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Reef Mapping Using Different Seabed Automatic Classification Tools

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Abstract: There is a great demand to develop new acoustic techniques to efficiently map the seabed and automate the interpretation of acoustic, sedimentological, and imaging data sets, eliminating subjectivity. Here, we evaluate the potential, limitations and complementariety of distinct supervised and automatic classification techniques in the mapping of reefs by comparing these results with a reference map. The study was carried out in the Abrolhos Continental Shelf (Eastern Brazilian Continental Margin) using a multibeam echosounder and side scan sonar (SSS) dataset. Two automatic supervised techniques were applied. A reference map was derived by detailed manual interpretation carried out by three experts. The two supervised classification techniques were: benthic terrain modeler (BTM), a morphometric classification with focus on spatial analyses of the bathymetric grid derivatives, and object-based image analysis (OBIA), a segmentation applied to the backscatter data from the SSS mosaic. Both automatic techniques obtained similar values of reef coverage area, but overestimated the reef area when compared with the reference map. The agreement between BTM and OBIA results and the reference map was 69% and 67%, respectively. Disagreement was mainly due to quantity of reef (both methods over-estimated reef), while the disagreement in spatial allocation was relatively low, it indicates that both methods are reasonable representation of the spatial patterns of reef. Efficient mapping of reef in the wider area of the Abrolhos Continental Shelf will be best achieved by a further development of automatic methods tested against reference maps obained from representative areas of the seabed. By combining the results of the two automatic methods, it was possible to create an ensemble map, which achieved better agreement with the reference dataset.

Keywords: reef mapping; seabed classification; supervised techniques; Abrolhos Shelf

1. Introduction

Terrestrial remote sensing has a comparatively long history since the 1970s and benefits from the availability of land surface imagery at various spatial and spectral resolutions, supplemented by ancillary data such as environmental data and digital terrain models. This enabled the development of sophisticated classification methods and algorithms that extract critical information for environmental management from remote sensing imagery [1,2]. Conversely, seabed automatic classification efforts are more recent [3–5] and mostly based on acoustic mapping technologies, since the application of electromagnetic methods has severe limitations due to the rapid attenuation of light in water.

The development of new technologies and classification tools is in great demand from the industry, government agencies and scientific institutions. The increasing interest and necessity for seabed habitat mapping in marine spatial planning initiatives has forced the industry of sonar makers, software developers and scientific research institutions to invest in new technology capable of producing seabed classification over regional areas [6]. Fisheries, oil and gas exploration, offshore engineering, as well as shallow and deep sea mining are examples of industries that are requiring seabed classification to support environmental risk assessments and spatial planning [6–8].

Side scan sonars (SSS) and multibeam echosounders (MBES) are among the most widely applied acoustic techniques for seabed mapping. Both systems have high sampling rates, which enables seabed mapping at a broad spatial scale, producing high resolution data sets in a relatively short period of time [9–12].

A series of classification models have been developed to reduce the subjectivity and automate the interpretation of geophysical, sedimentological and imaging data sets obtained from the seabed. Supervised and unsupervised classifications have improved the seabed classification [13,14] with the potential to also compile statistical analyses of those datasets.

The study presented here attempts to automatically classify and map submerged reefs. The identification and mapping of reefs through automatic classification from swath-mapping systems has great potential and applicability due to the global importance of these complex habitats, regarding planning and management of marine protected areas (MPA) and fisheries resources [15–17].

The analyses were carried out based on a dataset collected in the Abrolhos Continental Shelf (Eastern Brazilian Continental Margin), where diverse reef morphologies, including pinnacles, reef banks and rhodoliths, have been observed [18,19]. In order to automatically classify the distinct reef types, two supervised classification techniques were applied, taking into account that each of them has a different type of data input and distinct architecture. One technique is a morphometric classification tool (Benthic Terrain Modeler, BTM), with focus on the spatial analyses of the bathymetry derivative properties. The second technique is an object-based image analysis (OBIA, using eCognition software) applied only to the backscatter data from the SSS.

We have also compared the different methods using an assessment of map accuracy. To achieve this, the classification maps obtained from BTM and eCognition were compared against a reference dataset. In this context, the aim of this contribution is to analyze the potential benefits and limitations of the distinct techniques in the recognition and automatic classification of reefs through the complementary use of MBES or SSS or both data sets.

2. Materials and Methods

2.1. Acquisition, Processing and Analysis of Geophysical Data

The acoustic survey was carried out on the Abrolhos Continental Shelf (east Brazil), along the Abrolhos outer reef arc, known as California Reefs (Figure 1). The California Reefs are within the Abrolhos Marine National Park and the water depth ranges from 12 m (top of pinnacles) to 35 m deep (seabed).

MBES (Reson 7101-240 kHz) and SSS data (EdgeTech 4100-500 kHz) were acquired covering an area of approximately 20 km^2. Both systems acquired data simultaneously. Bathymetric data were processed using Caris HIPS and SIPS 9.1. The applied workflow included patch test correction, correction for tidal elevation and measured sound velocity and spikes removal. A 5 $\times$ 5 m resolution grid was exported as an XYZ file and a digital bathymetric model (DBM) was produced in a GIS platform (ArcMAP 10.6) and AUTOCAD 3D. The SSS data were processed with SonarWiz 7 software (Chesapeake Technology), applying bottom tracking and the EGN (empirical gain normalization) filter workflow. A 1 $\times$ 1 m resolution georeferenced sonographic mosaic was exported as a geotiff image.

