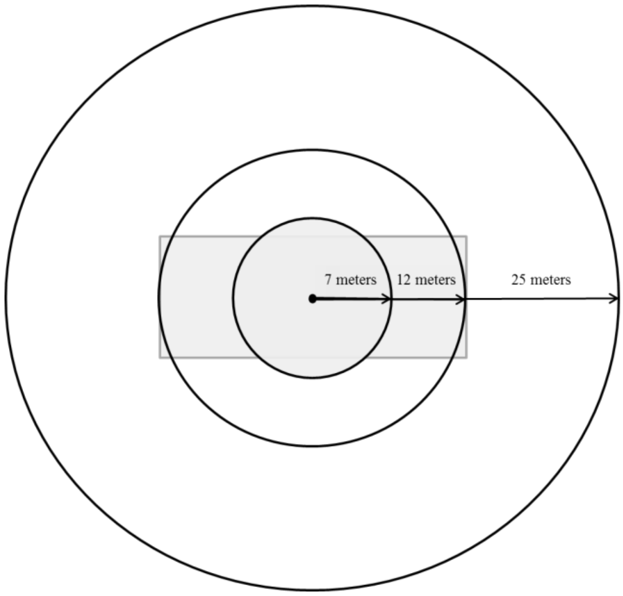

Figure 32 – Selected buffer sizes (7, 12 and 25 meters radii) for the calculation of landscape metrics, and its comparision with the fish survey areas (7 meters radius circle and 10 by 25 meters rectangle)

No statistically strong relationships or trends were found between the landscape metrics and fish variables. Nevertheless, results at the geomorphological and bottom cover levels indicate that in complex, heterogeneous zones (i.e. with higher patch and edge density), at finer spatial scales (≤ 12m), a larger variety of fish can be found. Similarly, areas with more relative coral field cover are expected to have more fish species for both finer and coarser scales (≤ 25 m) in benthic habitat maps. Additionally, higher fish numbers are to be expected in areas with more fore reef, but only at fine scales. Fish density and diversity seem to be the most representative indicators for the PSEPA system, regarding its habitat distribution.

The majority of the calculated Spearman rank correlation coefficients indicate positive relationships between variables, which was the expected behavior. These observations seem reasonable and in agreement with current common knowledge of reef systems ecology, where more complex habitats (higher edge and patch density) with higher proportion of coral (fore reef zones) and higher rugosity (coral spurs and groove and coral patches) are expected to support richer biodiversity with greater biomass

(McArthur, B. et al. 2009, Mellin, Andréfouët et al. 2009, Knudby, LeDrew et al. 2010, Knudby, Roelfsema et al. 2011). The presence of seagrass and other vegetation is another factor usually included with the above but, in the PSEPA, highly vegetated areas were mostly confined to very shallow waters and, as such, less rich in ichthyological biodiversity.

Although the majority of the pairs of variables indicate a non-significant rank order relationship ($N = 16$, $\alpha = 0.05$), there are some exceptions coinciding with the stronger correlations found. The aforementioned moderate correlations found at the geomorphologic, bottom cover and benthic habitat levels have p-values between 0.01 and 0.04. These values support the statistical significance of the correlations found and indicate that, in general terms, increases in patch density, edge density, relative fore reef and coral field area cause an increase in fish density and species richness across the different spatial scales under assessment.

These observations, although not based by very strong statistical relationships, could provide additional information to support, for example, the design of fish surveys or the delineation of non-fishing zones.

The conducted interviews revealed the general impression that detailed and verified data is lacking, and that more field surveys are needed. This acknowledgement coexists, however, with the expectation of better maintained and richer ecosystems towards south, namely on the Primeiras islands, which coincides with the area where research has been less consistently performed.

All the interviewees referred that marine fauna is declining with increasing speed, and most attribute this phenomenon to ever-growing fishing pressure, as artisanal fishermen numbers have been escalating. This is mentioned to be most significant on coastal areas, while no significant changes are typically mentioned for open waters within the artisanal fishing zone. The islands north of Njovo, closer to the main population centers, are under heavier fishing pressure. Data analysis confirm local ecosystem decline, with both coral and fish indicators reducing from 2006 to 2013. However, and contrary to other studies (Knudby, Roelfsema et al. 2011), distance to the main fishing port, Angoche, correlates weakly with fish density, fish biomass and species diversity, emphasizing the importance of exploring other potential causes for biodiversity loss in the region. Other impacts such as from mining activities in the vicinity of Caldeira are as of the moment unknown.

The interviews revealed the general impression that the main obstacle in addressing the conflicts related to natural resources management is the lack of administrative measures and specific regulations. Law and conservation strategy enforcement is considered poor, driven by ineffective and inadequate inspection and control and supported by limited resources. Coordination among sectors is lacking regarding local economic development and natural resources conservation.

Interviewees suggested solutions for the local natural resources management of conflicts such as new approaches to fishing practices regulation, in partnership with the industry, and through the creation of a pilot plan based on the funding of non-fishing periods and prohibited/restricted activity areas. Experience in the region has shown that education and awareness raising strategies fall short from its desired outcomes, and it is believed that local initiatives should be based on progressive changes with proven, successful results. There are currently two marine costal sanctuaries, started in 2010, that are showing promising results and a good level of community acceptance.

Other mentioned alternatives, such as large scale investment in alternative markets, e.g. tourism, seem unlikely as the local weather and natural conditions do not cater to current market trends, and the region has very poor accessibility.

All the above measures to counteract the local biodiversity loss problems could greatly benefit from an integrated approach, namely by the inclusion of spatial data analysis results. Despite the substantial effort and resources that have been put into the region's sustainable development, it is noticeable that coordination, communication and, in general, cooperative work could improve significantly.

7. Conclusion

With this research project it was possible to investigate and answer the proposed research questions, gathering knowledge on the previously unmapped coral reefs in the Primeiras and Segundas Environmental Protected Area (Mozambique).

<u>How are the benthic habitats distributed in the region?</u>

Twelve atolls were classified at the geomorphologic, sea cover and benthic habitat level to a maximum of 24 classes with average overall accuracy above 50%, totalling 130 m^2 of mapped extent. Among the identified components there was sand, rubble, rock, seagrass, brown macroalgae, and coral.

All islands present a very similar structure – a flat lagoon with shallow water on the northern side, surrounded by reef crest, fore reef and deep reef, the last usually extending towards southeast. Coral spurs and grooves dominate the south and east zones, becoming less developed, broader and flatter towards west. There are sand and seagrass and/or brown macroalgae extensions on the northwest and west, towards mainland, and coral patches on northeast. The lagoon is characterized by high occurrence of sand, together with mixed classes of rubble, rock, seagrass and brown macroalgae. Lagoon and reef crest are generally shallow, at about 2 meters deep during low tide, and likely to be exposed during low spring tides.

<u>How are the biodiversity indicators distributed in the region? Is there evidence of biodiversity decline?</u>

The analysis of the available coralline and ichthyological datasets could not verify or support the interviewees' assumptions of better fish biodiversity in the southern islands. Despite the increasing coral cover trend towards south, which could provide larger ecosystem availability, fish numbers shows a decreasing trend in that direction. Nevertheless, results support the local consensus of ecosystem decline. Both coralline and ichthyological data indicate a reduction from 2006 to 2013, although no relevant strong statistically significant correlations were found.

However, distance to the main fishing harbor doesn't correlate with fish biodiversity indicators. The mismatch between local perception and the collected data emphasizes the value of spatial analysis for conservation purposes. Management efforts, currently guided by the aforementioned perceptions and conditioned by escalating costs, focus both mitigation measures and further research mostly on the northern, closer islands. This is likely to perpetuate the current lack of information about a significant portion of the PSEPA, and with it the possibility of uncovering the causes of decreasing biodiversity in the region. For example, the effects of the maritime mining activity close to Caldeira, likely to have significant impacts on the coral reef system, are currently unknown.

