DATA FUSION FOR MAPPING CORAL REEF GEOMORPHIC ZONES: POSSIBILITIES AND LIMITATIONS

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ABSTRACT:

Mapping the geomorphology of coral reefs provides key information to scientists and managers about the distribution, extent and structure of reef landforms. Geomorphological zones within a reef system are underpinned by geological and environmental gradients in physical and biological processes, usually resulting in well-defined and clearly recognisable landforms. Mapping of such zones has been traditionally undertaken by visual interpretation of remotely sensed imagery, with mapping performance constrained by the operator's contextual interpretation and/or imagery characteristics. However, mapping criteria are subjective and often not transferable to other sites. This study explores a semi-automatic, GEO-Object-Based Image Analysis **(**GEOBIA) approach to mapping intra-reef geomorphological zones based on fusing high-resolution satellite imagery and seamless elevation data. The method is applied to Quickbird and Worldview2 imagery of two coral reefs in Australia: Bet Reef, an intertidal lagoonal reef platform in the central Torres Strait; and Lizard Island, a fringing reef in northern Great Barrier Reef (GBR). Combining optical and bathymetric information considerably improved classification results from ~ 80% to ~ 90% overall accuracy. Rule sets developed based on this data fusion approach have the potential to be transferable between different reef types across geographic settings.

1. INTRODUCTION

Coral reefs are some of the most vulnerable and threatened of global ecosystems, particularly in view of unprecedented anthropogenic-driven disturbances (Veron et al., 2009). The study of coral reef dynamics at geomorphological scales is very suitable for management as it bridges the temporal and spatial gap between long-term geological and short-term ecological processes (Hopley et al., 2007).

Mapping the geomorphology of coral reefs has provided key information to scientists and managers about the distribution and extent of reef landforms (Andréfouët, 2008). However, working on these ecosystems presents a series of challenges as coral reefs tend to be largely inaccessible, both in that they are isolated and because they are underwater or in intertidal settings where fieldwork is weather and tide dependent. In addition, field surveying rapidly becomes cost-prohibitive as the area of study increases or higher-frequency surveys are needed.

Mapping coral reef geomorphology has been traditionally undertaken by manual interpretation of aerial photography and other remotely sensed data. This has been time-consuming, site-specific (i.e. non-repeatable) and accuracy has been limited to the operator's skills. Recent studies employing Geographic Object-based Image Analysis (GEOBIA) to map coral reefs have successfully showed an improved performance across different spatial scales (Benfield et al., 2007; Leon and Woodroffe, 2011; Phinn et al., 2012). However, the transferability of semi-automatic rule sets between sites and different sensors remains questionable, despite this being one of the main advantages of GEOBIA (Blaschke, 2010).

The application of GEOBIA based on transferable rule sets to marine and coastal areas, particularly coral reefs, lags considerably behind terrestrial applications where semi-automated geomorphological mapping approaches are gradually replacing classical techniques due to improved geospatial techniques and increasing availability of high-quality digital elevation data (Anders et al., 2011; Drăguţ and Eisank, 2012; Seijmonsbergen et al., 2011). Data fusion approaches in which data from multiple sources are integrated into the rule set have greatly improved the performance of these terrestrial classification methods (Arroyo et al., 2010; Liu et al., 2008) and might become more common amongst coral reef applications with the advent and increasing availability of marine and coastal geospatial data such as high-resolution imagery (Eakin et al., 2010), sonar (Bejarano et al., 2010), AUV-mapping (Jaramillo and Pawlak, 2011) and bathymetric Laser (Klemas, 2011; Zawada and Brock, 2009) or bathymetry derived from remote sensed imagery (Gao, 2009).