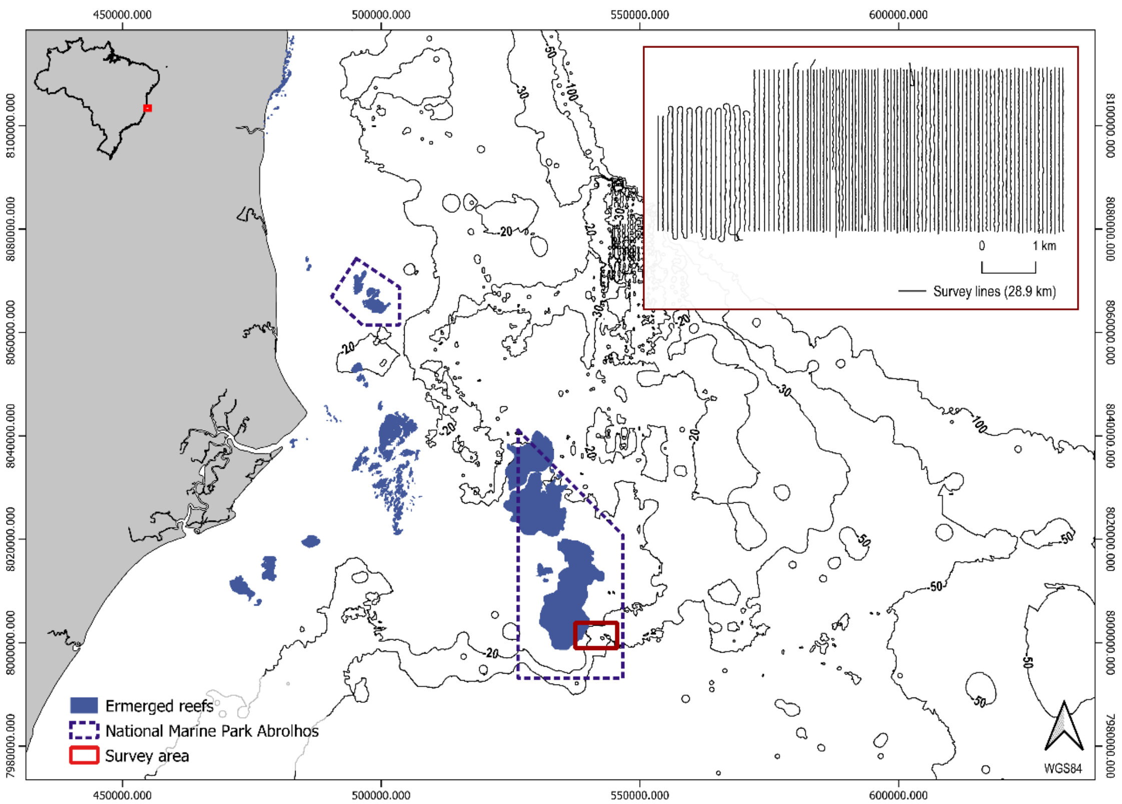

Figure 1. Survey area location, along the eastern Brazilian coast. The detailed frame in the top right corner shows the survey plan (28.9 km of acquisition tracklines).

2.2. Seabed Classification Techniques

Two automatic supervised techniques were applied to classify reef occurrence and distribution. The results were compared against a reference map to assess agreement with reference data and estimate map error. Moreover, an analysis of overlap among the results from the different classifications was carried out. The following flow diagram (Figure 2) summarizes the analysis steps. The analyses were executed by different experts under the supervision of the same third expert. Thus, the final analysis attempted to standardize all reef classes in a single class (reef structures).

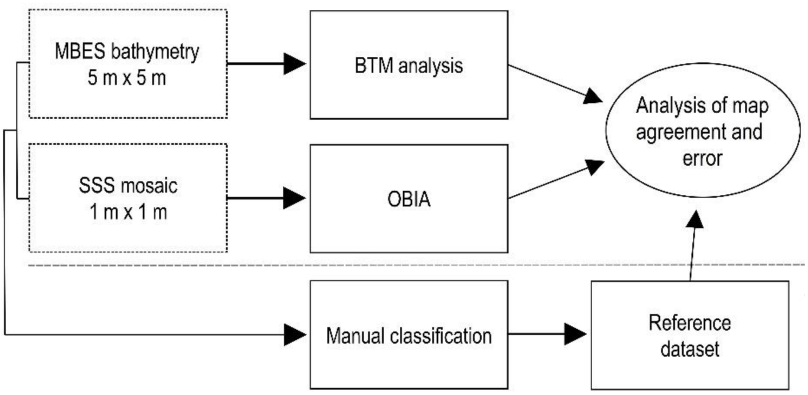

Figure 2. Flow diagram of the analyses.

Despite the difference of classes names for each method, all of them were subcategorized in "Reef presence" or "Reef absence". In terms of nomenclature, all classes categorized as "Reef absence" are defined as inter-reef areas.

2.2.1. Reference Map

The reference map was derived by manual interpretation of both the SSS backscatter and bathymetric data. Manual digitalisation of reef tops was guided by high backscatter, typical geomorphological shape and roughness produced by these conspicuous seabed features. To limit uncertainty in the reference map, the features were interpreted and reviewed by three experts to map the spatial occurrence of submerged reefs in the survey area. Extensive background knowledge [18,19] and the conspicuous nature of the reefs allowed us to confidently map reefs in the Abrolhos Continental Shelf even in the absence of ground-truth data.

2.2.2. Morphometry-Based Classification

The BTM is an ArcGIS® toolbox capable of analyzing digital terrain models derived from the different bathymetric derivative parameters, such as the Bathymetric Positioning Index (BPI) and the terrain slope [20]. The BPI is a bathymetric derivative that evaluates the elevation differences between a focal point and the mean elevation of its surrounding cells under broad and fine scales [21]. BPI and slope were calculated from the 5×5 m resolution grid. The inner and outer radius used for BPI fine was 5–50, and for BPI broad was 300–700. A final BTM map is generated using a rule-based classification of the morphometry based on a dictionary, where BPI, slope and depths are categorized into classes according to values designated by the user (Table 1). The dictionary was derived by an exhaustive testing of different parameter combinations and a visual assessment of the results. The categories within the dictionary work within a lower and upper bound. For BPI, the number 100 means the number of grid units that was used. Negative values mean below the standard deviation while positive values mean above it. For slope, we set the angle threshold as between 2 and 13°. Finally, in terms of depth, low relief reef banks were within 26 and 32 m water depth. All the 9 designated classes on the final result were elected due to the geomorphological heterogeneity of the seabed.