Are there significant relationships between benthic habitats and biodiversity indicators?

Biodiversity indicators vary with landscape indicators as expected according to current common knowledge of reef systems ecology – the higher habitat complexity and rugosity, the richer the biodiversity. It was, however, not possible to identify statistically strong relationships between the selected landscape metrics, across different spatial scales and hierarchical classification levels, and available ichthyological indicators. Likewise, the relationship between coral cover and genera and fish indicators was inconclusive, likely due to the dataset small size. These observations, although not supported by strong statistical relationships, could provide additional information to assist in the design of fish surveys or the delineation of non-fishing zones, for example.

Monitoring, planning and mitigation measures concerning local biodiversity loss would greatly benefit from an integrated approach, namely the use of remote sensing techniques and products. With their inclusion, future field efforts could be leveraged into better, more efficient, outcomes, and lead to the production of higher quality supporting documentation for PSEPA’s planning and management.

Despite its increasingly relevant role in conservation, communication between remote sensing and conservation specialists is still perceived as one of the main reason for its underusage in this field, together with data continuity, affordability and access (Wang, Franklin et al. 2010, Turner, Rondinini et al. 2015). With this work, an attempt was made to tackle these aspects by *“extract[ing] value from satellite imagery as well as link[ing] it with other types of information”* (Turner, Rondinini et al. 2015).

8. Recommendations

Several recommendations can be made based on the results of this mapping exercise.

Better definition of the geomorphological zones, namely of the conceptual assumptions underlying each zone, could support classification improvements. Similarly, the creation of benthic cover topology rules could increase product quality, as well as assist in better fieldwork design. The inclusion of bathymetric data would be fundamental for this purpose, allowing for the inclusion of topography information.

The resulting sample size and distribution was not compatible with the satellite imagery, nor were the samples assured to be uniformly distributed through all classes. A higher point density and better geographic distribution, particularly in the lagoon and reef crest zones would be recommended.

The quality of the maps would benefit from further, and more detailed, fieldwork, particularly in the locations with no field data. Fieldwork targeting deep benthic cover, as well as additional features that show some potential to be harbour coral reefs, would be advised. Likewise, further remote sensing efforts in the region should focus on the detection of further coral reef structures on historically mapped shallow areas. Due to the archipelagos morphological pattern, it is likely that these will also contain coral reef. As investigative work will require significant resources, it is recommended to start with the remote detection of these structures and, if possible, their classification. Knowledge on such deep benthic structures could significantly impact PSEPA’s management, improve the understanding of the region and alter the perception of its importance among the eastern Africa coral reefs.

Additionally, the adoption of a systematized coral reef hierarchical classification scheme would increase results comparability and knowledge transfer.

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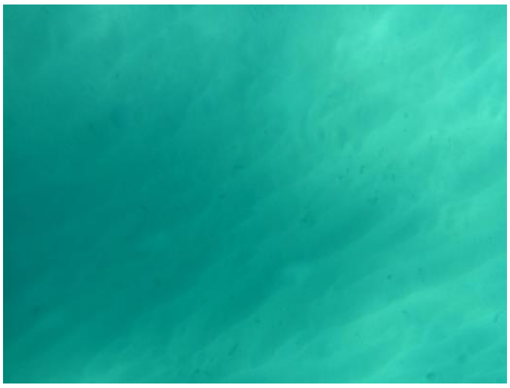
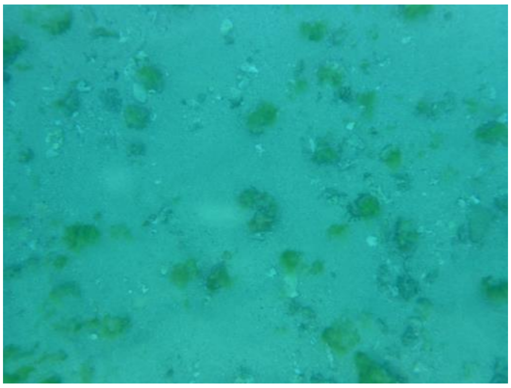
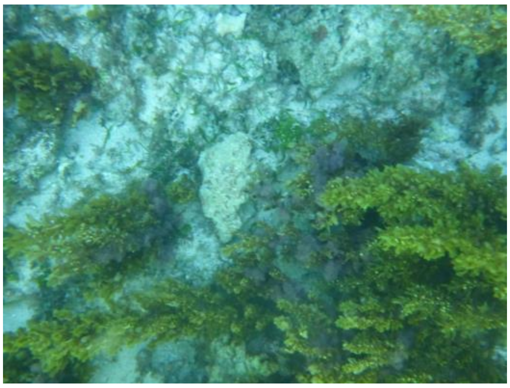
Appendix I.

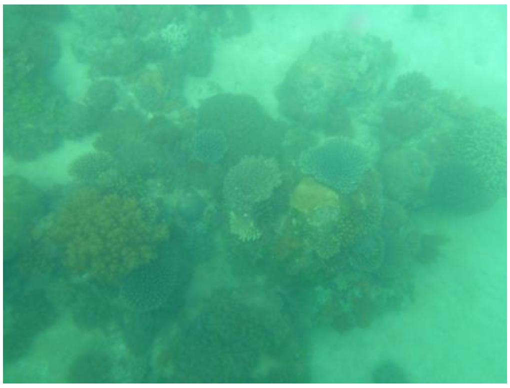
Examples of different benthic covers observed during fieldwork, and their corresponding benthic habitat classification