The study of coral reef geomorphology based on data fusion (e.g. Robinson et al., 2000) or combining field and remote sensed datasets is not new. For example, Andréfouët et al. (2009) combined different sources of data in New Caledonia, including synoptic remotely sensed imagery, detailed bathymetry and geological information to gain insights into the morphology of modern reefs in the context of contrasting patterns of reef growth, subsidence, and uplift rates. Unfortunately, key datasets such as nearshore bathymetry over complex reefs are only available for very limited areas, although recent research has showcased the potential of remote sensed-derived bathymetry based on high spatial resolution satellite imagery (Hedley et al., 2009; Kanno et al., 2011).

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In this paper, we hypothesize that fusing high-resolution satellite imagery and seamless elevation data within a GEOBIA framework improves the accuracy of mapping coral reef geomorphology. Our aim is to develop a robust rule set based on imagery and elevation data capable of achieving similar accuracy results when applied to different coral reef settings.

2. METHODS

2.1 Study sites and datasets

The GEOBIA data fusion methodology was applied to two coral reefs in Australia (Figure 1) encompassing two dissimilar geomorphological reef types based:

1. Bet Reef, an intertidal lagoonal reef platform in central Torres Strait.
2. South Reef - Lizard Island, a fringing reef in northern GBR.

Remote sensed imagery and bathymetry for both reefs are shown in Figure 2.

Bet Reef
A Quickbird image was acquired for Bet Reef on the 24th May 2008 when water level was approximately 0.93 m above MSL. Clouds, shadows and wave chop were masked out and a standard radiometric correction was undertaken.

A seamless DEM for Bet Reef was derived from bathymetric laser data surveyed between August and December 2008. Elevation and depth data (hereafter referred as elevation data) were thinned to an average spacing of 12.5 m. Data was interpolated and downscaled to 2.4 m resolution using regression-kriging (Hengl et al., 2008).

The Bet image was georeferenced to the DEM and projected to AMG 54 zone and GDA94 datum. Reference data for training and validation of the classification were collected as described in Leon and Woodroffe (2011)

Lizard Island
A Worldview2 image was acquired for Lizard Island on the 10th October 2011 at approximately MSL. Clouds, shadows and wave chop were masked out and a standard radiometric correction was undertaken. The image was georeferenced using RTK-GPS ground control points collected during December 2011 and projected to AMG 55 zone and GDA94 datum.

A 2 m DEM was derived for Lizard Island based on singlebeam bathymetry collected during December 2011 and regression-kriging spatial prediction.

Georeferenced field photos were collected during December 2011 following similar procedures as described in Roelfsema and Phinn (2010) and used as reference data for training and validation purposes.

2.2 GEOBIA classification

Intra-reef geomorphological zones for a schematic coral reef system (Figure 3) were generalized from work undertaken by Blanchon (2011), Hopley et al. (2007) and Holthus and Maragos (1995). The semantic model presented by Leon and Woodroffe (2011) was adapted for this study to define the hierarchical classification scheme and the ontology for the geomorphology objects guided the classification processes.

Figure 1. Location map showing Bet Reef and Lizard Island

The appropriate scales for image segmentation were defined using the local variance method, as implemented in the Estimation of Scale Parameter (ESP) tool (Drăguţ and Eisank, 2011; Drăguţ et al., 2010). Segmentation was undertaken at two scales. A finer scale was used to precisely delineate the reef system from the adjacent water or sand bodies. A second nested, coarser scale was then used to classify the objects. Finally, objects from the same classes were merged together.

The main features used to classify coral reef geomorphology included image-derived features, geometric characteristics from the objects, contextual features (e.g. distance from reef edge) and land-surface parameters derived from the DEM (e.g. slope, curvature). The rule set for classifying reef geomorphology was designed based on Bet Reef and subsequently transferred to Lizard Island. Classifications with and without land-surface parameters were undertaken to assess the performance of the data fusion approach.

Both segmentation and classification were performed using eCognition Developer 8.7 software.

2.3 Accuracy assessment and robustness of rules

Quantitatively assessing the topological accuracy of classified landform objects is very challenging due a lack of ground truth data for geomorphologic features beyond elevation (Reuter et al., 2009). For this reason we opted to use conventional thematic accuracy assessment based on the error matrix (Congalton and Green, 2009) as an indication of classification performance. 150 random points were used to select and label segmented objects based on field data and expert-knowledge. Labelled objects were used for validation.