Table 1. Dictionary classes.

Classes	Zone	BroadBPI Lower	BroadBPI Upper	FineBPI Lower	FineBPI Upper	Slope Lower	Slope Upper	Depth Lower	Depth Upper
1	Deepest Inter-reef shelf		−100		−100				
2	East deep Inter-reef shelf		−100	−100	100				
3	West deep Inter-reef shelf	−100	100		−100				
4	Inter reef structures				−100				
5	Pinnacles/Irregular relief reef Banks (IRRB)	100		100					
6	Pinnacles/IRRB (artifacts)	100		−100	100				
7	Edges of LRRB	−100	100	100		2	13		
8	Low relief reef banks (LRRB)		100	−100	100			−32	−26
9	Inter-reef shelf		100	−100	100				

2.2.3. Object-Based Image Analysis Classification

The eCognition 9.1 software was used to provide tools for image segmentation and classification. The segmentation methodology from eCognition is based on image characteristics such as color, texture and shape of the feature. This technique can be considered as Object-Based Image Analysis (OBIA) and has been widely used in terrestrial remote sensing applications but also successfully applied in marine habitat mapping research [17,22]. The 1×1 m resolution SSS mosaic was used for the image segmentation. The supervised analysis of the sonographic mosaic involved three main steps: (i) segmentation according to defined parameters (multiresolution segmentation algorithm);

(ii) determination of the number of classes based on the samples trained by user. The definition of the classes is a procedure performed by the analyst. In this case, they were determined according to the segmentation result. The sample training process is also a supervised process, in which the analyst chooses one or more segments to represent each defined class; (iii) automated classification. The eCognition scale parameter applied was 150 and a number of classes was determined as 5, according to a visual analysis of the mosaic.

2.2.4. Map Agreement and Error

The derived maps were simplified into reef presence/absence maps prior to further analysis. We carried out a direct map-to-map comparison in R [23] utilising the packages raster [24] and diffeR [25]. To that end, a contingency table between a comparison map and a reference map is created (Table 2). Disagreement between the comparison map and the reference map can be expressed with two simple metrics, quantity disagreement and allocation disagreement [26]. Quantity disagreement is defined as the amount of difference between the reference map and a comparison map that is due to the less than maximum match in the proportions of the categories (here: reef and non-reef). Allocation disagreement is defined as the amount of difference between a reference map and a comparison map that is due to the less than maximum match in the spatial allocation of the categories, given the proportions of the categories in the reference and comparison maps. The map agreement can be calculated by substracting the sum of quantity disagreement and allocation disagreement (both as fractions) from 1.

Table 2. Contingency table for reef presence-absence predictions.

	Reef Absence	**Reef Presence**
Predicted absence	True negative (TN)	False negative (FN)
Predicted presence	False positive (FP)	True positive (TP)

We also estimated the class-specific error of omission and error of commision based on the contingency table. Omission error refers to observations in the reference map that were classified in a category other than their true or known category. Commission error refers to observations that were incorrectly classified and do not belong in the category in which they were assigned according to the classification. Based on a 2 × 2 contingency table, errors of omission (omission absence—O_A, and omission presence—O_P) and commision (comission absence—C_A, and comission presence—C_P) can be calculated in the following way:

$$O_A = \frac{FP}{TN + FP}$$

$$O_P = \frac{FN}{FN + TP}$$

$$C_A = \frac{FN}{TN + FN}$$

$$C_P = \frac{FP}{FP + TP}$$

3. Results

3.1. Seabed Morphology and Geomorphometric Analysis with BTM

The DBM of the study site is shown in Figure 3. Table 3 presents the reef classes defined in each technique used. The seabed map presents a great variability of reef morphologies, showing pinnacles (Figure 3c,d) and banks (Figure 3e,f). Banks are described here as Low Relief Reef Banks (LRRB), occurring in areas deeper than 30 m and generally flat seabed. The California Reef area presents a morphological variation from west to east, as shown in Figure 3b. The reef tops range in depth from 9 to 34 m.