Sand	Sand with rubble
	
Sand with Rocks	Sand with Brown Macroalgae
	
Sand with Seagrass	
	

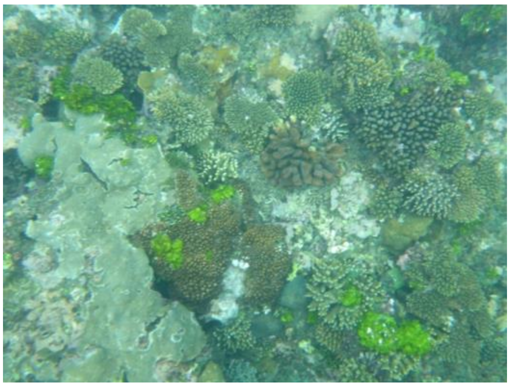
Rock with Brown Macroalgae



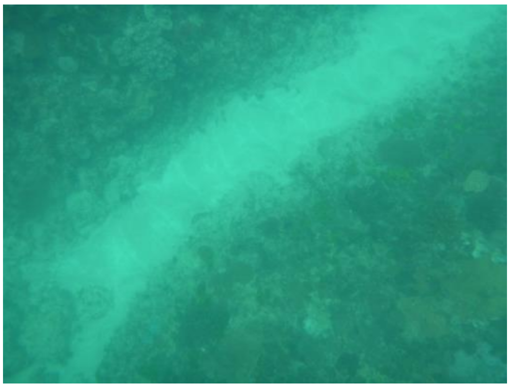
Coral Patches



Coral Fields

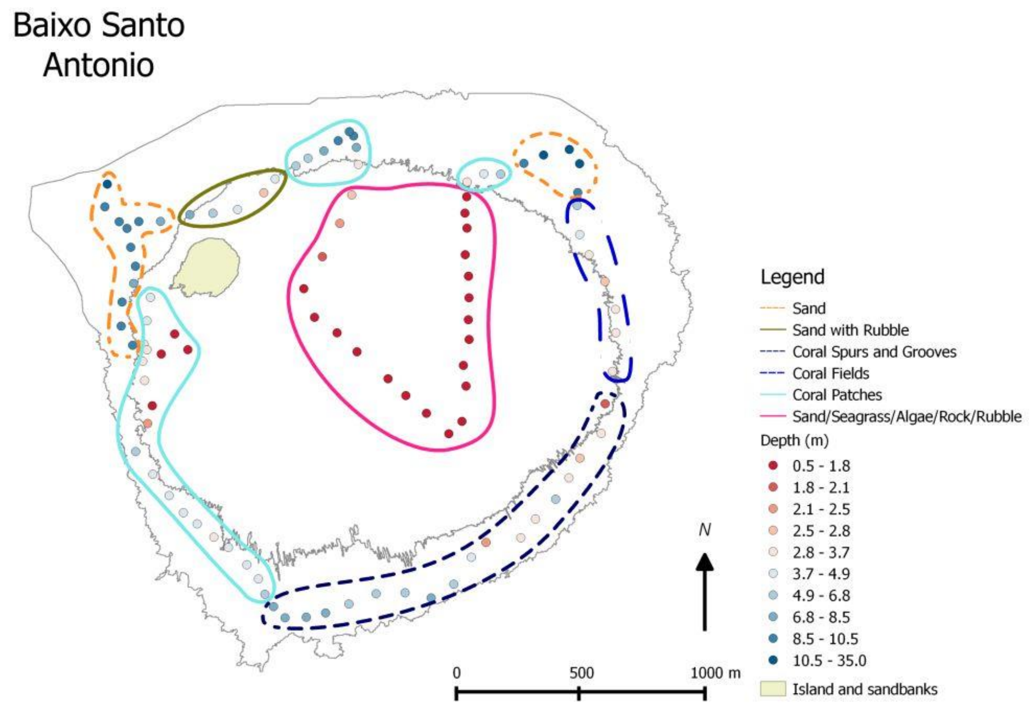


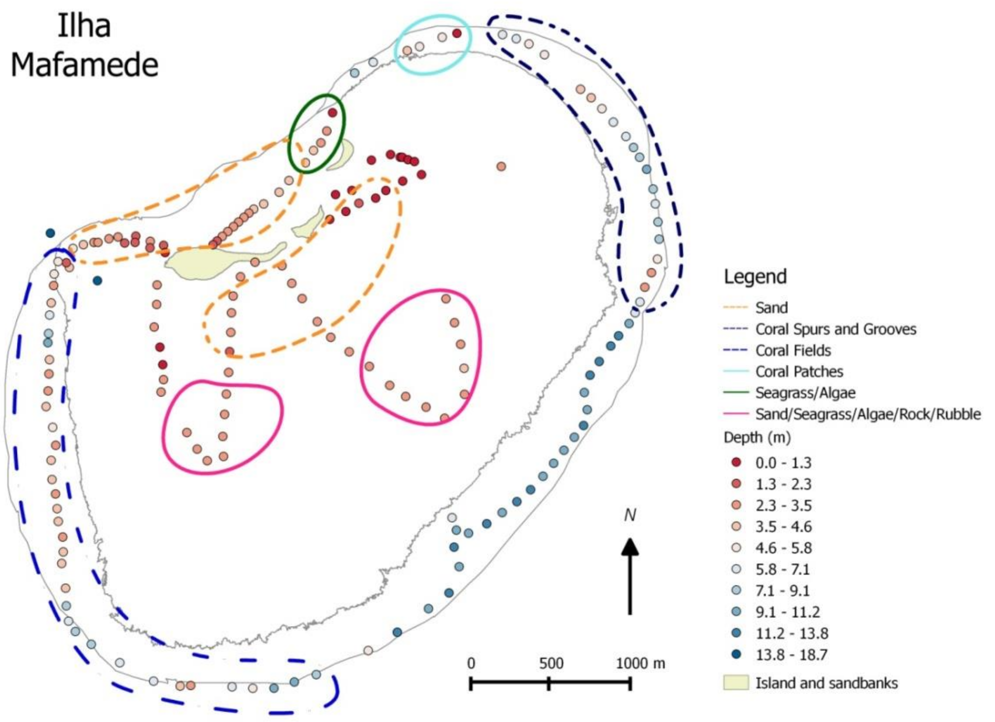
Coral Spurs and Grooves

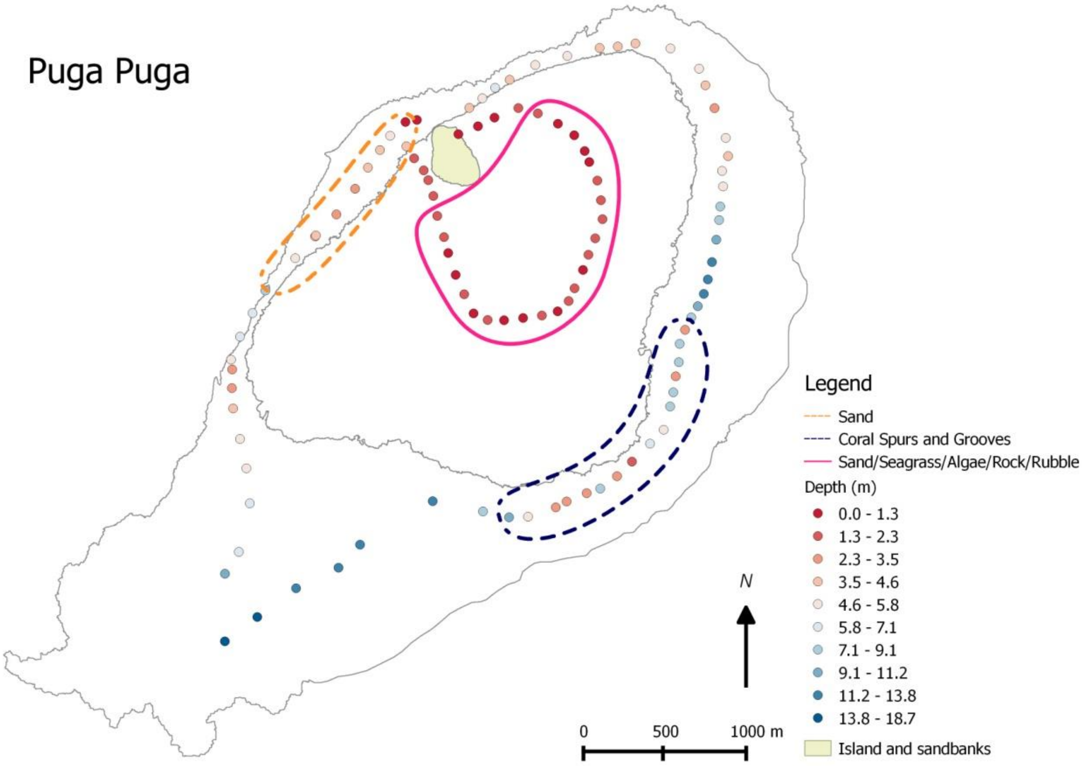


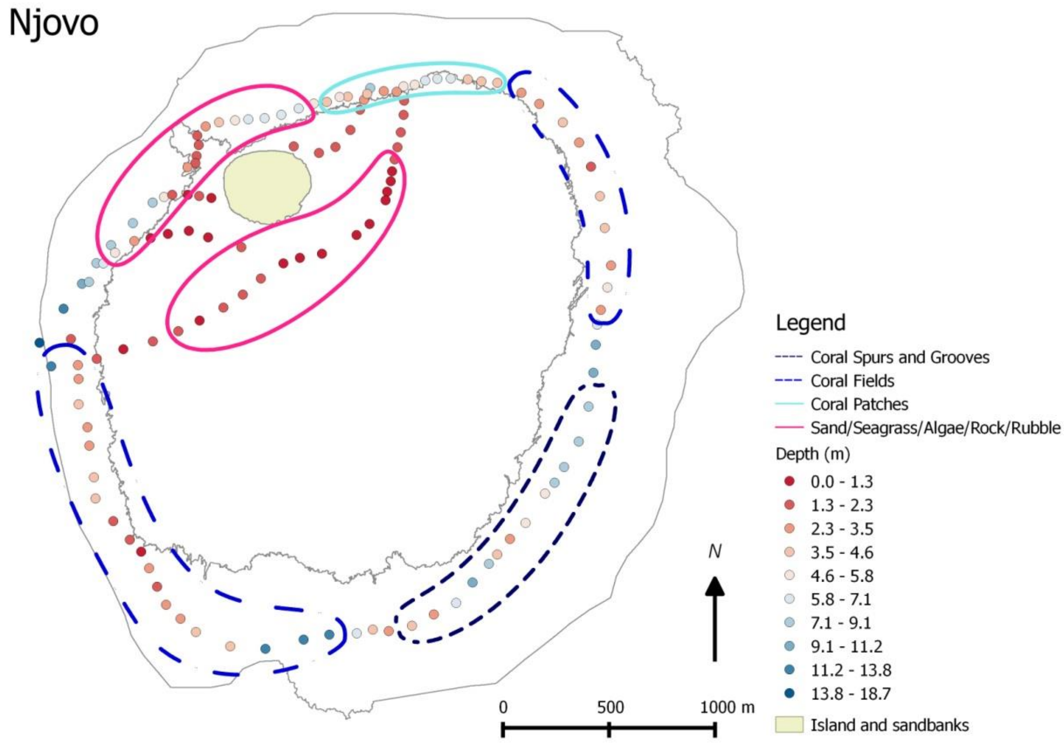
Appendix II.