Rule set robustness was qualitatively assessed based on the amount of adjustment required to achieve similar classification results between images.

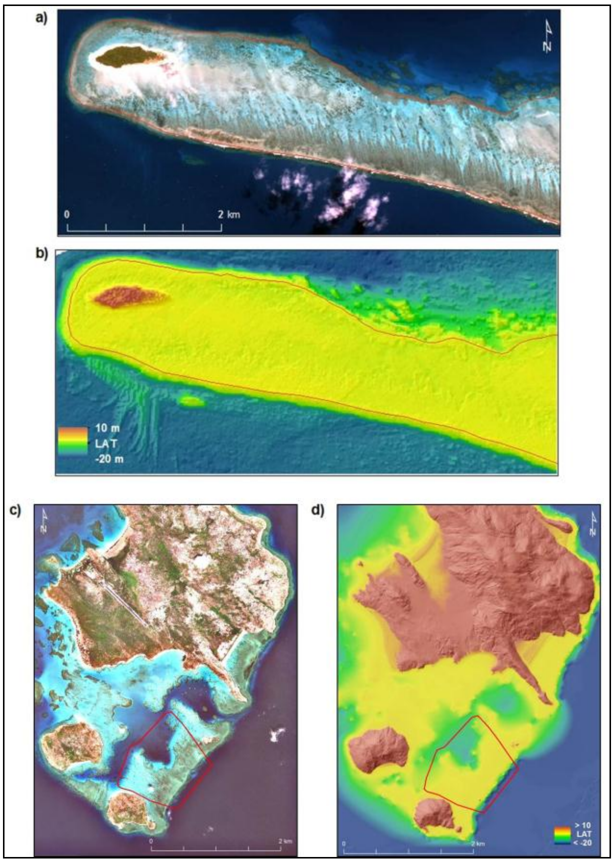


Figure 2. a) Bet Reef Quickbird true-colour (RGB 321) image and b) 2.4 m LADS-derived DEM. c) Lizard Island Worldview2 true-colour image (RGB 532) and d) 2 m Seamless DEM. South reef fringing reef study area delimited by red box.

3. RESULTS

The most 'optimal' scales for segmentation were identified using the ESP tool. The first major decrease in local variance or "sill" was identified at a scale parameter of 22 for Bet Reef and at 107 for Lizard Island. For the second coarser scale, a scale parameter of 113 was identified for Bet reef and 172 for Lizard Island.

Difference in scale parameter values between the images is due to the radiometric resolution of the Quickbird and Worldview2 sensors and the range in which the reflectance values were stretched. In the case of Bet Reef, values were stretched from 0 to 1,000 and from 0-10,000 for Lizard Island.

The resultant number of objects and their average areas are shown in Table 1. The average object size is very similar for the finer segmentation giving an indication of the transferability of the local-variance method at this scale. However, the mean value for the coarser segmentation scale differs considerably due to the large number of very small but distinct objects present in Lizard Island's South Reef.

The main features included in the rule set to classify coral reef geomorphology are shown in Table 2. An effort was made to select relative features such as the brightness index or the maximum difference between spectral bands which are more transferable than absolute features. However, both the green and red bands had to be included to better separate the classes.

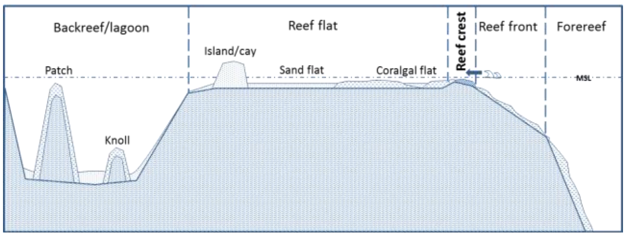


Figure 3. Geomorphological zones for a schematic coral reef platform or fringing reef

Table 2 also shows the range of values applied to Bet Reef and Lizard Island. The range of values employed for geometric (Asymmetry) and relative features (Max. diff., brightness) required very small tweaking, indicating the robustness of such features across reef types. In contrast, features based on spectral bands (Green band, Red band, NIR band) or land-surface parameters (elevation, slope) required more modification.