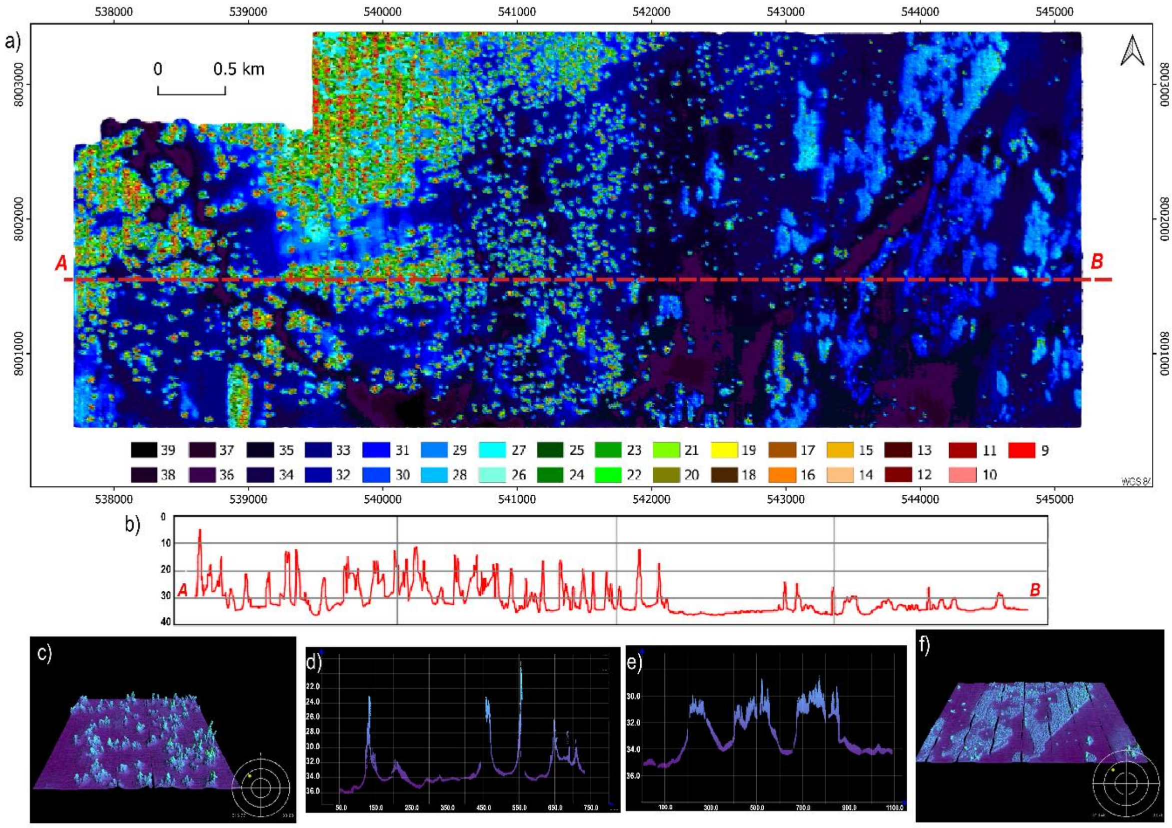

Figure 3. (**a**) DBM of the study area; (**b**) bathymetric profile A-B; (**c**) 3D view of the isolated pinnacles; (**d**) 2D view of the isolated pinnacles; (**e**) 2D view of the LRRB; (**f**) 3D view of the LRRB.

Table 3. Classes adopted for each classification method.

Classification Method	Classes	
	Reef Presence	Reef Absence
Morphometry	• "Inter-Reef Structures" • "Pinnacles/Irregular relief reef Banks (IRRB)" • "Pinnacles/IRRB (artifacts)" • "Low Relief Reef Banks-LRRB" • "Edges of LRRB"	• Deepest Inter-reef shelf • East deep Inter-reef shelf • West deep Inter-reef shelf • Inter-reef shelf
OBIA	• Pinnacles • LRBB (Low relief reef banks) • IRRB (Irregular Relief reef banks)	• Inter-reef shelf
Manual interpretation	• Pinnacle • Reef bank • Mixed (pinnacle and bank)	-

Results of the morphometric (BTM) analysis are shown in Figure 4. Nine classes were defined based on the dictionary: "Deepest inter-reef shelf", "East deep inter-reef shelf", "West deep inter-reef shelf" and "Inter-reef Shelf" are associated with the deepest and the lowest roughness regions, which can also be interpreted by the slope and BPI parameters, respectively; "Inter-Reef Structures", "Pinnacles/Irregular Relief Reef Banks (Irregular Relief Reef Banks-IRRB)", "Pinnacles/IRRB (artifacts)", “Low Relief Reef Banks-LRRB” and “Edges of LRRB” are associated with reefs, having higher slope values and are also depicted in the BPI maps.

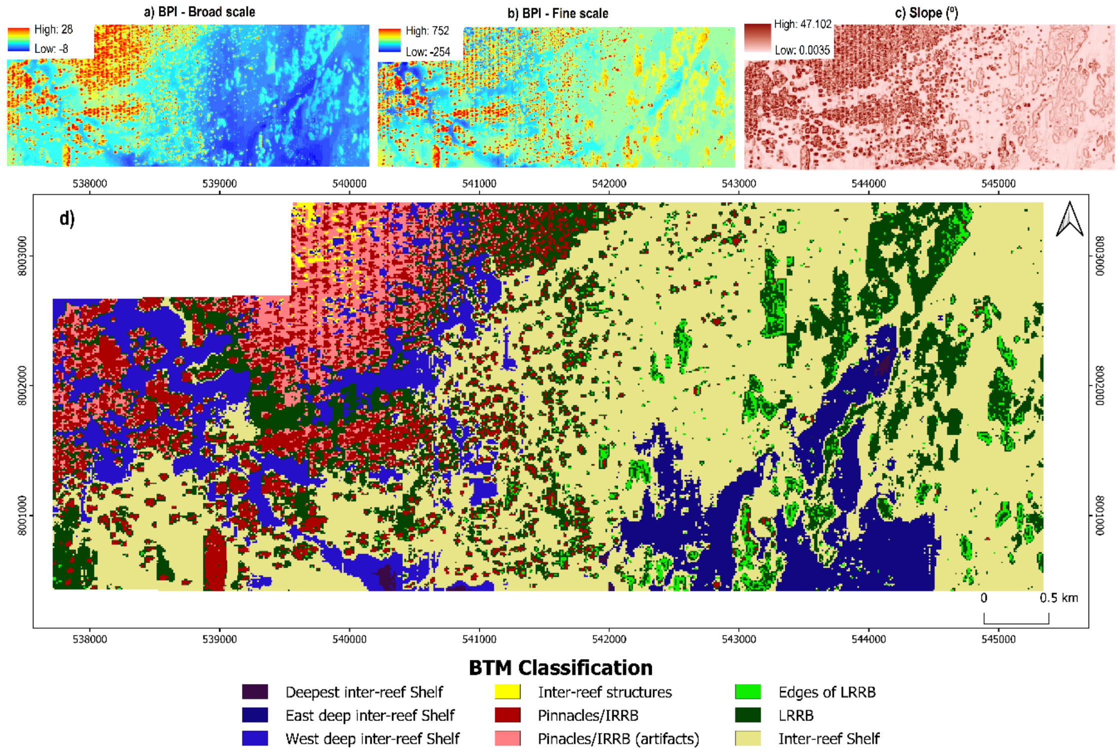

Figure 4. Products generated with the BTM toolbox: (**a**) BPI broad scale; (**b**) BPI fine scale; (**c**) Slope; (**d**) BTM classification.