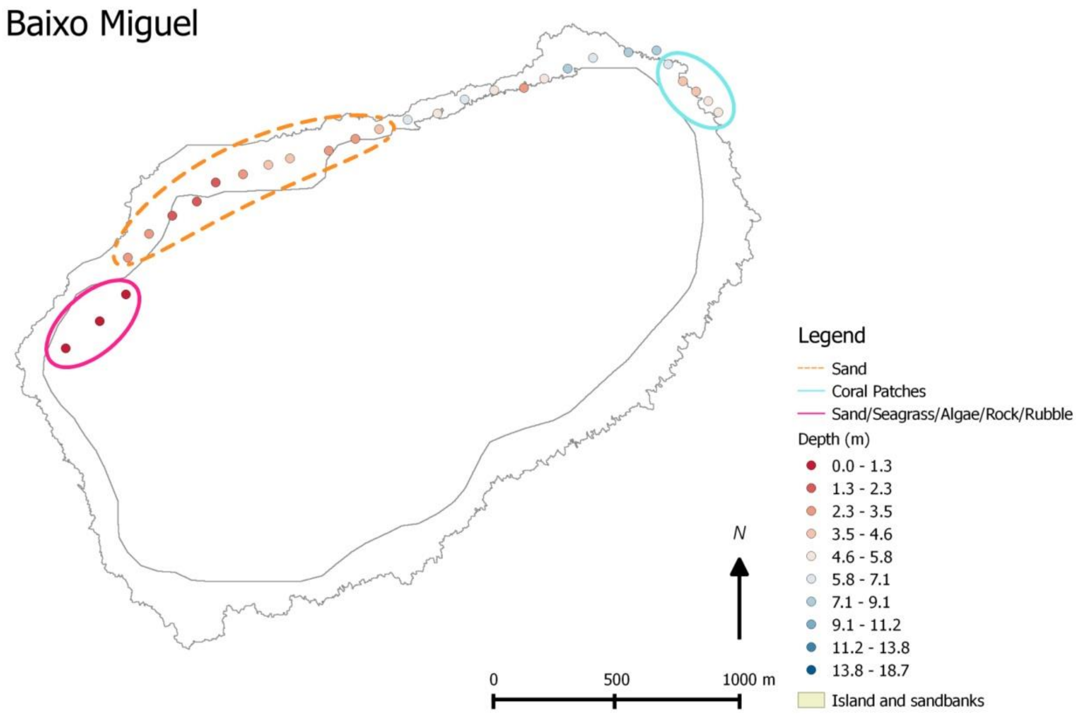
Overview of the data collected during fieldwork



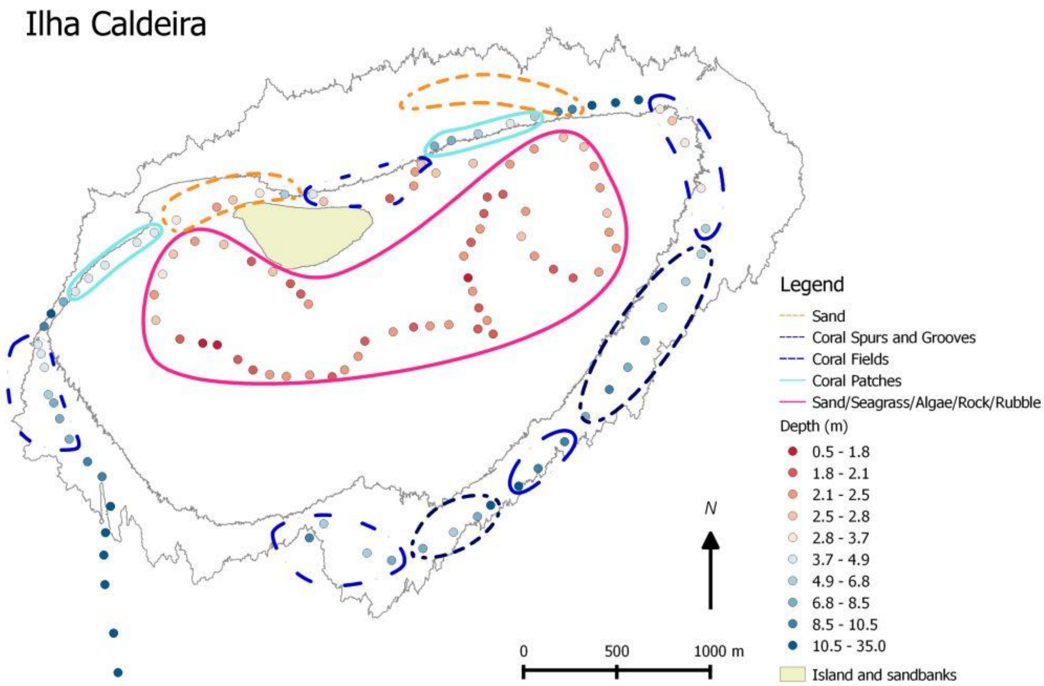



Puga Puga
Legend
Sand
Coral Spurs and Grooves
Sand/Seagrass/Algae/Rock/Rubble
Depth (m)
0.0 - 1.3
1.3 - 2.3
2.3 - 3.5
3.5 - 4.6
4.6 - 5.8
5.8 - 7.1
7.1 - 9.1
9.1 - 11.2
11.2 - 13.8
13.8 - 18.7
Island and sandbanks
N
0
500
1000 m


Njovo
Legend
Coral Spurs and Grooves
Coral Fields
Coral Patches
Sand/Seagrass/Algae/Rock/Rubble
Depth (m)
0.0 - 1.3
1.3 - 2.3
2.3 - 3.5
3.5 - 4.6
4.6 - 5.8
5.8 - 7.1
7.1 - 9.1
9.1 - 11.2
11.2 - 13.8
13.8 - 18.7
Island and sandbanks
N
0
500
1000 m



Baixo Miguel
Legend
Sand
Coral Patches
Sand/Seagrass/Algae/Rock/Rubble
Depth (m)
0.0 - 1.3
1.3 - 2.3
2.3 - 3.5
3.5 - 4.6
4.6 - 5.8
5.8 - 7.1
7.1 - 9.1
9.1 - 11.2
11.2 - 13.8
13.8 - 18.7
Island and sandbanks
N
0
500
1000 m



Ilha Caldeira
Legend
Sand
Coral Spurs and Grooves
Coral Fields
Coral Patches
Sand/Seagrass/Algae/Rock/Rubble
Depth (m)
0.5 - 1.8
1.8 - 2.1
2.1 - 2.5
2.5 - 2.8
2.8 - 3.7
3.7 - 4.9
4.9 - 6.8
6.8 - 8.5
8.5 - 10.5
10.5 - 35.0
Island and sandbanks
N
0
500
1000 m

Appendix III.