The mapped reef geomorphology for Bet Reef based on the data fusion approach is shown in Figure 4. Visually, the classification seems to adequately discriminate the classes. This is corroborated by the relatively high overall accuracy of 78%, as estimated from the error matrix for the classification based on the image only (Table 3). Further, a considerable improvement is evidenced when using the data fusion approach and incorporating land-surface parameters. This approach yields an overall accuracy of 87% (Table 4). The improvement is particularly notable for the reef crest and lagoon classes.

The geomorphic map based on the data fusion approach for the South Reef fringing reef at Lizard Island is shown in Figure 5. Only four classes are present on this reef type compared to the seven classes present at Bet Reef lagoonal reef type. Visually, the classification does not seem to adequately represent all of the classes, particularly the reef front class. Most of the classified reef front in the leeward backreef lagoon is not topologically correct. This is also evidenced in the relatively low producer accuracy value of 26% shown in the error matrix for the image only classification (Table 5).

The overall accuracy of 88% for the classification using only the image is relatively very high. Noteworthy is the improvement of the classification performance for Lizard Island when using the data fusion approach. This is evidenced by the increase in overall accuracy to 95% (Table 6). However, as previously mentioned, this thematic assessment has to be taken only as a proxy and not as an actual indicator of the topological or geometrical accuracy of classified objects.

Table 1. Statistics of image objects

	Number of objects / Mean size (ha)			
	Fine segmentation	Coarse segmentation	Classification (DEM)	Classification (No DEM)
Bet Reef	4,811 / 0.2	270 /3.6	55 / 17.6	45 / 21.6
Lizard Island	793 / 0.11	336 / 0.26	119 / 0.74	103 / 0.86

Table 2. Rule set to classify intra-reef geomorphology

CLASS	Feature	Bet Reef	Lizard Is.
Reef front	Brightness (RGB)	< 0.1	<3600
	Slope (degrees)	> 1.4	>3.7
Reef crest	Red band	> 0.09	>2930
	Elevation (MSL)	[-0.73 - -0.2]	[-1.5 - -0.5]
	Max. Diff (RGB)	[0.3 - 0.5]	[0.45 - 0.5]
	Asymmetry	>0.8	>0.86
Coralgal flat	Asymmetry	<0.97	<0.922
	Max. Diff (RGB)	[0.45-0.95]	[0.41-0.65]
	Red band	<0.1	<3500
	Elevation (MSL)	<-0.45	<-0.88
Sand flat	Max. Diff (RGB)	<0.45	NA
	Green band	>0.17	
	Red band	>0.12	
Vegetated cay	NIR	>0.3	NA
Lagoon	Max. Diff (RGB)	[0.4-0.75]	[0.6-0.82]
	Green band	[0.149-0.18]	[4500-6080]

The relatively small adjustments in the rule set developed for Bet Reef required to achieve a comparable high accuracy classification in Lizard Island can be taken as an indication of the robustness and transferability of the developed rule set.

4. DISCUSSION AND CONCLUSIONS

The use of remotely sensed optical imagery to map coral reefs at the geomorphic scale (10s to 100s meters) has been very effective because of the correlation between energy gradients and coral assemblages. Even though coral assemblages can be highly diverse and heterogeneous within reefs, the resultant structures and zonation are remarkably similar across different reef types from different geographical settings (Blanchon, 2011; Done, 1999).

Recently, the better performance and improvement in overall accuracy when mapping coral reefs within a GEOBIA framework as opposed to using per-pixel approaches have been demonstrated (Benfield et al., 2007; Phinn et al., 2012). This increase in accuracy is attributed to the better depiction of landforms as multi scale objects and their associated topology. Geometric and contextual attributes are more robust than highly variable pixel spectral properties making them more suitable and transferable for the analysis of very-high resolution or complex images, such as those of intertidal and underwater environments.