In general, the classes described as Inter-reef Shelf and Deep inter-reef shelf (west and east) predominate over the area. Both classes are characterized by relatively low BPI and bathymetric slope (Figure 4a–c). The BPI classifies them as depressed regions. The Deep Inter-Reef Shelf was separated in East and West, and although these classes are morphologically similar, they are placed in regions with distinct shelf morphologies (higher BPI/more rugged relief in the West than the East).

Reefs are well defined from the morphometric analysis. BPI fine and broad scale can easily depict reef distribution considering their elevation in relation to the adjacent seafloor. The LRRB class was also defined by the applied depth boundary (between 26 and 32 m). The LRRB edge was recognized as a class due to positive values of BPI and the limitation of the bathymetric slope values. The Edges of the LRRB class has a steeper slope value than the adjacent shelf and the tops are flatter than the pinnacles. In class LRRB, it is possible to note a limitation in the BTM application in the west-northwest sector of the study area, where there is a greater concentration of Pinnacles/IRRB and Pinnacles/IRRB (artifacts). LRRB were recognized due to both the relatively high values of BPI from the adjacent seabed and the bathymetric range. This may represent a transition from inter-reef shelf to reef dominated shelf.

The “Pinnacles/IRRB” class (dark red in Figure 4) corresponds to the structures with the highest absolute values of BPI (broad and fine scale) and is also highlighted by high bathymetric slope values. Therefore, this class represents either isolated reef structures or merged pinnacles. The other classes (pink and yellow) are in the northwest sector, a region where there is a high concentration of pinnacles and irregular relief reef banks. It is inferred that these regions were distinguished due to the interpolation of the bathymetric data in a fairly irregular region. This can’t be considered as a limitation of the classification technique, but rather a data input gap (from acquisition survey) to the construction of the model.

In total, approximately 6.85 km^2, equalling 34.5% of the total area, were mapped as reef.

3.2. Seabed Backscatter and OBIA

The sonographic mosaic (Figure 5) presents three major backscatter features that were interpreted as: inter-reef shelf (more homogeneous)—framed in yellow in Figure 5a, pinnacles (isolated or merged)—framed in blue in Figure 5a, and low relief reef banks—framed in red in Figure 5a (Table 3).

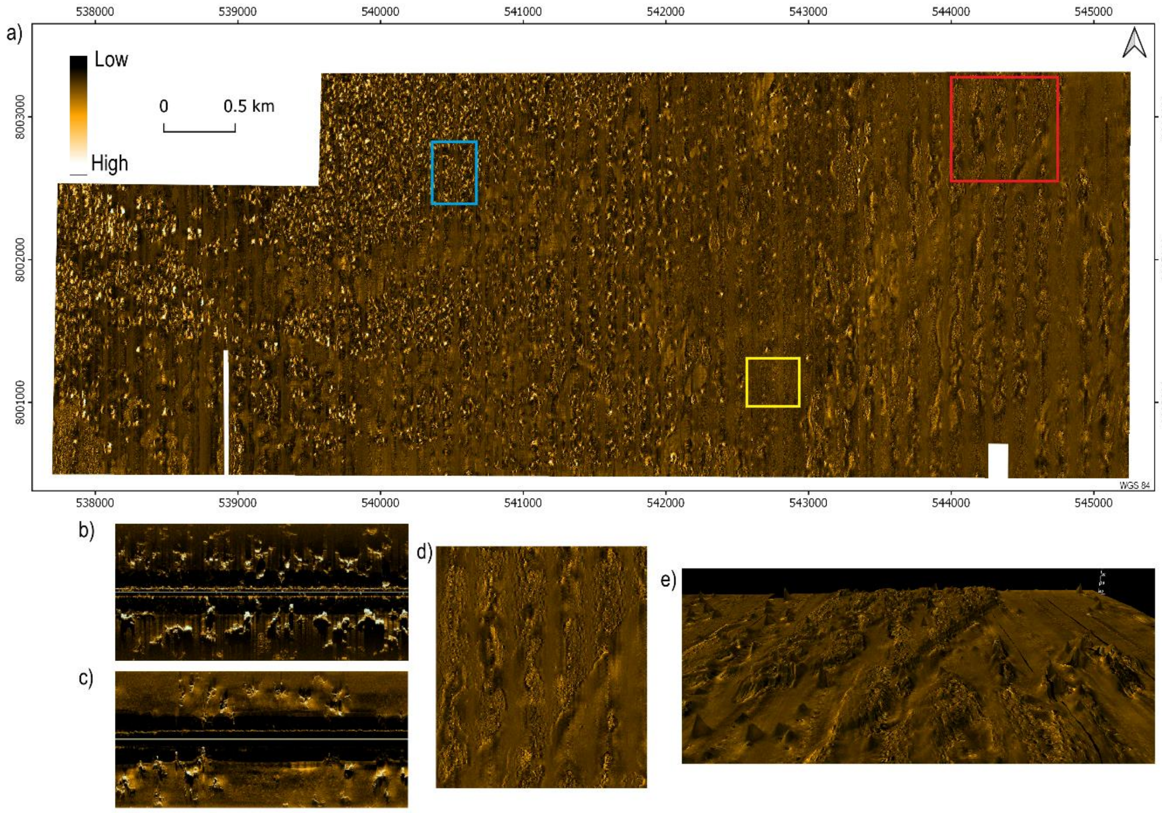

Figure 5. (**a**) SSS mosaic over the survey area; (**b**,**c**) detailed backscatter showing reef pinnacles; and (**d**,**e**) backscatter pattern of low relief banks as viewed from above or in 3D.

The inter-reef shelf presents a more homogeneous backscatter pattern, with low roughness, representing a flat area. Although the backscatter seems to be more homogeneous and lower values than the reef areas, slight variations in signal intensity can be observed. Reefs are well characterized by a high backscatter and roughness, creating clear acoustic shadows that point to distinct morphologies (Figure 5b–e).