Benthic habitat main constituents' characterization

Sand, generally follows water movement readily and as such long term deposits are mostly calm areas, for examples in slumps or as substratum for vegetation, however entities like ridges, mounds and islands are also areas where deposit occurs and in truth where it is most prevalent. Relevant for remote sensing applications is the fact that sand has a very high albedo and on its own has no texture.

Rubble, while heavier than sand and thus a higher force is required to move it, it still deposits in a manner comparable to that of sand. Rubble has lower albedo than sand and the effect of mixed deposits of sand/rubble is a slightly lowered brightness level, comparable to the effect of depth; therefore it is hard to distinguish sand/rubble from sand without an indication of depth. Additionally, it is too fine to create texture at this scale.

Rocks, here both encompassing single entities and consolidated like bedrock and pavement. Quite high albedo, although depending on rock type.

Algae (micro and macro/seaweed), is a very large and diverse group of organisms that come in a large spectrum of sizes, shapes and colors; in our application we are interested in the macro and seaweed varieties. Algae are very versatile and may grow both on consolidated and unconsolidated substratum, although when on sand substratum they generally do not grow as dense as seagrass, which may be used as the signal from the substratum will be stronger. In the field rocks overgrown with algae were frequently observed and algae are a natural component in coral habitats, possibly confusing separation.

Seagrass[1], thus named for their characteristically long and narrow leaves and the fact that they often grow on large dense sea beds. Their characteristic of growing with a somewhat consistent density is especially interesting out of a RS perspective since it gives a consistent hue in the imagery, though they may grow in patches. Seagrass needs some degree of unconsolidated substratum to root.

Coral, also a diverse group and perhaps one of the more sensitive habitats, requiring light but sensitive to high levels of it, sensitive to high temperatures and high turbidity. These characteristics make coral sparse in the shallow lagoon and in the turbulent reef crest and less developed in the less nutrient rich, periodically turbid and warm waters of the landward side of the reef system. Coral may colonize any of the other substrates if conditions allow, albeit it is very rare in the case of sand.

[1] It should be noted that while Brown Macroalgae corresponds directly to what it refers to, the term Seagrass is used to refer to all remaining algae and aquatic plants observed during field work, mostly of green coloration.

Appendix IV.

Description of RA and EAMT data collection methodologies

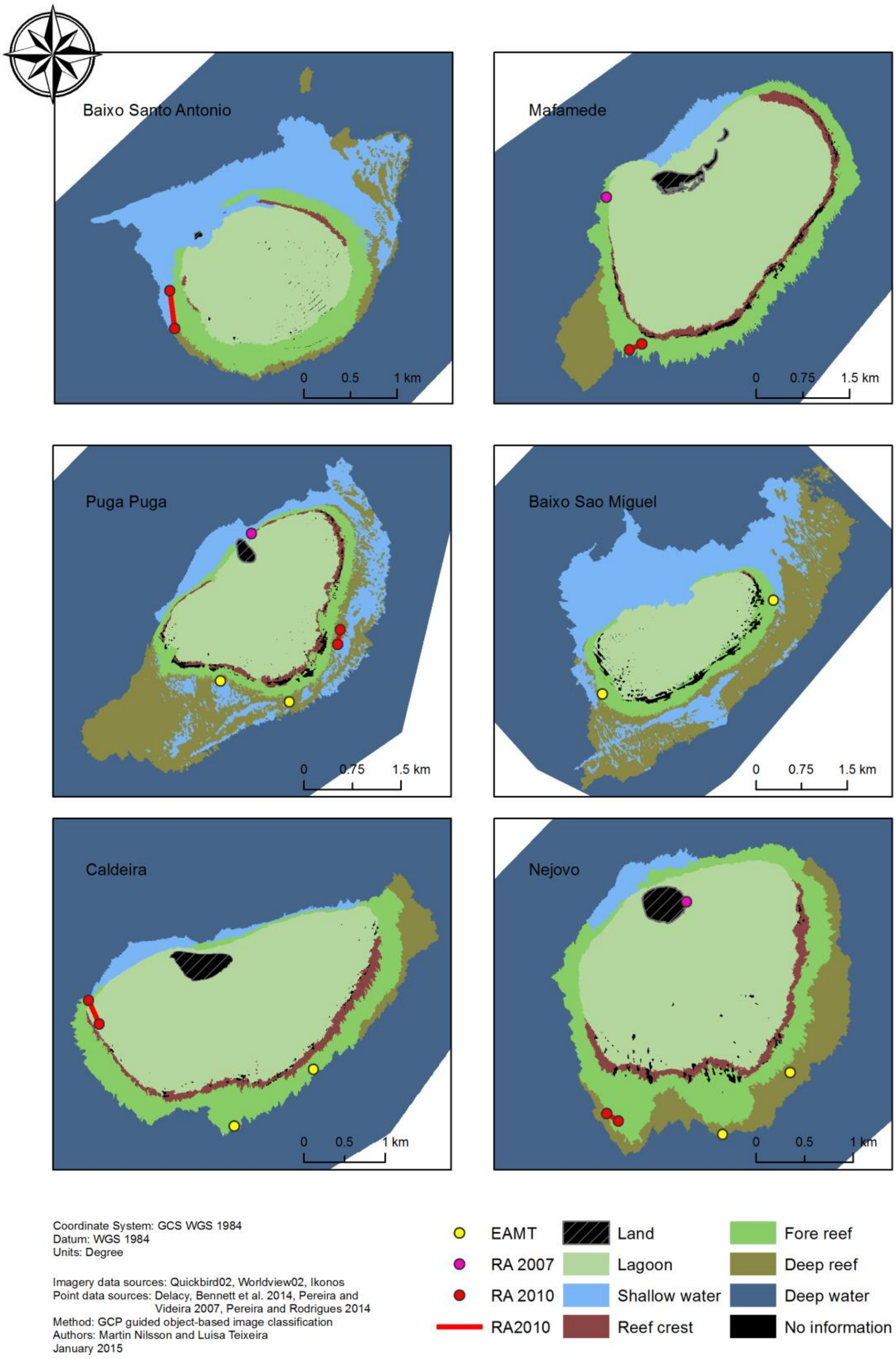
In the Rapid Assessment (RA) reports SCUBA diving based surveys were conducted. Photo-transect surveys were used for coral cover assessment, in which high-resolution underwater digital photography was used to record constant area photo-quadrats (approximately 0,3 m^2) at 10 to 15 meters intervals along a reef transect (Schleyer and Celliers 2005, Pereira and Videira 2007, Pereira 2008, 2014). Georeferrencing was conducted at the beginning and at the end of each 30 to 60 pictures transect. The photographs were analyzed with the CPC software, applying the Point Count technique, where eight randomly located points were superimposed on each image and the benthic category underneath each point identified to the lowest possible taxonomic level. On each location, two to four transects of 20 by 2 meters were performed at different depths, of which there was no information of detailed geolocation nor depth available. Fish surveys were based on the Point Count (PC) technique as per Bohnsack and Bannerot (1986). The observer counts fish visible 5 meter above the substrata and within a 7 meter or less, if visibility is reduced. Each PC lasts about 3 minutes, and were placed 15 to 20 meters from the previous. The size of commercially significant fish was estimated according to 10 cm incremental categories and their biomass estimated through weight-dimension relationships as in Froese and Pauly (2007). Only fish species considered relevant were counted[2], and their relevance was determined based on their commercial interest, known correlation with coral reef health, and representativeness of largest trophic categories (Pereira and Videira 2007, Pereira and Rodrigues 2014). A the moment, there are no results available concerning fish data from the latest survey.