Regardless of reefs forming clear and ‘visible’ geomorphic structures and the advances on image analysis, the classification of coral reef geomorphology based solely on optical imagery remains limited. This is particularly evident for classes that are similarly spectrally such as the reef crest and other areas within the reef flat (Leon and Woodroffe, 2011). Combining the optical imagery with elevation data helps to discriminate amongst these classes and solve such issues, as evidenced from the mapping of Bet Reef and Lizard Islands.

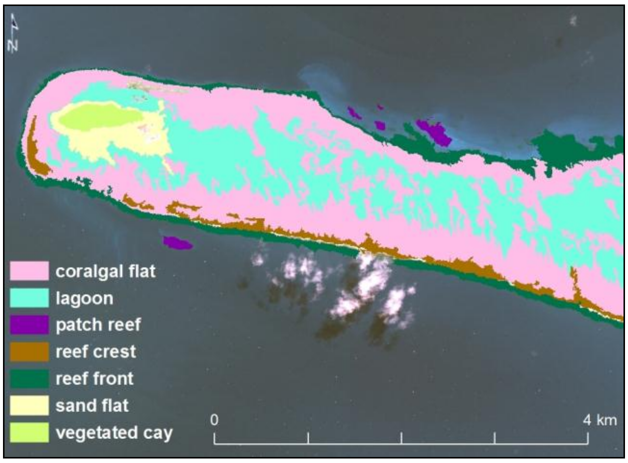


Figure 4. Data fusion GEOBIA classification of Bet reef

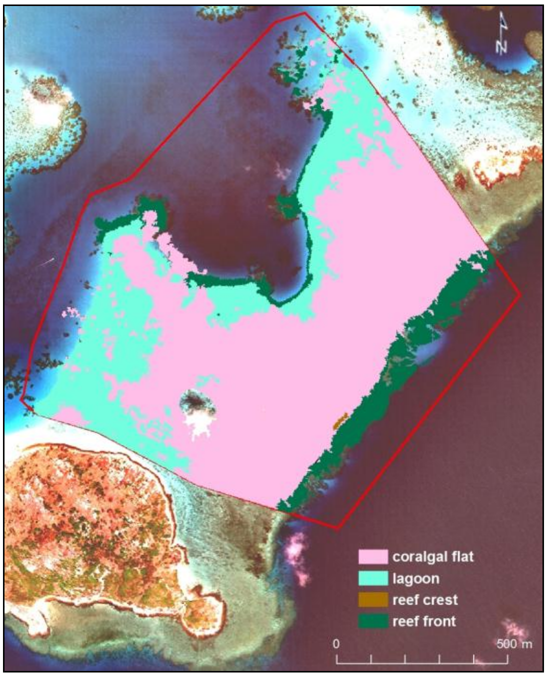
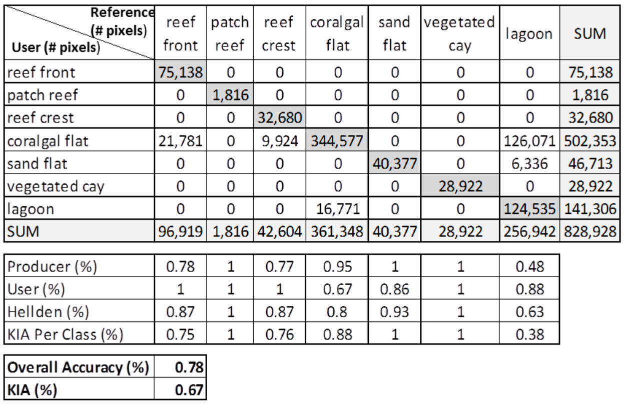


Figure 5. Data fusion GEOBIA classification of Lizard Island

The data fusion approach employed in this work represents an important contribution to the mapping of coral reef geomorphology. The benefit of implementing this method within a GEOBIA framework is that it allows to seamlessly integrate disparate datasets without problems such as mis-registration of high-resolution data. The combination of optical and terrain information improved classification results from an average 80% overall accuracy (consistent with values reported by Phinn et al. 2012) to 90%.