Aiming to adjust the classification to the spatial scale of this study, the spatial parameters of the segmentation needed to be adequate in a way that would make it possible to detail and recognize isolated reef structures such as pinnacles. In other words, it was necessary to set up a segment small enough for identification of pinnacular structures. Seeking to make the comparison easier, we choose to maintain the greatest similarity among the classes names used in each classification technique. After the segmentation, the sonographic mosaic was divided in the following classes: Inter-reef Shelf, Pinnacles, LRRB and IRRB (Figure 6).

In total, approximately 7.61 km^2, equalling 38.3% of the total area, was mapped as reef.

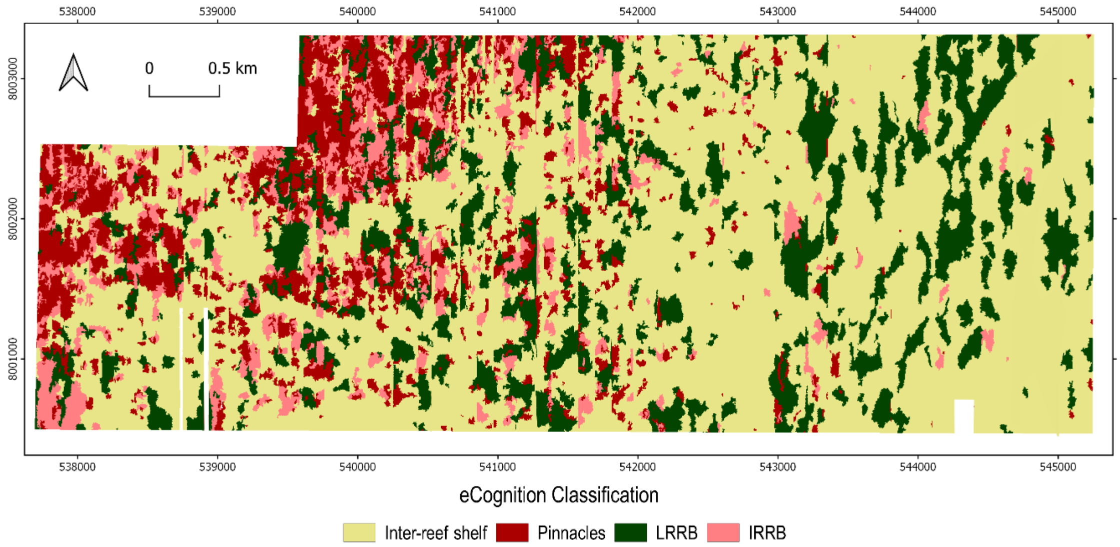

Figure 6. Supervised SSS data segmentation.

3.3. Reference Map

The results of the manual interpretation using the backscatter data from the SSS mosaic (1m resolution) and the digital bathymetric model are shown in Figure 7. The analysis was focused on reef recognition. The result shows three main classes distinguished: pinnacles, reef bank and mixed reef structures (pinnacle and bank). Pinnacles appear isolated in central region, as well as in great concentration as seen in northwest area. Reef Banks (similar to LRRB) are mainly distributed on the east region of the study site.

The merged reef area is 2.96 km^2, which represents approximately 15% of the total area.

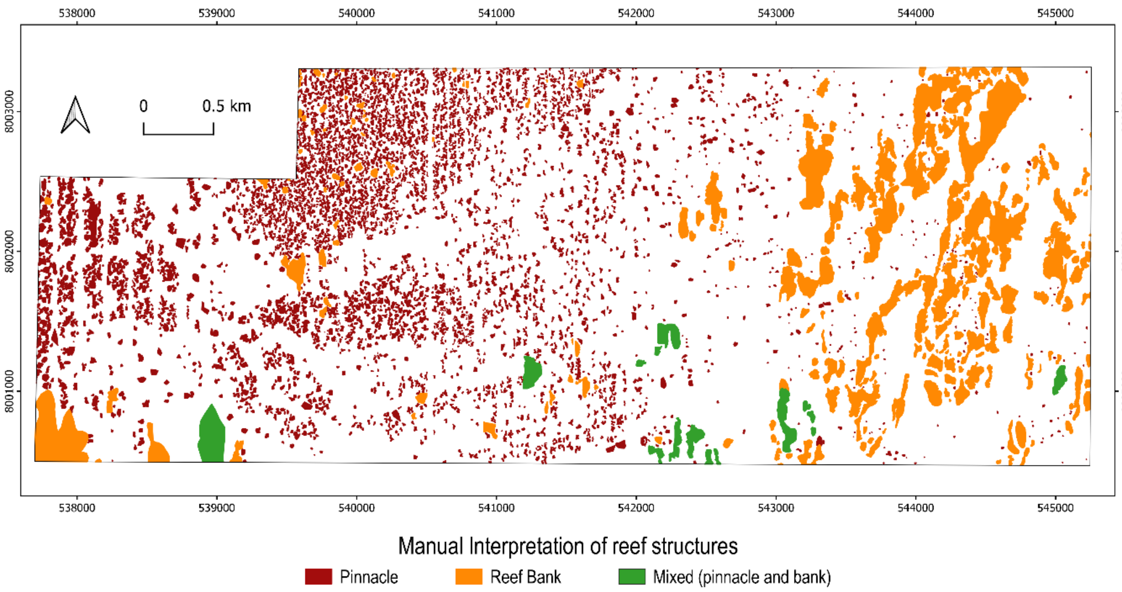

Figure 7. Map showing baseline map of reef distribution derived by manual interpretation.

3.4. Map Agreement and Error

Full details of the analysis can be found in the Supplementary information (S1 and S2). A summary of the analysis of agreement is provided in Table 4. Both methods show similar trends: Agreement with the reference map is 69.1% for BTM and 67.1% for OBIA. The quantity component of disagreement is more pronounced than the allocation component. The disparity is more pronounced in the case of the OBIA result. This is mostly because both methods over-estimate the reef area (BTM: 6.85 km^2 and OBIA: 7.61 km^2) by a factor of >2. Low allocation disagreement does, however, indicate that the spatial configurations approximate the reference map.