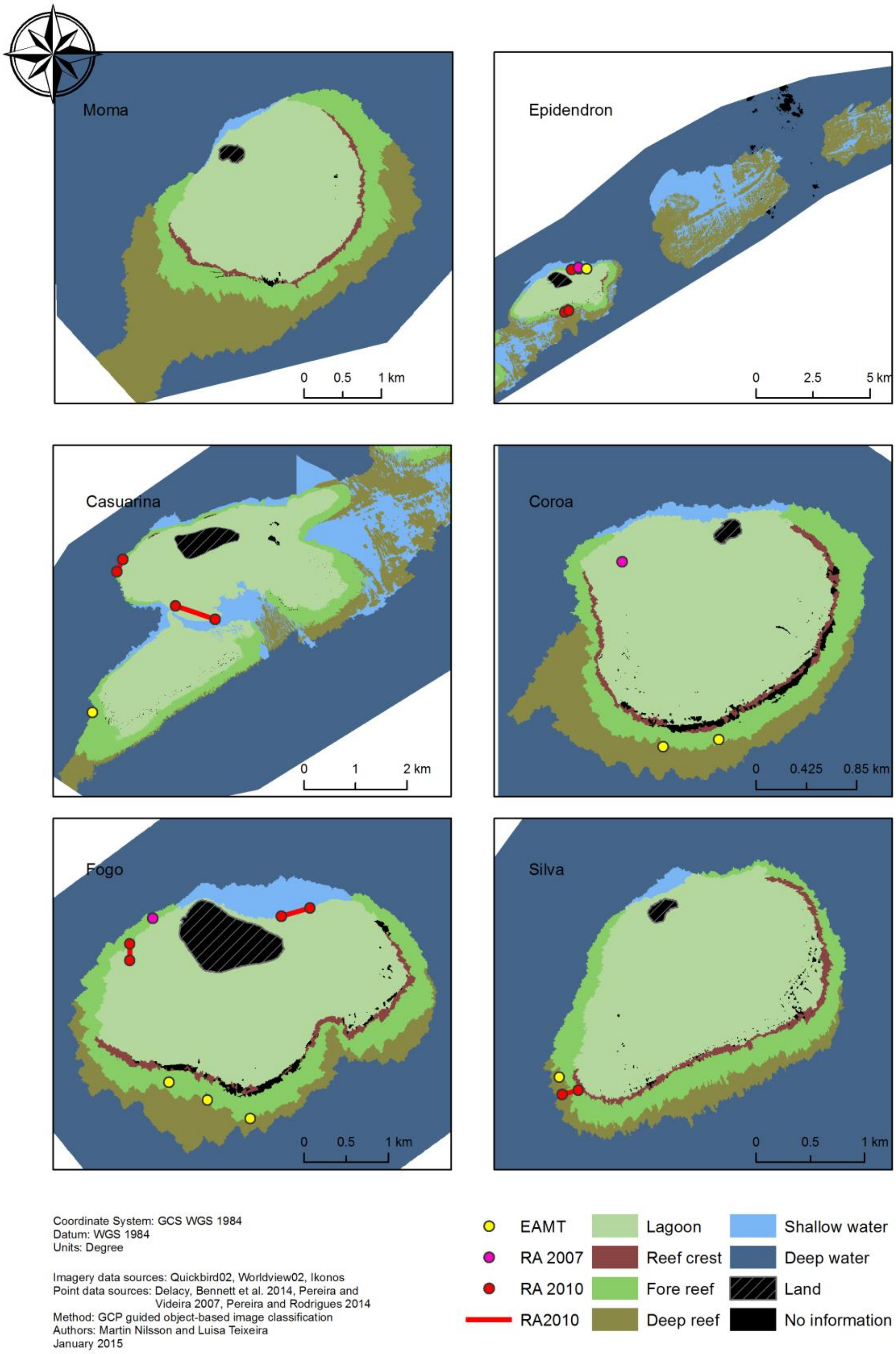
In the Eastern Africa Marine Transect (EAMT) only fish data was collected. The database was derived from field surveys with a diver-operated stereo video census technique according to Harvey and Shortis (1996) and Harvey et al. (2001, 2002, 2004) (Delacy, Bennett et al. 2014). In each dive 12 transects were conducted, in line, and mostly kept at the same depth contour. Each transect was 25 meters long and 10 meters wide. Between two consecutive transects there was a 10 meter buffer zone. Each transect has an associated pair of geographical coordinate, however there is no indication of a second point or direction, nor to which point – beginning, middle, or end – of the transect the existence location refers to. Video image was processed with EventMeasure software.

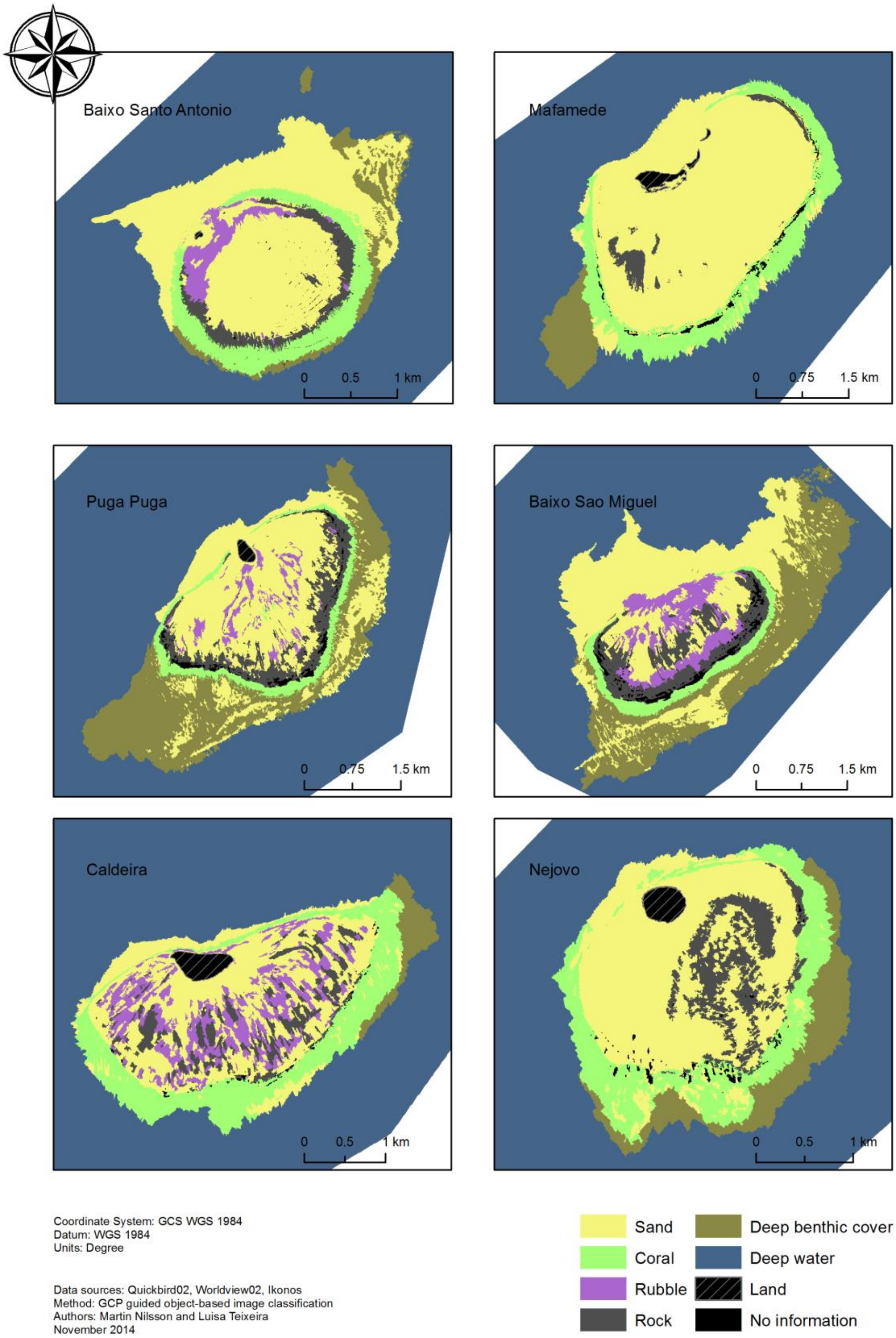
[2] Identified at the Family level: Acanthuridae, Chaetodontidae, Haemulidae, Lethrinidae, Lutjanidae, Mullidae, Pomacanthidae, Scaridae, Serranidae, Siganidae