The real value of this increased accuracy is that it reflects an improvement in the actual robustness of the rule set. As demonstrated by this preliminary work, the combination of data-driven segmentation based on the local variance method and a classification derived from both optical and land-surface parameters proved to have more potential to be transferable between different sensors and across different reef types. However, two limiting factors have to be taken into account.

Table 3. Error matrix for Bet Reef (image only)

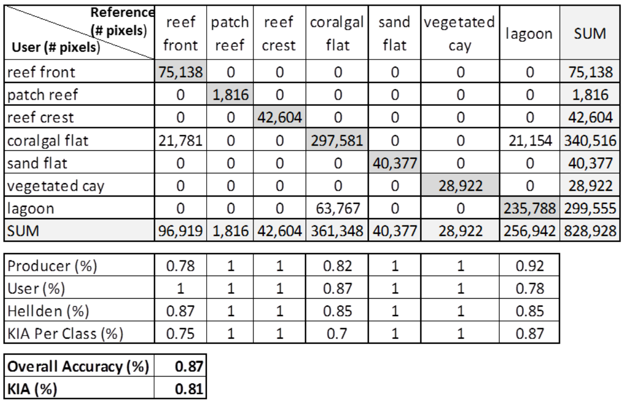


Reference (# pixels) User (# pixels)	reef front	patch reef	reef crest	coralgal flat	sand flat	vegetated cay	lagoon	SUM
reef front	75,138	0	0	0	0	0	0	75,138
patch reef	0	1,816	0	0	0	0	0	1,816
reef crest	0	0	32,680	0	0	0	0	32,680
coralgal flat	21,781	0	9,924	344,577	0	0	126,071	502,353
sand flat	0	0	0	0	40,377	0	6,336	46,713
vegetated cay	0	0	0	0	0	28,922	0	28,922
lagoon	0	0	0	16,771	0	0	124,535	141,306
SUM	96,919	1,816	42,604	361,348	40,377	28,922	256,942	828,928

Producer (%)	0.78	1	0.77	0.95	1	1	0.48
User (%)	1	1	1	0.67	0.86	1	0.88
Hellden (%)	0.87	1	0.87	0.8	0.93	1	0.63
KIA Per Class (%)	0.75	1	0.76	0.88	1	1	0.38

Overall Accuracy (%)	**0.78**
KIA (%)	**0.67**

Table 4. Error matrix for Bet Reef (data fusion)

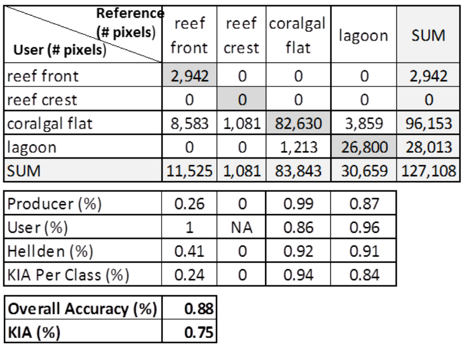


Reference (# pixels) User (# pixels)	reef front	patch reef	reef crest	coralgal flat	sand flat	vegetated cay	lagoon	SUM
reef front	75,138	0	0	0	0	0	0	75,138
patch reef	0	1,816	0	0	0	0	0	1,816
reef crest	0	0	42,604	0	0	0	0	42,604
coralgal flat	21,781	0	0	297,581	0	0	21,154	340,516
sand flat	0	0	0	0	40,377	0	0	40,377
vegetated cay	0	0	0	0	0	28,922	0	28,922
lagoon	0	0	0	63,767	0	0	235,788	299,555
SUM	96,919	1,816	42,604	361,348	40,377	28,922	256,942	828,928