Table 4. Results of the agreement analysis.

Method	Agreement	Quantity Disagreement	Allocation Disagreement
BTM	0.691	0.196	0.113
OBIA	0.671	0.235	0.094

The class-specific error analysis for the BTM map (Table 5) reveals that approximately 30% of reef absences and 38% of reef presences are omitted from the map. The error of commission is low for reef absences (9%), but high for reef presences (73%). Again, this can be linked to the over-estimation of reef. The above described patterns are similar for the analysis of the OBIA map (Table 6), although the error of omission for reef presence is slightly lower (32%).

Table 5. Class-specific errors of omission and commission for the BTM method.

Class	Error of Omission	Error of Commission
Reef absence	0.297	0.086
Reef presence	0.379	0.732

Table 6. Class-specific errors of omission and commission for the OBIA method.

Class	Error of Omission	Error of Commission
Reef absence	0.331	0.076
Reef presence	0.316	0.735

4. Discussion

We have presented the results of two automated methods (BTM and OBIA) for mapping reefs in a test site situated in the Abrolhos outer reef arc. The accuracy of these methods in detecting reef against a background of non-reef was estimated by comparing them with a reference map that was obtained by detailed manual interpretation of SSS backscatter and MBES bathymetry data. In the following, we will discuss the obtained results qualitatively and quantitatively.

The estimation of map accuracy requires a reference dataset that can be acquired in different ways, but needs to fulfill at least one of the following two conditions: (1) The reference source data has to be of higher quality than the data used for map classification, or (2) if using the same source data for both map and reference classification, the process to create the reference data needs to be more accurate than the process used to generate the map classification to be evaluated [27]. Here, we use the same datasets, but both SSS and MBES data were used to create the reference map, while the two methods utilised either one or the other. Also, we are satisfied that the process of creating the reference map is more accurate due to the following reasons: (1) There exists substantial expertise from previous studies [18,19] on which the interpretation is based, (2) the reference map is the consensus of the interpretation of three skilled experts, and (3) reefs are conspicuous features that are easily recognizable in the acoustic data. We acknowledge that the reference map is not "the truth", but under the given circumstances we are satisfied that it is close to reality and can be used as a reference against which the other methods are assessed.

The quantitative analysis of agreement with the baseline map showed that both methods, despite being very different in terms of input data and methodology, gave comparable results regarding map agreement and error. The map agreement of 67% (OBIA) and 69% (BTM) is acceptable, although lower than what has been reported in some recent studies that mapped reef [28–30]. These differences might be related to various factors, e.g., shallow warm-water coral reefs can be mapped with satellite or drone-based optical sensors, which give more spectral information than a one-band SSS backscatter dataset. However, this also indicates that there is room for future improvements and the potential to transfer mapping approaches from the optical remote sensing community [4]. The use of the accuracy statistics proposed by [26] gives some interesting insights: for both methods, disagreement is predominantly associated with quantity, i.e., the proportions of predicted reef and non-reef differ from the reference. This is also reflected in the high errors of commission for reef presence and is due to the over-estimation of reef area by both approaches, mainly attributable to reef pinnacles (see Figure 8a,b). Conversely, allocation disagreement is relatively low (around 10%) for both methods, indicating that the overall patterns and trends are mapped correctly.

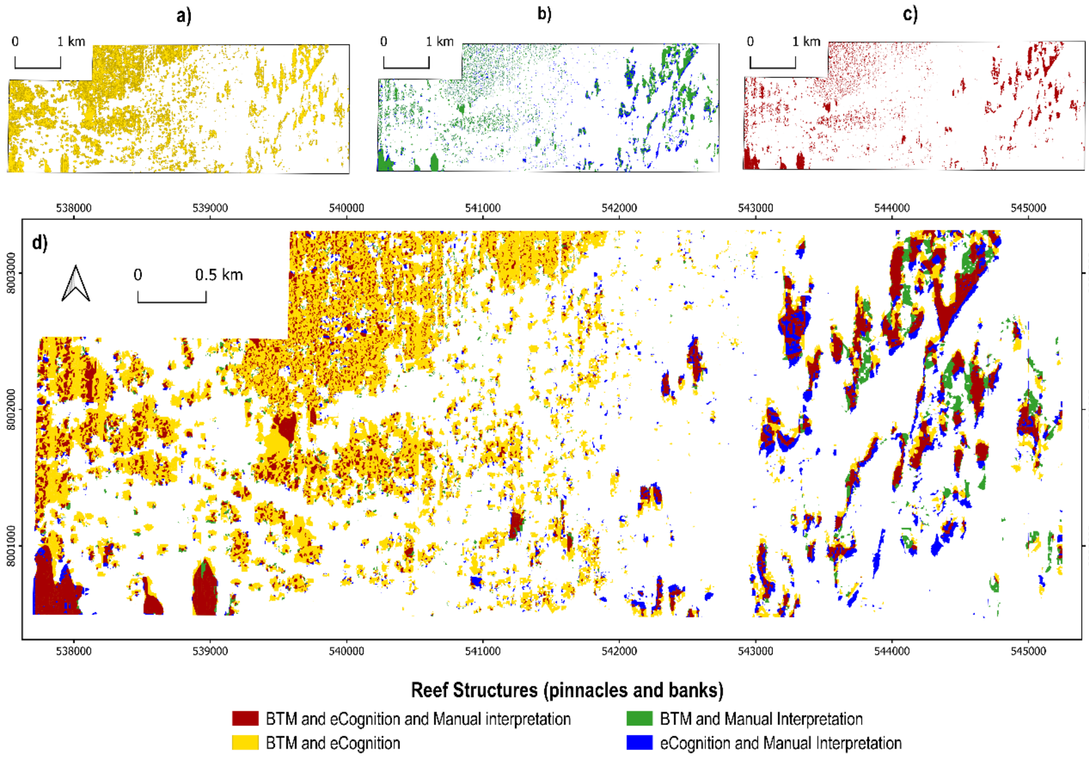

Figure 8. (**a**) Intersection of reef structures mapped by BTM and OBIA; (**b**) Overlapping of reef structures mapped by "BTM and reference map" as well by OBIA and the reference map; (**c**) Intersection among the three techniques; (**d**) Spatial distribution of all mapped reefs indicated by the two automatic classification techniques and the reference map, as well as the intersection and spatial coverage indicated by both.