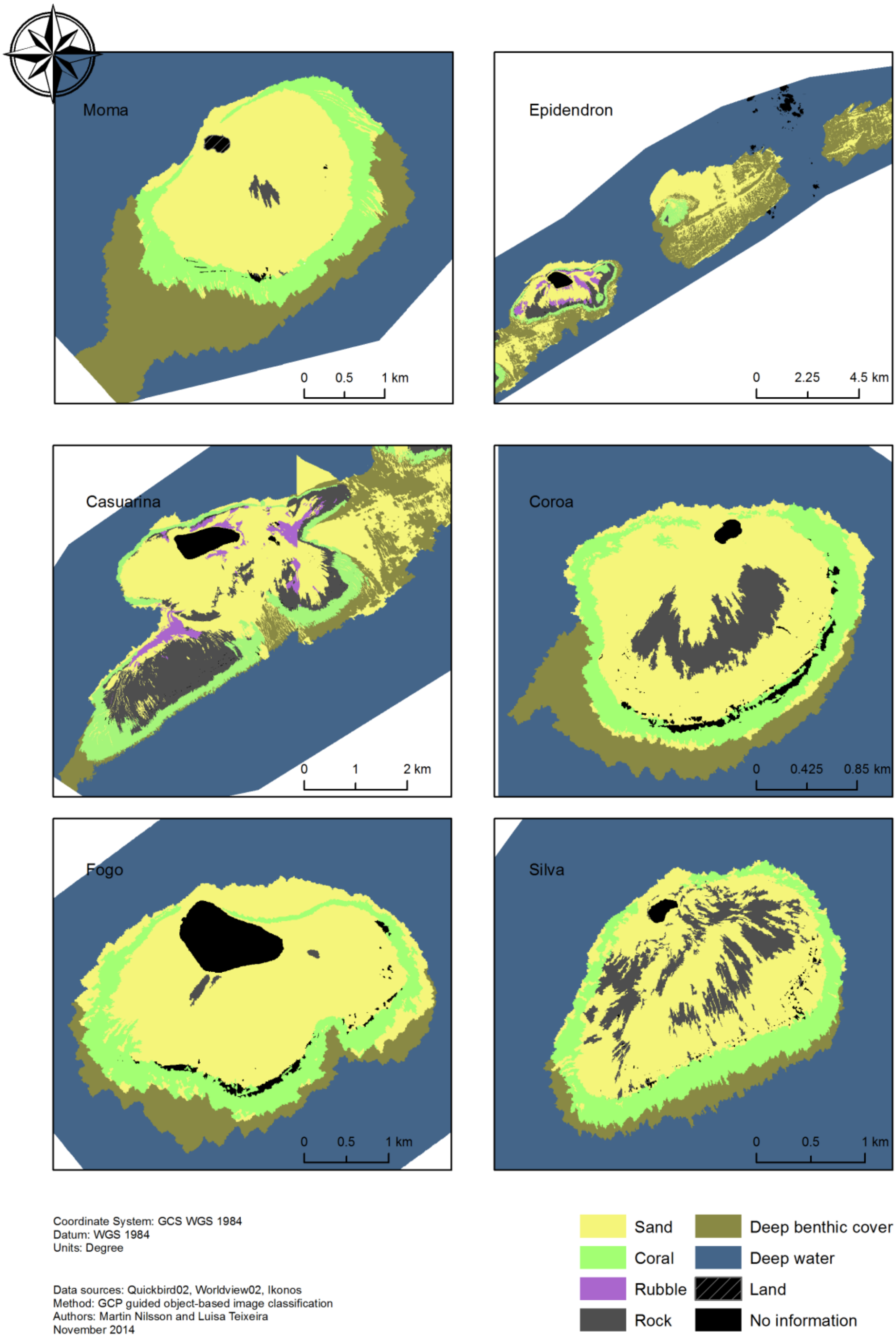
Appendix V.

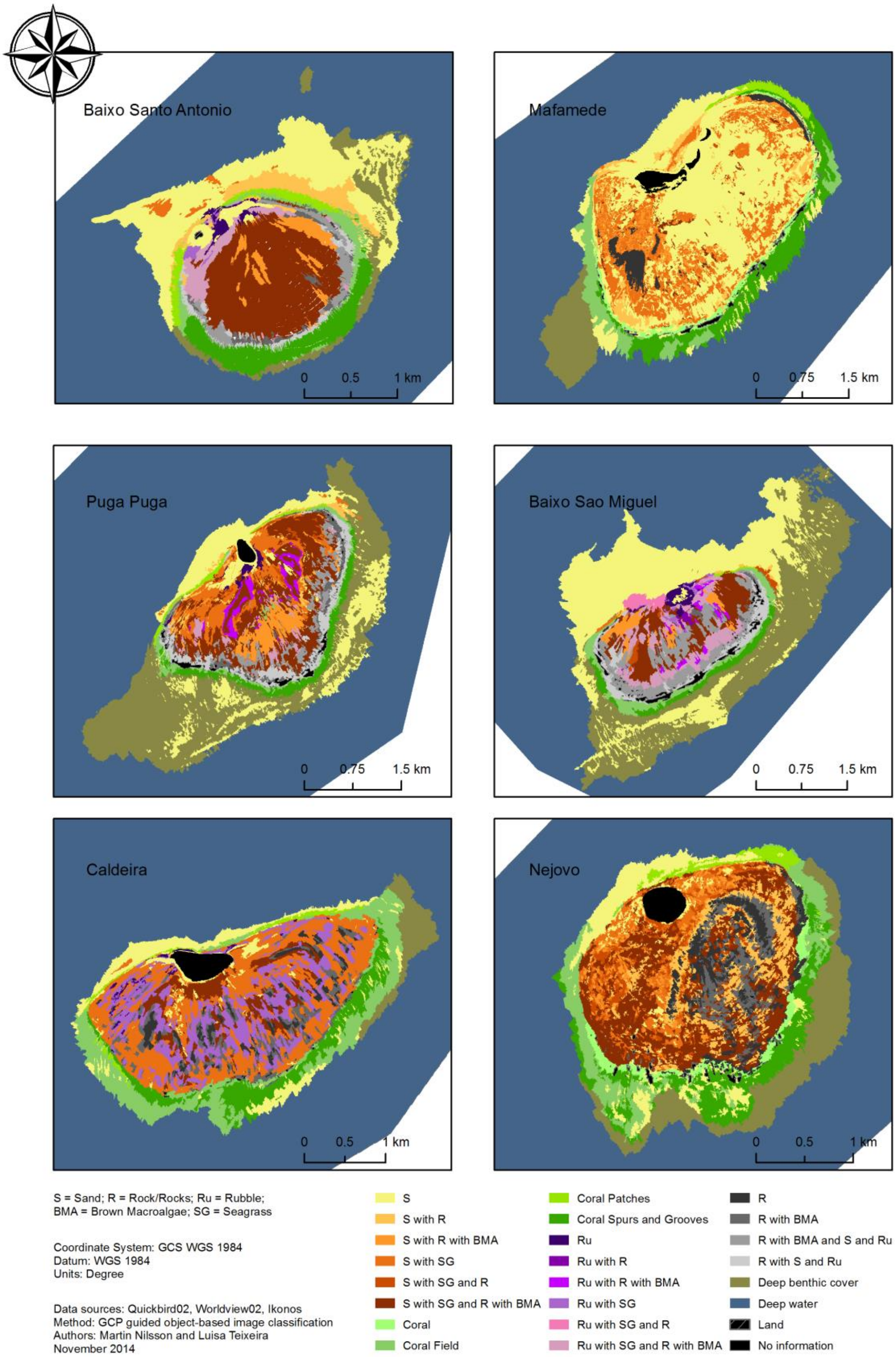
Mapping results of the PSEPA at geomorphological (L1). bottom cover (L2) and benthic habitat (L3) classification levels