Producer (%)	0.78	1	1	0.82	1	1	0.92
User (%)	1	1	1	0.87	1	1	0.78
Hellden (%)	0.87	1	1	0.85	1	1	0.85
KIA Per Class (%)	0.75	1	1	0.7	1	1	0.87

Overall Accuracy (%)	**0.87**
KIA (%)	**0.81**

Table 5. Error matrix for Lizard Island (image only)

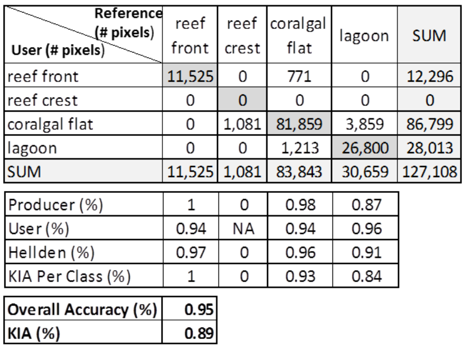


Reference (# pixels) User (# pixels)	reef front	reef crest	coralgal flat	lagoon	SUM
reef front	2,942	0	0	0	2,942
reef crest	0	0	0	0	0
coralgal flat	8,583	1,081	82,630	3,859	96,153
lagoon	0	0	1,213	26,800	28,013
SUM	11,525	1,081	83,843	30,659	127,108

Producer (%)	0.26	0	0.99	0.87
User (%)	1	NA	0.86	0.96
Hellden (%)	0.41	0	0.92	0.91
KIA Per Class (%)	0.24	0	0.94	0.84

Overall Accuracy (%)	**0.88**
KIA (%)	**0.75**

Table 6. Error matrix for Lizard Island (data fusion)



Reference (# pixels) User (# pixels)	reef front	reef crest	coralgal flat	lagoon	SUM
reef front	11,525	0	771	0	12,296
reef crest	0	0	0	0	0
coralgal flat	0	1,081	81,859	3,859	86,799
lagoon	0	0	1,213	26,800	28,013
SUM	11,525	1,081	83,843	30,659	127,108

Producer (%)	1	0	0.98	0.87
User (%)	0.94	NA	0.94	0.96
Hellden (%)	0.97	0	0.96	0.91
KIA Per Class (%)	1	0	0.93	0.84

Overall Accuracy (%)	**0.95**
KIA (%)	**0.89**

The first one is associated with data quality. Subtle and smooth changes in terrain can only be resolved with highly precise and high-resolution datasets such as terrestrial LiDAR. High-resolution bathymetric LiDAR is rarely available and downscaled or interpolated bathymetric datasets are not always suitable for this type of geomorphometric analysis. For example, the average difference between Bet's reef flat and reef crest was approximately 0.5 m and the vertical accuracy of the DEM was estimated to be around 0.6 m.

The second limitation is based on the approach to assess GEOBIA-based mapping accuracy. This is an on-going and challenging field of research. Conventional approaches to assess classification accuracy such as the error matrix (Congalton and Green, 2009) are well suited for assessing thematic accuracy, as traditionally done for pixel-based classifications, but not to assess the object's geometry or reliability of contextual rules. Recent attempts to validate the geometric characteristics of objects (e.g. Persello, 2010; Whiteside et al., 2010) have used reference objects sourced from *ad-hoc* manual interpretation of more 'accurate' or 'reliable' datasets such as aerial photos or high-resolution imagery (Hofmann et al., 2011). However, this is not well-suited for objectively assessing large and fuzzy underwater objects such as intra-reef geomorphological zones. The lack of an adequate framework to quantitatively assess the 'quality' of objects at different scales limits the effective assessment of rule set's robustness and transferability.

In summary, combining optical imagery and elevation data within a GEOBIA framework considerable improves the mapping of coral reef geomorphology and shows great potential for developing robust and transferable rules that could be applied to different reef types across geographic regions. Future research needs to focus on creating rules based on appropriate semantics and ontologies and on adequate approaches to assess the accuracy of GEOBIA-derived products.

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