Automated OBIA classification based on SSS backscatter intensity did not show seabed differences among inter-reef areas. Conversely, this was possible with the morphometric BTM classification. In these regions, the image characteristics (such as texture) did not respond to the differentiation presented by the BTM. Knowing that distinct morphometric characteristics are not necessarily reflected through SSS backscatter intensity, this technique's complementarity was essential to achieve a better result, even with this limitation in the image classification.

Regarding reef structure classification (Figure 8d), the results by both automatic techniques were quantitatively similar considering the area covered by reef and disregarding reef sub-type (for example pinnacle or low relief bank). The BTM classification resulted in a coverage area of reef structures (classes: "Inter Reef Structures", "Pinnacles/IRRB", "Pinnacles/IRRB-artifacts", "Edges of LRRB", "LRRB") of 6.85 km^2, while the OBIA classification gave an area value of 7.61 km^2 (classes: "Pinnacles", "LRRB" and "IRRB").

Reef classes, such as pinnacles, IRRB and LRRB, were not completly differentiated by both techniques. The BTM approach did not differentiate the isolated Pinnacles from IRRB (the value for the sum of the classes “Inter Reef Structures”, “Pinnacles/IRRB-Artifacts” and “Pinnacles/IRRB“ was 3.04 km^2), while the OBIA method gave values of 1.57 km^2 and 1.75 km^2 for Pinnacles” and IRRB, respectively. The OBIA classification provides a better differentiation of these reef features due to their textural characteristics and form being more easily distinguished.

The LRRBs were spatially overestimated by both automatic techniques. The key factor for the overestimation with BTM was the BPI, since some regions presented this index in a similar way to the morphometric characteristics of those banks. When considering the image segmentation in the OBIA process, the selected scale parameter probably contributed to the overestimation of LRBB. In other words, since one of the objectives was to recognize isolated pinnacles, a large number of segments were generated in the image and this made some of these segments more susceptible to small changes in image characteristics (shape, color, and texture), and therefore the classification became particularly vulnerable to these slight differences.

While under the given circumstances, i.e., mapping of reefs, which exhibit specific morphometric and textural characteristics against a relatively flat and featureless background (non-reef areas) manual mapping can be an appropriate approach, it must be recognized that this is nevertheless a slow and painstaking process, especially when carried out by three analysts as it was done here. It is therefore unlikely that such a mapping approach is a viable option for larger seafloor areas. In this study, we mapped approximately 3 km^2 of reef, while the reef area in the wider Abrolhos Shelf was estimated to 8844 km^2 [18]. By contrast, automatic techniques can deal more efficiently with larger datasets. It might still be necessary to adapt classification dictionaries and rule-set parameters, but the general workflows could still be applied to other (larger) datasets. A viable process might be to develop reference maps for selected test areas, which are characteristic for the wider area. Then, automatic methods can be trialled and improved, with quantitative assessments of agreement and error as tools to decide on the most promising method.

Alternatively, the results of different automatic approaches could be combined to yield an ensemble map [31]. Such an approach is most efficient with complementary methods, which was the case in this study. By combining the results of the two methods, it was possible to create a new map, which does only include areas classified as reef by both methods. The new map was derived by multiplying BTM with OBIA. For this purpose, we consider reef presence as a value of 1, and absence as a value of 0. This final analysis (full details in Supplementary information S3) shows the over-estimation of reef extent is reduced (Agreement = 75.3%), and the argument of the complementarity of the methods is strengthened.

Future directions for comparing automatic mapping with a manual reference map should consider the combined use of bathymetric and backscatter dataset. Here, we used two different approaches considering the data availability and computer processing limitations, but OBIA could also be tested using both datasets and a higher resolution grid, e.g., 1-m grid cell. Further investigations in this reseacrh should consider the biological description in order to test if the reef morphology could be used as a proxy for reef benthic community changes along water depth. Also, the use of a higher resolution multibeam sonar could provide a better detail mapping of the Abrolhos reefs. The pinnacles in Abrolhos present a specific morphology that changes with depth [32]. Shallower reefs (<10 m deep) have wide tops, forming a mushroon-like morphology. Deepward, reef tops decrease in width and can form a single column at depths around 25–30 m. This was observed using scuba diving, but the resolution of the multibeam sonar used in this study was not able to map these detailed changes in pinnacle morphology.

5. Conclusions

The combined use of the bathymetric and sonographic mapping was fundamental for the characterization and comprehension of seabed geomorphology of the study area. The results provided important information about reef morphologies and have great potential to be integrated with studies aiming to examine the associated biodiversity, mainly in terms of mesophotic reefs.

The presented analysis employing a reference map and two automatic techniques for seabed classification (morphometry and object-based image segmentation) have shown limitations and potential for each one. Morphological variations in inter-reef areas were better captured by the morphometric analysis. Conversely, the object-based image classification achieved a greater differentiation between the types of reef morphologies. The assessment of agreement and error also highlighted that both automatic approaches over-estimated the reef area, while at the same time giving a reasonable representation of the spatial patterns of reef distribution. Both automatic techniques obtained similar values of agreement with the reference map and reef coverage area. The results confirm the usefulness of the two methods for reef mapping purposes in potential future studies. The purpose in using these three distinct techniques was not only to compare their effectiveness, but rather to achieve a better recognition of the reefs and inter-reef areas through their potential complementarity. The final analysis achieved a better agreement with the reference dataset through combining the results of the two methods.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3263/10/2/72/s1, S1: Map Comparison BTM, S2: Map Comparison OBIA, S3: Map Comparison.

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