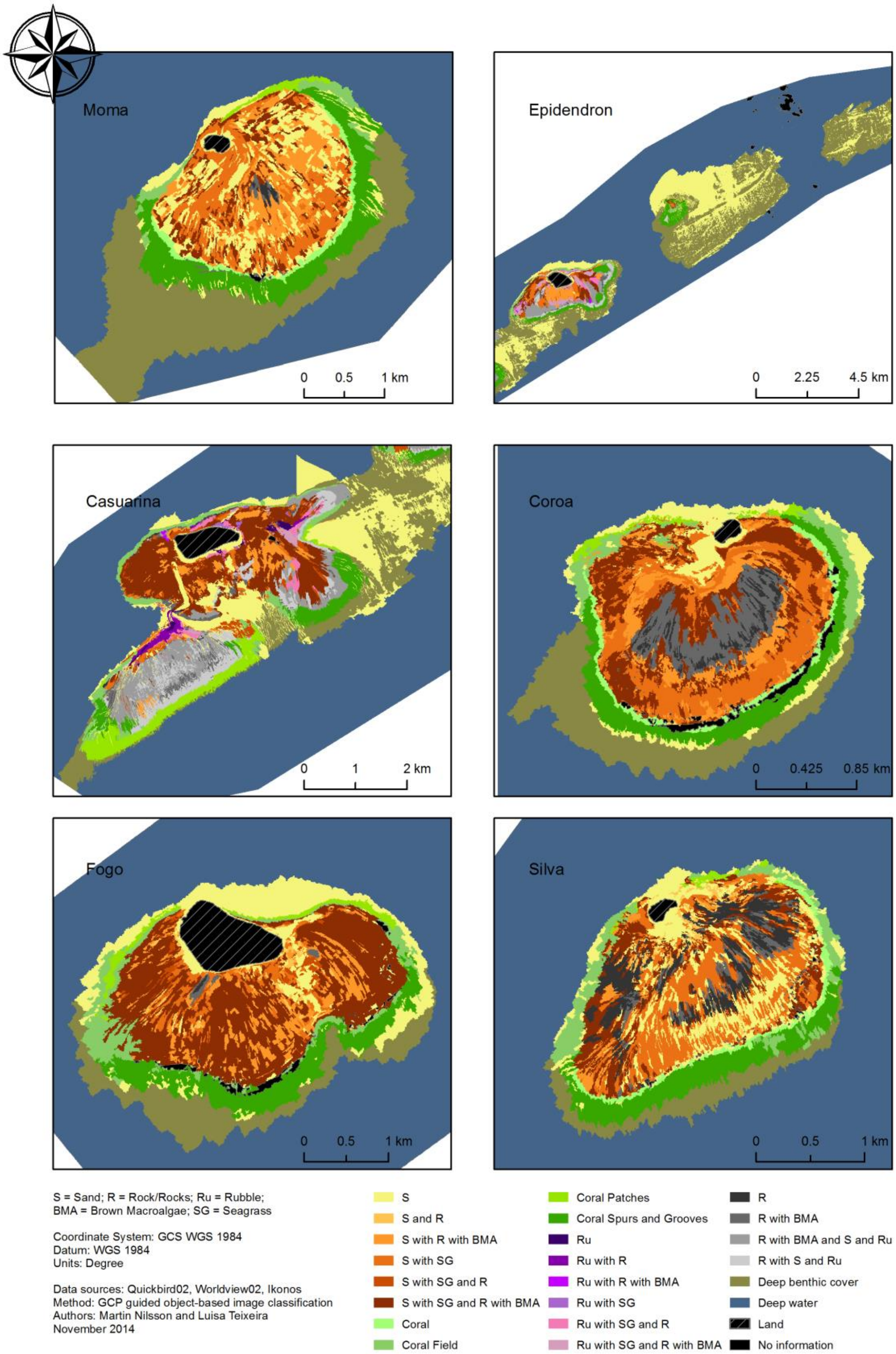



Moma
0 0.5 1 km
Epidendron
0 2.5 5 km
Casuarina
0 1 2 km
Coroa
0 0.425 0.85 km
Fogo
0 0.5 1 km
Silva
0 0.5 1 km
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
Imagery data sources: Quickbird02, Worldview02, Ikonos
Point data sources: Delacy, Bennett et al. 2014, Pereira and Videira 2007, Pereira and Rodrigues 2014
Method: GCP guided object-based image classification
Authors: Martin Nilsson and Luisa Teixeira
January 2015
EAMT
RA 2007
RA 2010
RA2010
Lagoon
Reef crest
Fore reef
Deep reef
Shallow water
Deep water
Land
No information


Baixo Santo Antonio
0 0.5 1 km
Mafamede
0 0.75 1.5 km
Puga Puga
0 0.75 1.5 km
Baixo Sao Miguel
0 0.75 1.5 km
Caldeira
0 0.5 1 km
Nejovo
0 0.5 1 km
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
Data sources: Quickbird02, Worldview02, Ikonos
Method: GCP guided object-based image classification
Authors: Martin Nilsson and Luisa Teixeira
November 2014
Sand
Coral
Rubble
Rock
Deep benthic cover
Deep water
Land
No information


Moma
0 0.5 1 km
Epidendron
0 2.25 4.5 km
Casuarina
0 1 2 km
Coroa
0 0.425 0.85 km
Fogo
0 0.5 1 km
Silva
0 0.5 1 km
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
Data sources: Quickbird02, Worldview02, Ikonos
Method: GCP guided object-based image classification
Authors: Martin Nilsson and Luisa Teixeira
November 2014
Sand
Coral
Rubble
Rock
Deep benthic cover
Deep water
Land
No information


Baixo Santo Antonio
0 0.5 1 km
Mafamede
0 0.75 1.5 km
Puga Puga
0 0.75 1.5 km
Baixo Sao Miguel
0 0.75 1.5 km
Caldeira
0 0.5 1 km
Nejovo
0 0.5 1 km
S = Sand; R = Rock/Rocks; Ru = Rubble;
BMA = Brown Macroalgae; SG = Seagrass
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
Data sources: Quickbird02, Worldview02, Ikonos
Method: GCP guided object-based image classification
Authors: Martin Nilsson and Luisa Teixeira
November 2014
S
S with R
S with R with BMA
S with SG
S with SG and R
S with SG and R with BMA
Coral
Coral Field
Coral Patches
Coral Spurs and Grooves
Ru
Ru with R
Ru with R with BMA
Ru with SG
Ru with SG and R
Ru with SG and R with BMA
R
R with BMA
R with BMA and S and Ru
R with S and Ru
Deep benthic cover
Deep water
Land
No information


Moma
0 0.5 1 km
Epidendron
0 2.25 4.5 km
Casuarina
0 1 2 km
Coroa
0 0.425 0.85 km
Fogo
0 0.5 1 km
Silva
0 0.5 1 km
S = Sand; R = Rock/Rocks; Ru = Rubble;
BMA = Brown Macroalgae; SG = Seagrass
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree
Data sources: Quickbird02, Worldview02, Ikonos
Method: GCP guided object-based image classification
Authors: Martin Nilsson and Luisa Teixeira
November 2014
S
S and R
S with R with BMA
S with SG
S with SG and R
S with SG and R with BMA
Coral
Coral Field
Coral Patches
Coral Spurs and Grooves
Ru
Ru with R
Ru with R with BMA
Ru with SG
Ru with SG and R
Ru with SG and R with BMA
R
R with BMA
R with BMA and S and Ru
R with S and Ru
Deep benthic cover
Deep water
Land
No information

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